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Research on the Weights of Subjective Evaluation Metrics of Automobile Squeak & Rattle based on Entropy Method

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Abstract

This study aims to objectively quantify the weights of subjective evaluation metrics for automobile squeak and rattle (S&R) using the entropy method. The paper first elaborates on the theoretical foundation and calculation steps of the entropy method, then integrates the core principles of the Analytic Hierarchy Process (AHP) to construct a comprehensive subjective evaluation framework. The test roads and operating conditions for subjective evaluation were clearly defined. In the evaluation experiment, three experienced engineers assessed five passenger vehicles on a proving ground using a 10-point scoring system. The collected rating data were processed using the entropy method to determine the weights of each metric, followed by the calculation of the overall subjective evaluation score for each vehicle. The results demonstrate that the entropy method, relying on objective data, effectively determines metric weights with high objectivity, providing a more scientific assessment approach for target setting in the early stages of vehicle development.

Keywords

Squeak & Rattle; Subjective Evaluation; Entropy Method; Metric Weights.

1. Introduction

With growing environmental awareness and rapid technological advancements, new energy vehicles (NEVs) have been steadily increasing their market share in the automotive industry. Compared with conventional internal combustion engine (ICE) vehicles, battery electric vehicles (BEVs) exhibit distinct noise, vibration, and harshness (NVH) characteristics[1], primarily due to the elimination of dominant noise sources such as engines, transmission systems, and exhaust systems. However, this technological transition has simultaneously amplified the relative prominence of Buzz, Squeak, and Rattle (BSR) phenomena, which were previously masked by the higher noise levels of ICE vehicles[2]. Recent studies have shown that BSR noise has emerged as a critical factor affecting consumer purchasing decisions and overall product satisfaction[3]. Beyond deteriorating the driving experience, BSR issues also increase post-sales maintenance costs and can negatively impact brand image[4]. Therefore, the development of a scientific and effective BSR evaluation framework is of considerable importance for improving automotive product quality.

Currently, automotive BSR evaluation methods can be broadly divided into subjective and objective approaches[5-7]. Among these, subjective evaluation is widely recognized as the ultimate benchmark for vehicle performance, as it captures human perceptual responses in a comprehensive manner. Nevertheless, conventional subjective evaluation methods face inherent limitations: first, the results are strongly influenced by inter-individual differences among evaluators; second, the assignment of indicator weights is typically based on expert judgment, which lacks objective quantitative

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justification. To overcome these challenges, researchers have proposed a variety of weighting methods. For example, Kang et al.[8] developed a regression analysis–based Analytic Hierarchy Process (RA-AHP) model for subjective evaluation of vehicle dynamic performance. Liu et al.[9] incorporated fuzzy theory to propose the Fuzzy Analytic Hierarchy Process (FAHP), thereby reducing uncertainties in subjective decision-making. Similarly, Liu[10] and Wang[11] applied the Entropy Weight Method (EWM) to objectively determine indicator weights for evaluating vehicle ride comfort and dynamic performance, respectively, and achieved promising results.

Despite these advancements, several limitations remain in the application of subjective evaluation methods to BSR research: (1) most existing studies focus on traditional performance domains such as ride comfort and dynamic performance, with relatively few systematic investigations dedicated to BSR noise evaluation; (2) although AHP and FAHP methods can structurally analyze expert judgments, they are essentially subjective weighting techniques, making it difficult to eliminate evaluator bias[12]; and (3) while the entropy weight method theoretically enables objective weight determination, its application in automotive BSR evaluation has not been thoroughly validated.

To address these gaps, this study adopts the entropy weight method to establish a weight determination model for subjective evaluation indicators of automotive BSR. By quantitatively analyzing the information entropy of evaluation indicators, this method constructs an objective weighting mechanism aimed at enhancing the accuracy and reliability of BSR evaluation. The feasibility and effectiveness of the proposed approach are verified through practical case studies. This research not only offers a novel perspective on BSR performance assessment but also broadens the application scope of the entropy weight method in the NVH domain.

