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Research on Comprehensive Performance Testing and Evaluation Method of Vehicle Parking Radar

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Abstract: As a critical component of parking assistance systems, their performance directly influences the accuracy and reliability of vehicle parking operations. This paper enriches the testing scenarios for automotive parking radars. Specifically, it employs multiple test vehicles to conduct acoustic index tests on different types of obstacles at various testing angles. Acoustic signal characteristics, including frequency, signal-to-noise ratio, loudness, and response timeliness, were analyzed using Fast Fourier Transform (FFT), signal-to-noise ratio analysis, and sensor analysis techniques to investigate the correlations among various acoustic indicators under differing conditions. The test data is processed through the ICC analysis method, the quadratic polynomial regression analysis method, and the technique for order preference by similarity to ideal solution (TOPSIS). The results show that the comprehensive test scenario for parking radar established in this paper can comprehensively test and verify the acoustic performance indicators of the radar, and provide a comprehensive evaluation of the parking performance of the vehicle's parking radar.

Keywords: Parking Radar; Comprehensive Performance Evaluation; Obstacle; Fast Fourier Transform; Quadratic Polynomial Regression Analysis; Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

1. Introduction

With the rapid development of the automotive industry and accelerated urbanization, vehicle ownership has continued to rise, leading to increasingly complex urban road and parking environments. Parking safety has thus become a critical research focus in the field of automotive safety [1]. According to statistics from the Ministry of Public Security, China's vehicle fleet exceeded 400 million units in 2024, with passenger cars accounting for approximately 84% of the total. Incidents occurring during parking constitute a significant proportion of urban traffic accidents [2]. As a core component of parking assistance systems, automotive parking radar operates by emitting and receiving ultrasonic signals to detect the distance between the vehicle and surrounding obstacles in real time, providing feedback to the driver. This effectively reduces the incidence of parking-related accidents, and its performance reliability is directly linked to the safety of occupants and the surrounding environment[3-4].

The performance metrics of parking radars-such as frequency, response time, and signal-to-noise ratio-are influenced by multiple factors including test scenarios, obstacle types, and environmental conditions. Current testing methodologies, both domestically and internationally, primarily focus on performance validation using single-type obstacles and standard angles. Existing test standards offer insufficient coverage of complex scenarios, resulting in significant discrepancies between laboratory results and real-world applications. Moreover, while existing research often emphasizes distance detection accuracy[5], there is limited analysis of the relationship between acoustic indicators (e.g., signal frequency, signal-to-noise ratio, loudness) and practical user experience (e.g., response timeliness), making it difficult to comprehensively evaluate the overall performance of parking radars[6]. Therefore, establishing a comprehensive evaluation system for parking radars that integrates multiple scenarios and synergistic indicators holds significant theoretical and engineering value for advancing parking assistance technology and enhancing vehicle safety.

International research on parking radar testing began relatively early. For instance, EU Regulation No. 158[7] specifies certification requirements for parking radars using only cylindrical obstacles. Similarly, although the Euro NCAP[8] parking assistance scoring system incorporates various obstacle types (e.g., pedestrians, cylindrical objects), its testing angles remain limited to common forward-facing orientations. The ISO 15006[9] standard developed by the European Standards Institute includes tests for various acoustic performance indicators but lacks comprehensive research on the integrated acoustic performance in dynamic scenarios. Domestically, researchers from the State Key Laboratory of Automotive Simulation and Control at Jilin University[10] developed a model for ultrasonic radar performance in automatic parking systems under varying atmospheric conditions and identified the impact of such conditions on radar performance. However, this study did not address subjective errors arising from multiple test samples, nor did it establish a correlation model between acoustic indicators and performance evaluation.

Addressing issues such as limited test scenarios and incomplete evaluation systems in existing studies, this paper focuses on the comprehensive performance testing and evaluation of automotive parking radars. A multi-angle test scenario was constructed involving multiple testers and five experimental vehicles, with three types of obstacles: juvenile soft mannequins, traffic cones, and stone curb blocks. Post-test analysis employed Fast Fourier Transform (FFT) to extract signal frequency characteristics, combined with signal-to-noise ratio analysis and response time analysis techniques to quantify differences in acoustic indicators across scenarios. The Intraclass Correlation Coefficient (ICC) method was used to eliminate subjective variances among testers, and quadratic polynomial regression analysis was applied to examine the effect of test angle on response time. Finally, a multi-dimensional acoustic indicator evaluation model was established based on the Technique for Order of

Preference by Similarity to Ideal Solution (TOPSIS), forming a comprehensive evaluation system. This provides new methodologies and theoretical support for parking radar testing and parking safety research in the automotive industry.

2. Research Methodology and Analytical Framework

2.1. Frequency Signal-to-Noise Ratio and Loudness Test

The five test vehicles, all provided by their respective manufacturers, are designated as Vehicle A, B, C, D, and E. Testing was conducted at the Whole Vehicle Image Laboratory of China Automotive Technology and Research Center (Tianjin) Co., Ltd. The experimental test platform is configured as illustrated in Figure 1. Since frequency testing is performed under static conditions and is unaffected by the Doppler effect, and as frequency values are fixed parameters determined by the ultrasonic radar hardware, a single obstacle was utilized for frequency evaluation. The raw signals of the parking radar alerts, captured in the time domain, underwent preprocessing involving DC component removal and filtering. Given the complex and non-strictly periodic nature of the signals, conventional periodic analysis methods are inadequate; hence, Fast Fourier Transform (FFT) was employed to convert the time-domain signals into the frequency domain.

In accordance with the Nyquist sampling theorem:

$$Fs \geq 2F\text{max}$$

where Fs denotes the sampling rate;

Fmax denotes the maximum frequency of the signal.

The preprocessed time-domain signal x[n] (n=0,1,...,N-1) is subjected to Fast Fourier Transform (FFT), yielding a frequency-domain complex array X[k] (k=0,1,...,N-1), where k denotes the frequency index.

The actual frequency corresponding to each index k in the frequency domain is:

$$F_k = \frac{kFs}{N}\left(\text{k} < N/2\right)$$

where N denotes the length of the acquired signal.

In the frequency domain, the frequency F_k corresponding to the peak of X[k] (magnitude spectrum) represents the dominant frequency of the signal. The data analysis is illustrated in Figure 2.

In the calculation of signal-to-noise ratio, the voltage amplitude (root mean square value) is employed for computation, where power is proportional to the square of the voltage.

Signal average power:

$$Ps = \frac{1}{Ns}\sum_{i=1}^{Ns} s[i]^2$$

Average noise power:

$$Pn = \frac{1}{Nn}\sum_{j=1}^{Nn} n[j]^2$$

Where:

s[n] (length Ns) denotes the voltage sequence in the signal interval;

n[n] (length Nn) represents the voltage sequence in the noise interval.

The SNR calculation formula is expressed in decibels as:

$$\text{SNR（d}B\text{）} = 20\lg\left(\frac{Vs,rms}{Vn,rms}\right)$$

Among them: Vs,rms=$\sqrt{Ps}$, Vn,rms=$\sqrt{Pn}$.

Data analysis results are presented in Figure 3.

During the loudness analysis, multiple measurements were averaged to account for environmental influences. The alarm sound signals were captured via a microphone sensor and subjected to preprocessing and noise reduction procedures. The subsequent data analysis is illustrated in Figure 4.