2. Subjective Evaluation Methods for Automotive Squeak and Rattle

Table 1. 10-point Subjective Evaluation

<table>
<tr><td>Evaluation criteria</td><td colspan="4">Unacceptable area</td><td colspan="2">Critical area</td><td colspan="3">Acceptable area</td><td>Perfect</td></tr>
<tr><td>Rating score</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td>Requirements description</td><td>Serious defect</td><td>Defective</td><td>Serious unsatisfied</td><td>Unsatisfied</td><td>Normal</td><td>Critical</td><td>Satisfied</td><td>Highly satisfied</td><td>Excellent</td><td>Exceed expectation</td></tr>
<tr><td rowspan="2">Users' assessment and reaction</td><td colspan="3">absolutely unacceptable</td><td>conditionally acceptable</td><td>extremely disappointed</td><td>Disappointed</td><td>Acceptable</td><td>Convincing</td><td>Compelling</td><td>Astonishing</td></tr>
<tr><td colspan="4">Rejected</td><td>complain</td><td>Tolerant</td><td>acceptable</td><td>appreciate</td><td>admirable</td><td>masterful</td></tr>
<tr><td>Users' complaints</td><td colspan="4">All users complain</td><td>Most of users complain</td><td>Critical users complain</td><td colspan="4">No complaint</td></tr>
<tr><td>Problem symptom</td><td>Totally failed</td><td>General failed</td><td>Functional degraded</td><td>Extremely failed</td><td>severely insufficient</td><td>Insufficient</td><td>Expert-identified defects</td><td colspan="3">No defect</td></tr>
<tr><td>Consequences for the users</td><td colspan="2">Vehicle failure</td><td colspan="2">Pattern failure</td><td>Frequently failure</td><td>Occasionally failure</td><td>Satisfied</td><td>Very satisfied</td><td>Delighted</td><td>Thrilled</td></tr>
<tr><td>Necessity of implementing the design optimization</td><td>Comprehensive optimization</td><td colspan="3">Repair immediately</td><td colspan="2">Guaranteed enhancement</td><td colspan="3">Highly refined</td><td>Potential for cost savings</td></tr>
</table>

Automakers are facing growing demands to reduce development costs and accelerate product development cycles. Consequently, the number of physical prototype vehicles available for validation has been substantially reduced[13]. To meet this challenge, the deployment of advanced squeak and rattle (S&R) development and validation techniques has become increasingly important, as these methods can effectively lower production expenses, improve product quality, and enhance manufacturing efficiency.

In response to such cost constraints, leading international automakers have established systematic approaches for evaluating S&R phenomena and implementing targeted measures to ensure vehicle quality. Two decades ago, the subjective evaluation framework for vehicle quality has been primarily shaped by the methodologies developed by Professors Bernd Heising and Hans-Jürgen Brandl[14]. Both scholars have made significant contributions to the theoretical underpinnings, application contexts, and engineering practices of subjective vehicle assessment. With extensive prior experience at Germany OEMs, their work is firmly rooted in practical industrial applications, resulting in a mature, validated, and widely adopted system for subjective vehicle quality evaluation. Within this framework, S&R performance degradation is quantified using a standardized 10-point scale, as summarized in Table 1.

In parallel, Japanese OEM has also developed systematic vehicle evaluation standards. Nissan introduced the Vehicle Evaluation Standard (VES) , which later became widely recognized as the Alliance Vehicle Evaluation Standard. The VES was issued to better accommodate the demands of global manufacturing plants and the growing expectations of international markets. In light of the increasing globalization of quality management, dynamic corporate activities, and continuous innovations in operational practices. To ensure its long-term applicability, the AVES standard was designed to undergo annual revisions. Importantly, the AVES framework emphasizes evaluation from the customer's perspective, with a particular focus on identifying quality defects and potential issues that are most likely to trigger consumer complaints. Within this framework, evaluation levels are sequentially classified into four categories: V1+, V1, V2, and V3.

Table 2. AVES Evaluation Standard

Evaluation Levels	Definition of Evaluation Levels
V1+	The vehicle exhibits no detectable BSR issues under any operating conditions.
V1	Minor BSR noises may occur under extreme conditions but are not perceptible during normal operation.
V2	Noticeable BSR noises are present under normal driving conditions, potentially causing customer dissatisfaction.
V3	Severe BSR issues that significantly impact customer experience and brand perception.