Figure 1. Setup of Frequency and Signal-to-Noise Ratio Experiment

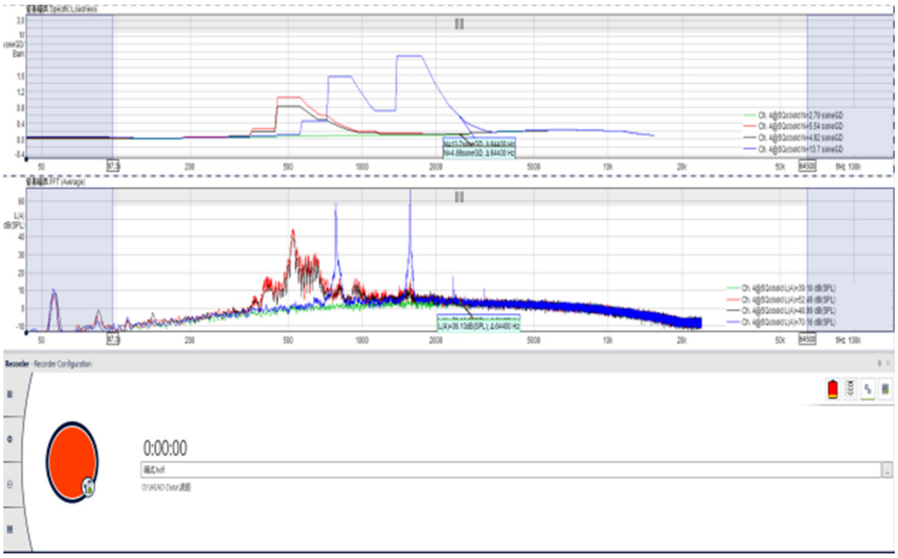

Figure 2. Data Analysis of Frequency Testing

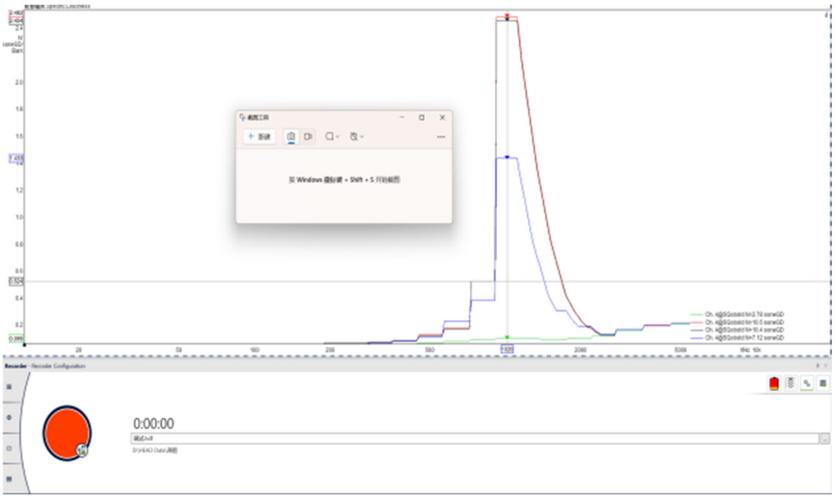

Figure 3. Data Analysis of Signal-to-Noise Ratio Testing

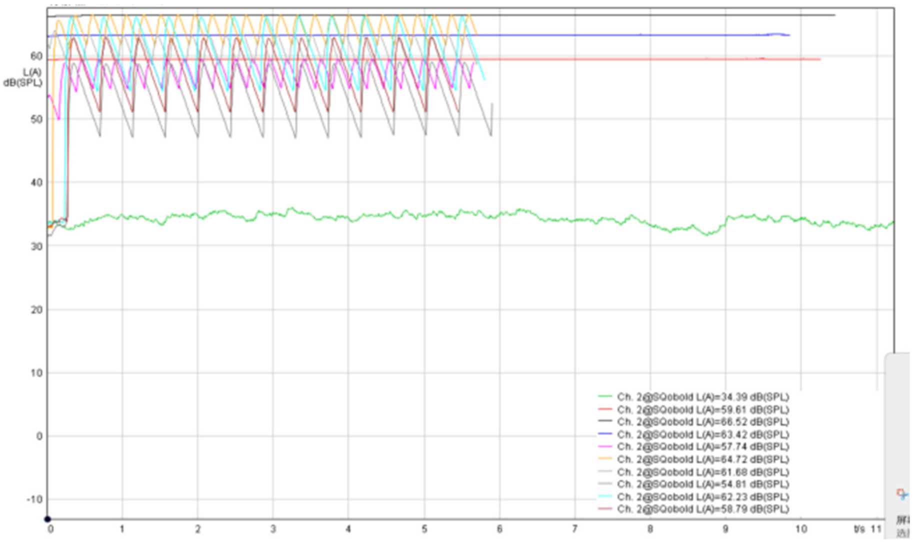

Figure 4. Data Analysis of Loudness Testing

Following the final testing of five experimental vehicles, the data pertaining to frequency, signal-to-noise ratio, and loudness are presented in Tables 1, 2, and 3 respectively.

Table 1. Frequency Test Data

Item	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E
Direct frequency (Hz)	850	410	2800	335	1800
centre frequency (Hz)	800	400	2500	315	2000

Table 2. Signal-to-Noise Ratio Test Data

Item	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E
Signal-to-Noise Ratio (Dummy)	10.5	33.5	2.74	35.3	5.8
Signal-to-noise ratio (traffic cone)	10.7	34.5	2.88	35.9	5.9
Signal-to-noise ratio (stone isolation pylon)	11.7	35.1	3.01	36.2	6.5

Table 3. Loudness Test Data

Item	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E
Volume 1	45.2	55.8	65.1	62.3	40.5
Volume 2	45.2	55.7	39.9	62.0	40.5
Volume 3	45.2	55.9	40.1	63.2	40.6
average value	45.2	55.8	40.0	62.5	40.5

As shown in Table 1, the acoustic signal frequencies of Vehicle C and E are significantly higher. The sound frequencies of Vehicle B and D fall within the range most comfortable to human perception, with no subjectively noticeable dullness or harshness. Table 2 indicates that the signal-to-noise ratio undergoes subtle variations with changes in obstacles. The performance disparity in signal-to-noise ratio across different vehicles is significantly more pronounced for concrete barriers compared to traffic cones, while traffic cones slightly outperform dummy obstacles, though the difference is marginal. The primary reason is that the characteristics of obstacles directly affect the quality of the raw signals received by the reversing radar system. Table 3 reveals considerable variations in loudness among the test vehicles. Vehicles A and E exhibit lower decibel levels, making them susceptible to environmental interference that may impair driver judgment. In contrast, Vehicle C has an excessively high decibel value, which may cause auditory discomfort to the driver.

2.2. Response Time Performance Testing

In the study on the responsiveness of parking radar systems, a juvenile soft manikin was selected to represent common pedestrians for investigating temporal characteristics. The experimental setup is illustrated in Figure 5. During the test, a constant-speed cart carrying an obstacle approached the vehicle from 1.5 meters behind at a speed of 3 km/h, following various angles relative to the vehicle's central axis. The moment the parking radar alarm sounded was recorded as t1, and the instant the driver pressed the brake pedal immediately upon hearing the alarm was recorded as t_2. The time difference between t_1 and t_2 constitutes the response time of the parking radar, reflecting the driver's reaction speed in braking promptly after hearing the alert in a parking scenario. A shorter time interval indicates quicker auditory feedback, enabling faster braking response by the driver, thereby demonstrating superior promptness and facilitating more timely user reactions. Time data acquisition was accomplished using sensor technology and an oscilloscope, with data analysis presented in Figure 6.

In the design of test angles, the fundamental principle is to cover both the core detection range and the threshold values at the periphery. The initial test angle is set at 0° relative to the vehicle's central axis, representing the direct rear scenario—the most common use case—to validate the radar's accuracy in detecting obstacles directly behind the vehicle. Test angles of 15° and 30° are designated to evaluate the radar's performance within its core operational zone. Angles of 45° and 60° are selected to assess the radar's detection capabilities at the outer edges. Finally, an 80° test angle is established to examine the system's response speed at the extreme limits of its detection range.