The corresponding customer requirements and responses for each evaluation level are as follows:

Table 3. Customers Evaluation Levels Requirements

<table>
<tr><th>Evaluation levels</th><th>Customer responses</th><th>Maintain requirement</th><th>Detection difficulty</th><th>Quality survey reporting</th></tr>
<tr><td>V1+,V1</td><td>Strong unsatisfied</td><td>Required</td><td>Easily detectable</td><td>Reported by nearly all customers</td></tr>
<tr><td>V2</td><td>unsatisfied</td><td rowspan="2">Not required</td><td rowspan="2">Difficult to detect</td><td>Reported by some customers</td></tr>
<tr><td>V3</td><td>Acceptable</td><td>Rarely reported by customers</td></tr>
</table>

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By adopting a customer-centered philosophy, the AVES system serves as both a quality monitoring tool and a driver of continuous improvement. Given that squeak and rattle (S&R) performance is a critical determinant of perceived vehicle quality, the evaluation of its degradation at high mileage is particularly aligned with real-world customer experiences.

In the United States, SAE J1441 provides the standard for subjective rating scales in automotive evaluation. However, this standard exhibits several limitations. First, SAE J1441 does not provide detailed descriptions or specific guidance for each score level, resulting in vague and imprecise definitions[15]. Second, the scale consists of an even number of points without a central neutral option, instead relying on a broad intermediate range. This structure reduces sensitivity and precision. In practice, because S&R performance represents a negative attribute of vehicle quality, most ratings fall within the undesirable range and frequently cluster near the boundary zone. Such clustering effectively shortens the usable length of the rating scale to approximately four points. Consequently, even well-trained evaluators encounter difficulties in reliably distinguishing between performance levels.

Table 4. SAE（J1441）Subjective Rating Standard

Very poor		Poor		Normal		Good		Excellent	
1	2	3	4	5	6	7	8	9	10
No expectation area			boundary			expectation area			

To address this issue, a ten-point continuous subjective evaluation scale was later developed, with descriptive adjectives provided at every two-point interval, as shown in Table 4. In this scale, scores of 1–3 represent the “undesirable” range, scores of 7–10 represent the “desirable” range, and scores of 4–6 define the transitional boundary zone. This refined structure enhances both rating sensitivity and evaluator discrimination, thereby improving the reliability of subjective S&R assessments.

3. Determination of Subjective Evaluation Metric Weights

3.1 Fundamental Principles of the Entropy Method

The basic concept of the entropy method is that within a system, the greater the amount of information, the smaller the degree of uncertainty and the entropy, resulting in a higher weight; conversely, the smaller the amount of information, the greater the uncertainty and the entropy, leading to a lower weight[16]. Suppose there are m alternative schemes to be evaluated and n evaluation indicators, forming an original indicator data matrix $X=(X_{ij})_{m\times n}$， where $0\le i\le m$， $0\le j\le n$. For the j-th indicator, the greater the variation among the indicator values x_{ij}, the more significant its role in the comprehensive evaluation[17]. Conversely, if the values of a particular indicator are identical across all alternatives, that indicator contributes no discriminatory power and thus plays no role in the comprehensive evaluation.

3.2 Entropy Method Calculation Procedure

This paper constructs a subjective evaluation system for squeak and rattle (S&R) performance by integrating the fundamental principles of the Analytic Hierarchy Process (AHP) and determining indicator weights using the entropy method. The specific computational steps are as follows[18]:

(1) Analyze the relationships among indicators influencing S&R performance to establish a hierarchical structural model, and construct the original data matrix:

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$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

where X denotes the original evaluation matrix; x_{ij} represents the value of the j-th indicator for the i-th scheme; mm is the number of schemes to be evaluated; and n is the number of evaluation indicators.

(2) Normalize the indicators to ensure dimensional homogeneity, and calculate the normalized weight p_{ij} of the i-th scheme under the j-th indicator:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (2)$$

where p_{ij} denotes the normalized weight of the i-th scheme under the j-th indicator.

(3) Calculate the entropy E_j of the j-th indicator:

$$E_j = -k\sum_{i=1}^{m} p_{ij}\ln(p_{ij}) \ \text{with}\ k = \frac{1}{\ln(n)} \quad (3)$$

where E_j is the entropy value of the j-th indicator; $E_j \geq 0$, $k>0$, and $0 \leq E_j \leq 1$. Information entropy is inversely proportional to the degree of order within the information system. When the information is completely disordered, $E_j=1$.

(4) Calculate the divergence (or variation coefficient) dj of the j-th indicator:

$$d_j = 1 - E_j \quad (4)$$

where d_j denotes the divergence coefficient of the j-th indicator, and E_j is its entropy value.

(5) Determine the weight wj of each indicator in the overall evaluation:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad (5)$$

where w_j is the weight of the j-th indicator.