Figure 5. Setup of the Response Timeliness Experiment

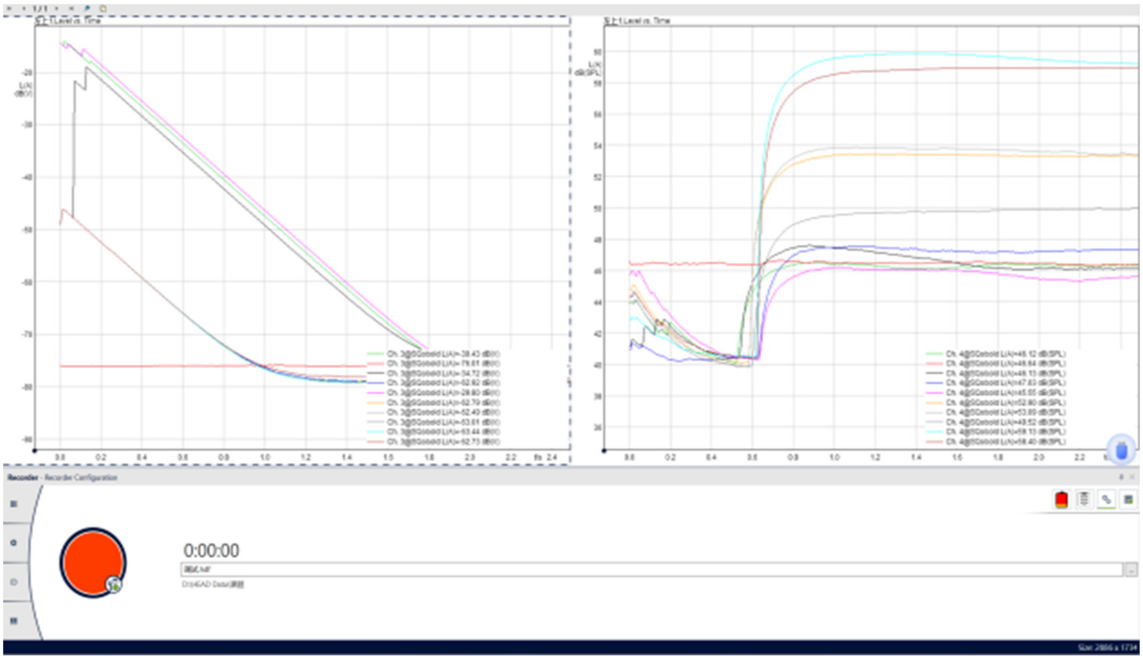

Figure 6. Data Analysis of Responsiveness Timeliness Testing

Table 4. Response Time Test Data 1

Item	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E
0°	0.3420	0.3258	0.5328	0.2447	0.5350
15°	0.3539	0.3371	0.5329	0.2488	0.5477
30°	0.3128	0.3121	0.5210	0.2328	0.5328
45°	0.3157	0.3157	0.5120	0.2431	0.5341
60°	0.3579	0.3597	0.5328	0.2488	0.5476
80°	0.3593	0.3579	0.5355	0.2580	0.5491

Table 5. Response Time Test Data 2

Item	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E
0°	0.4430	0.3769	0.5330	0.3465	0.5337
15°	0.4554	0.3901	0.5331	0.3502	0.5479
30°	0.4127	0.3638	0.5318	0.3318	0.5326
45°	0.4157	0.3677	0.5319	0.3359	0.5343
60°	0.4579	0.3111	0.5333	0.3571	0.5478
80°	0.4544	0.3124	0.5357	0.3572	0.5488

Table 6. Response Time Test Data 3

Item	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E
0°	0.3425	0.3263	0.5328	0.2456	0.5369
15°	0.3548	0.3390	0.5331	0.2497	0.5479
30°	0.3130	0.3128	0.5317	0.2322	0.5330
45°	0.3159	0.3169	0.5319	0.2377	0.5349
60°	0.3577	0.3600	0.5330	0.2581	0.5455
80°	0.3582	0.3604	0.5357	0.2579	0.5480

In the evaluation of temporal characteristics, the subjective bias of drivers may introduce significant measurement errors. To mitigate this, three independent testers conducted evaluations on five test vehicles respectively. The resulting data are presented in Tables 4, 5, and 6.

As evidenced in Tables 4, 5, and 6, the results from the three test subjects demonstrate a high degree of consistency. Vehicles D and B exhibit superior response time characteristics, indicating that drivers promptly applied the brakes upon hearing the alarm signal. This enhanced alert effectiveness facilitates more timely user reactions and provides superior cueing performance.

2.3. Research Method

2.3.1. Data Initialization

Prior to conducting data analysis, data normalization must be completed, as subsequent analytical procedures will be based on standardized data. Data normalization refers to the process of index standardization for statistical data. This procedure primarily involves two aspects: data homogenization and non-dimensionalization. The core objective of data homogenization is to address issues arising from data of differing natures. Direct summation of indicators with disparate characteristics fails to accurately reflect comprehensive outcomes; hence, it is necessary to transform the properties of inverse indicators so that all indicators exert a consistent directional influence on the evaluation scheme before aggregation, thereby ensuring correct results. Non-dimensionalization, on the other hand, focuses on resolving data comparability issues. It eliminates unit constraints by converting data into dimensionless pure numerical values, enabling effective comparison and weighting of indicators with different units or magnitudes. Numerous methods exist for data normalization, and this study employs the min-max normalization approach:

$$X_i = \frac{P_i - P_{\min}}{P_{\max} - P_{\min}}$$

In the formula: P_i represents the data of the i-th vehicle, $P_{\min}$ is the minimum value, and $P_{\max}$ is the maximum value.

2.3.2. Intraclass Correlation Coefficient (ICC) Consistency Assessment

The Intraclass Correlation Coefficient (ICC) consistency analysis is a statistical method used to evaluate the degree of agreement among measurements obtained from multiple observers (or different measurement methods or time points) when assessing the same set of subjects. This method is primarily employed to assess the reliability of measurement outcomes, particularly for continuous variables, as it effectively reflects the closeness among observed values, i.e., the actual measurements.

In practical applications, the key aspect of ICC consistency analysis lies in quantifying the relationship between "the variability inherent to the measured subjects" and "the total variability (which encompasses both subject-specific variability and variability introduced by observers, methods, time, etc.)" through the calculation of the intraclass correlation coefficient:

When the ICC value approaches 1, it indicates a high level of consistency in the measurement results, suggesting that the variability among observers (or under different measurement conditions) is minimal, and the differences in measurements are primarily attributable to the true characteristics of the subjects themselves.

Conversely, when the ICC value is closer to 0, it signifies weak consistency, implying that the variability in the measurements arises more from external factors such as observers, measurement methods, or time points, rather than from actual differences among the subjects.

The ICC encompasses multiple computational models, including one-way random effects models, two-way random effects models, and two-way mixed effects models. The selection of an appropriate model depends on the research design, such as whether observers are randomly selected or whether consistency among specific observers is of interest. Given that three testers participated in the response timeliness experiment discussed herein, a one-way random effects model was adopted for the ICC consistency analysis to mitigate the influence of subjective human factors on the experimental outcomes.

2.3.3. Regression Analysis

Regression analysis constitutes a critical category of statistical analytical methods designed to quantify the dependent relationships between two or more variables. Based on the number of independent variables, it can be classified as simple or multiple regression; according to the number of dependent variables, it may be categorized as univariate or multivariate regression; and depending on the functional form of variable relationships, it is further divided into linear and nonlinear regression. Its primary objective is to elucidate the magnitude and direction of the influence exerted by independent variables on the dependent variable, while precisely interpreting the mechanism underlying changes in the dependent variable by controlling for confounding factors from other variables.

As a specific form of regression analysis, polynomial regression demonstrates robust curve-fitting capabilities. By incorporating higher-order terms of independent variables (such as quadratic, cubic, and beyond), it flexibly approximates observed data, making it particularly suitable for addressing various nonlinear problems. Given that any function can be locally approximated via polynomials, polynomial regression is widely applied in empirical research to characterize complex relationships between independent and dependent variables.

Within the context of this study, wherein multiple vehicles undergo response time testing across six distinct angles, quadratic polynomial regression is employed to accurately identify the optimal obstacle angle corresponding to the shortest response time for each vehicle. This approach involves constructing separate regression models for each vehicle, effectively capturing individual angle-specific effects while mitigating interference from inter-vehicle variability. Through model fitting, the optimal angle for each vehicle can be determined, thereby providing concrete directional guidance for enhancing vehicular performance.

2.3.4. Technique for Order of Preference by Similarity to Ideal Solution

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is a classical approach widely employed for comprehensive intra-group evaluation. This method effectively utilizes the information inherent in raw data, ensuring that evaluation results accurately reflect distinctions among different alternatives. The fundamental procedure involves: first normalizing the original data matrix; subsequently identifying the positive-ideal and negative-ideal solutions within the finite set of alternatives; then calculating the distances between each evaluation object and these ideal solutions; and ultimately deriving the relative closeness coefficient to the positive-ideal solution, which serves as the basis for ranking and evaluation. This technique imposes no stringent requirements on data distribution or sample size, and its computational process is straightforward and practicable. It not only clearly demonstrates inter-alternative disparities but also objectively and authentically reflects actual conditions, boasting advantages such as result reliability, strong intuitiveness, and high authenticity, while imposing no special requirements on sample data. The TOPSIS method enables holistic analysis and evaluation from an integrated perspective, exhibiting broad applicability and significant universal value across diverse contexts.