(6) Calculate the comprehensive subjective evaluation score yi for each sample:

$$y_i = \sum_{j=1}^{m} x_{ij} \times \left(w_j\right) \quad (6)$$

where y_i represents the overall evaluation score of the i-th sample.

4. Weight Determination of Subjective Evaluation Metric Using Entropy Method

4.1 Initial Squeak and Rattle Evaluation Matrix

Based on the fundamental principles of the Analytic Hierarchy Process (AHP), this study categorizes the test conditions for evaluating automotive squeak and rattle (S&R) performance into three types: smooth road, typical road, and rough road. Additionally, S&R severity is classified into three levels:

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severe, moderate, and slight. Combining these conditions and severity levels yields a total of nine evaluation indicators. On a specialized S&R evaluation course at a test track, engineers conducted subjective assessments on five passenger vehicles according to standardized operating procedures and assigned scores. These scores constitute the initial evaluation matrix. The test conditions and S&R severity levels are detailed in Tables 5 and 6, respectively.

Table 5. Test Conditions and Road Surface Descriptions

Test Condition	Road Surface Description	Remarks and Explanation
Smooth Road	Road surface condition is classified as excellent or good according to the Pavement Condition Index (PCI), equivalent to highways or similarly graded roads with smooth asphalt surfaces.	Low surface roughness and high flatness; low cumulative bump or gap values; uniform distribution of paving materials (e.g., asphalt, concrete) without local accumulation or loss.
Typical Road	Road surface condition is classified as fair or poor according to PCI, equivalent to secondary or tertiary roads in the public road network.	Moderate degree of surface distress, functional degradation, or structural damage present.
Severe Rough Road	Road surface condition is classified as poor or failed according to PCI, equivalent to unpaved roads or severely deteriorated, unrepaired roads in the public network.	Very severe damage; reconstruction is typically required.

Table 6. Squeak and Rattle Severity Levels and Descriptions

Severity Level	Severe S&R (A)	Moderate S&R (B)	Slight S&R (C)
10-Point Rating	< 4 points	5–6 points	> 7 points
Evaluation Description	A clearly audible and loud noise originating from the evaluation point is distinctly perceived by assessors under normal seating conditions at any seating position.	A moderately audible noise from the evaluation point is clearly perceived by assessors under normal seating conditions at any seating position.	A faint noise from the evaluation point is barely perceptible to assessors under normal seating conditions at any seating position.
Customer Perception and Reaction	Severely unsatisfactory	Moderately unsatisfactory	Marginally unsatisfactory
Customer Complaint Level	All customers would complain	Most customers would complain	Only trained or professional evaluators may complain
Necessity for Design Optimization	Comprehensive optimization required	Further improvement required	Improvement required only when necessary

In this study, the subjective evaluation scores from one of the three engineers (Engineer A) were selected for analysis. The results are presented in Table 7.

Table 7. Hierarchical Analytic Structure for Subjective S&R Evaluation and Scoring Results from Engineer A

Evaluation Objective	Evaluation Indicator	Road Conditions	Vehicle type				
			VehicleI	VehicleII	VehicleIII	VehicleIV	VehicleV
Squeak & Rattle	Customer Satisfaction and Reaction	Smooth Road	7. 25	7.00	6.50	7. 25	7. 25
		Typical Road	7. 00	6. 75	6. 50	7. 50	7. 25
		Rough Road	7. 00	7. 00	7. 25	6. 75	7. 00
	Customer Complaint Level	Smooth Road	7. 25	6. 75	7. 00	7. 00	6. 75
		Typical Road	7. 25	7. 25	7. 00	6. 50	6. 75
		Rough Road	7. 25	7. 00	6. 50	6. 75	7. 00
	Necessity for Design Optimization	Smooth Road	7. 25	6. 75	6. 50	6. 75	6. 75
		Typical Road	7. 25	6. 75	7. 00	6. 50	6. 75
		Rough Road	7. 00	6. 50	7. 25	6. 25	6. 50

4.2 Determination of Indicator Entropy Values and Weights

Using the entropy method calculation procedure outlined in Section 2.2, the entropy values, information utility values, weights, and comprehensive evaluation scores for the subjective evaluation indicators of overall vehicle squeak and rattle (S&R) performance were computed. The entropy values, information utility values, and weights are presented with six decimal places, while the comprehensive evaluation scores are rounded to two decimal places. The results are summarized in Tables 8 and 9.