The TOPSIS method is formulated as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \left(Z_{ij\max} - Z_{ij}\right)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} \left(Z_{ij\min} - Z_{ij}\right)^2}$$

$$L_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

Among them, Z_{ijmax} is the maximum value of the same indicator in the initial matrix, and Z_{ijmin} is the minimum value of the same indicator in the initial matrix.

3. Data Analysis and Findings

3.1. Intraclass Correlation Coefficient Consistency Analysis

In the responsiveness test, three evaluators were selected to ensure the stability of measurement results for subsequent analysis. An inter-rater reliability assessment was consequently performed on the experimental data. ICC2 (two-way random effects model) was employed, accounting for random effects from both raters and measured subjects.

Using the Reliability Analysis module in SPSS software, the corresponding model parameters were configured with the following selections: correlation analysis—intraclass correlation coefficient (ICC), and the analysis method set to two-way random–absolute agreement (ICC2). The ANOVA results are presented in Table 7, and the iterative computation outcomes are shown in Table 8.

Table 7. Analysis of Variance (ANOVA) Table

origin	sum of squares	free degree	mean square	F
target	1.324	29	0.0457	75.23
Test engineer	0.246	2	0.123	202.3
residual	0.035	58	0.000607	

Table 8. Analysis Results

	ICC	95% confidence interval	F-test (DF1, DF2)	p
value	0.942	0.897 - 0.970	F(29,58) =75.23	< 0.001

The results indicate that the Intra - Class Correlation (ICC) value is 0.942 (close to 1), suggesting a high level of consistency among the measurement results obtained by the three testers. The differences in the measured values stem almost entirely from the vehicle - angle combinations being measured, rather than from the different testers. Therefore, the testing method for the response time is highly reliable. When different testers use this method to test the same vehicle, they can obtain highly consistent and reproducible results. The measurement error is extremely small, and the data quality is very high. The data can be used for subsequent analysis and comparison of vehicle performance.

3.2. Quadratic Polynomial Regression Analysis

In the SPSS software, select regression analysis - polynomial regression analysis and choose the independent and dependent variables. The relative relationship is shown in Figure 7. This paper selects the response time data of 5 test vehicles driven by 1 tester at different angles for quadratic polynomial regression analysis to determine the angle range where each vehicle has the shortest response time (optimal performance). The analysis uses the quadratic polynomial model $Y = aX^2 + bX + c$ to fit the relationship between the angle and the response time, determines the optimal angle by calculating the vertex of the parabola, and determines a reasonable range based on the actual data distribution. The final results indicate that vehicles B and D exhibit the best performance. All models of the 5 test vehicles open upward, with high goodness - of - fit R^2 values, demonstrating strong explanatory power of the models. In the actual test, the 30° to 45° interval precisely covers the stage where the response time decreases and then just starts to increase. Moreover, the response times within this interval are the measured lower values for each vehicle (without a significant increase to the deterioration level). Therefore, the 30° to 45° interval is determined as the optimal angle range for response timeliness.

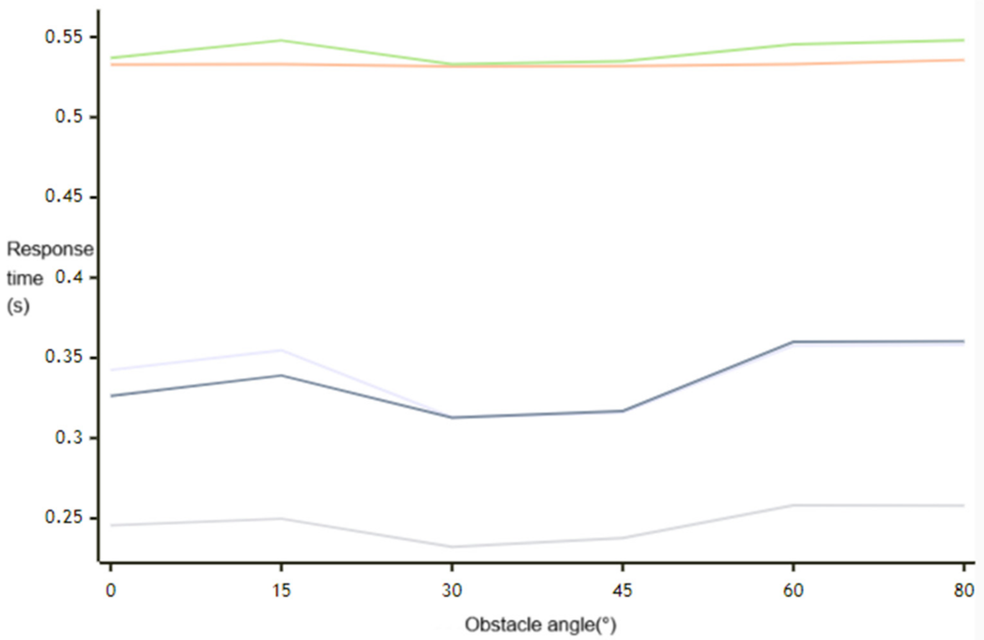

Figure 7. Original Data Graph for Quadratic Polynomial Regression Analysis

3.3. Analysis using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Due to the differences in the inherent attributes and units of different indicators, and when comparing the different performances of multiple vehicles, it is impossible to intuitively judge the superiority or inferiority of their comprehensive performances. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) effectively addresses the aforementioned issues. Prior to using this method, data pre - processing is required. The optimal frequency indicator falls within a specific range, and it is impossible to distinguish between positive and negative directions. Therefore, the frequency indicator is not included in this analysis. Among all the data of the loudness indicator, the maximum value is 65.1 decibels. In this analysis, it is tentatively assumed that this indicator is positive. Equal weights are assigned to each indicator. Through calculation, the comprehensive evaluation values of five evaluation objects are obtained. The analysis results are presented in Table 9.

Table 9. Analysis Table of TOPSIS Results

vehicle	Distance to the ideal solution	Distance to the negative ideal solution	close degree	comprehensive ranking
A	0.0792	0.0578	0.4203	4
B	0.0324	0.1041	0.7623	2
C	0.1186	0.0312	0.2078	5
D	0.0241	0.1182	0.8405	1
E	0.1163	0.0335	0.2227	3

Based on the comprehensive evaluation using the TOPSIS method, Vehicle D exhibits the highest closeness degree (0.8405) and thus boasts the optimal performance. Vehicle B ranks second. Vehicles A, E, and C have relatively lower closeness degrees and therefore occupy the lower positions in the ranking.

4. Conclusion

In response to the issues of the single testing scenario and the imperfect evaluation system in the existing automotive parking radar tests, this research has constructed a comprehensive testing scenario involving multiple obstacles and multiple angles. By integrating various analytical methods, a comprehensive performance evaluation system has been established, leading to the following conclusions:

(1)Through testing five experimental vehicles against three types of obstacles, namely child - sized soft dummies, traffic cones, and stone isolation piers, at multiple angles ranging from 0° to 80°, the testing dimensions of parking radars have been enriched, and the limitations of traditional single - scenario testing have been addressed. Acoustic index tests indicate that the frequencies of Vehicles B and D fall within the human - comfort range. They exhibit excellent signal - to - noise ratios, with the influence of obstacle characteristics on the ratios showing a clear pattern. Moreover, their loudness indices better meet the requirements of actual usage.

(2)The high reliability of the test data (ICC = 0.942) was verified through ICC analysis, effectively eliminating the influence of subjective factors of personnel. The quadratic polynomial regression analysis determined that the optimal angular range for the timely response of the parking radar is between 30° and 45°, providing a clear direction for performance optimization. Finally, the comprehensive evaluation based on the TOPSIS method showed that Vehicle D had the optimal comprehensive performance (closeness degree of 0.8405), followed by Vehicle B (0.7623), and

Vehicle C performed the worst (0.2078). For the prompt tones with good response timeliness, the frequency range is between 335 Hz and 410 Hz, the signal - to - noise ratio range is between 33.5 and 35.3, and the loudness range is between 55.8 and 62.3.

In conclusion, the testing and evaluation method established in this study can comprehensively verify the acoustic performance of the radar, provide guidance for the product development and optimization of enterprises, promote the development of the parking safety field, and play an important role in ensuring parking safety.

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