Table 8. Weights of Subjective Squeak and Rattle Performance Evaluation Indicators

Evaluation Indicator		Entropy Value E_j	Information Utility Value d_j	Weight w_j
Customer Satisfaction and Reaction	A	0.8958	0.1042	0.0846
	B	0.9073	0.0927	0.0739
	C	0.8971	0.1029	0.0839
Customer Complaint Level	D	0.9079	0.0921	0.0736
	E	0.9046	0.0954	0.0752
	F	0.9029	0.0971	0.0761
Necessity for Design Optimization	G	0.9027	0.0973	0.0762
	H	0.9074	0.0926	0.0736
	I	0.9060	0.0940	0.0748

Table 9. Comprehensive Squeak and Rattle Performance Scores

Comprehensive S&R Scores	VehicleI	VehicleII	VehicleIII	VehicleIV	VehicleV
	7. 144 948	6. 846 108	6. 816 682	6. 797 314	6. 903 466

4.3 Analysis of Evaluation Indicator Weight Results

The results indicate that among the five test vehicles, Vehicle I achieved the highest subjective comprehensive score for squeak and rattle (S&R) performance, suggesting it exhibits the best S&R

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performance under the established evaluation system. Vehicles V, II, and III obtained relatively lower comprehensive scores, reflecting correspondingly inferior S&R performance. Vehicle IV received the lowest comprehensive score, indicating the poorest S&R performance among the tested vehicles.In automotive industry practice, radar charts are commonly employed during the subjective evaluation of overall vehicle S&R performance to visually represent the scores of different test vehicles across all evaluation indicators. This visualization enables a straightforward comparison of vehicle performance for each specific indicator. In such radar charts, a larger enclosed area generally corresponds to better overall subjective comfort performance. The radar charts depicting the subjective evaluation scores for each test vehicle are presented in Figure 1.

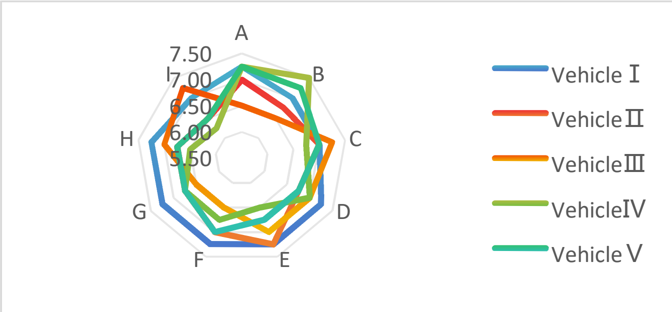

Figure 1. Chart of S&R Evaluation Scores for Different Vehicles

As shown in Figure 1, Vehicle I achieves the highest subjective comprehensive score for comfort performance, while Vehicle IV obtains the lowest subjective comprehensive score for squeak and rattle performance. Among all test vehicles, Vehicle III exhibits the largest variation across individual evaluation indicators, indicating that its S&R scores are the most dispersed.

5. Conclusion

This study integrates the entropy method with subjective evaluation indicators to establish a comprehensive assessment framework for automotive S&R. By relying on objective sample data, the proposed approach provides a quantitative basis for subjective evaluation.

(1) The entropy method enables an objective quantitative analysis of the subjective evaluation system for automotive S&R performance. By calculating indicator weights from the original information entropy of sample data, the method uncovers intrinsic relationships among evaluation indicators. Specifically, larger variability in indicator values corresponds to greater information content, reduced uncertainty, lower entropy, and thus higher assigned weights. Conversely, higher consistency among indicator values indicates less information content, increased uncertainty, higher entropy, and correspondingly lower weights.

(2) Five test vehicles were selected as representative samples. Based on their S&R performance evaluation data, the entropy method was applied to obtain a comprehensive subjective assessment of vehicle comfort. The results show that, across different test conditions, the overall ranking of the five vehicles in terms of subjective comfort performance is: Vehicle I > Vehicle V > Vehicle II > Vehicle III > Vehicle IV.

(3) The weight coefficients determined by the entropy method are inherently dependent on the input sample data. In subjective evaluations, differences in evaluators' understanding of the indicators lead to variations in scoring, which subsequently affect the calculation of entropy values and weight distributions. As a result, the comprehensive subjective S&R performance scores not only reflect the statistical properties of the data but also embody evaluators' preferences and interpretations of specific criteria.

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