Research on AEB Function Testing and Evaluation in Underground Garages

Zhiyu Wang [1], Weiting Ma [2], Liangyi Shen [1 *], Dongliang Geng [1]

[1] CATARC Intelligent Technology(Tianjin)co., Ltd, Tianjin 300300, China
[2] CATARC Automotive Rescarch and Inspection Center (Tianjin)co., Ltd, Tianjin 300300, China

*shenliangyi@catarc.ac.cn

Abstract. The acceleration of urbanization in China has led to a rapid increase in the number of underground garages. Due to the low road adhesion coefficient in these environments, the risk of collision accidents is significantly higher. To enable a more specialized evaluation of Autonomous Emergency Braking (AEB) system performance in underground garage scenarios, this paper reviews existing standards and NCAP test assessment protocols. Based on this review, an Analytic Hierarchy Process (AHP) is employed to determine the relevant indicators and their weights, thereby proposing a novel AEB test and evaluation system specifically for underground garages. Finally, the proposed system is validated through real vehicle tests. The results demonstrate that this evaluation system can effectively conduct quantitative assessments, providing a basis for guiding system optimization.

Keywords: Underground Garages, AEB, Evaluation Method.

1 Introduction

The rapid development of the global automotive industry has led to a continuous increase in vehicle ownership worldwide, accompanied by persistently high rates of traffic accidents. The Autonomous Emergency Braking (AEB) function, a relatively mature active safety technology in recent years, has demonstrated significant safety benefits in preventing collisions and mitigating impact severity[1]. In recent years, driven by the rapid iteration of intelligent connected vehicle technologies, updates in global road safety regulations, and the growing consumer demand for safety, the development and application of AEB systems have become a research focal point within the automotive industry. During the first half of 2025, the installation rate of AEB systems in passenger vehicles had reached 64.%[2]. Currently, the performance enhancement of AEB systems remains primarily focused on highways, urban roads, and rural roads. Some manufacturers have begun to address collision avoidance on low-adhesion surfaces, such as those covered with ice and snow. Underground garages commonly utilize epoxy flooring materials due to their ease of cleaning and maintenance. However, these epoxy sur-

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faces are smooth and characterized by a low adhesion coefficient. This condition significantly reduces the deceleration effect of vehicles upon AEB activation, thereby increasing the risk of collisions. Consequently, establishing a dedicated AEB test and evaluation method for underground garage environments is imperative to promote the enhancement of AEB system safety performance in such settings within the automotive industry.

2 Research Status of AEB Test Methods

Based on the technological evolution of AEB, its development can be categorized into three distinct phases. The first phase, the preliminary application stage, is characterized by "single-sensor perception with fixed-threshold decision-making." This phase features a relatively low technical barrier and primarily addresses forward collision risks. The mainstream configuration involved only a single millimeter-wave radar, with the core function being the identification of vehicles traveling ahead in the same direction. The second phase is the multi-sensor fusion stage. The integration of camera and millimeter-wave radar architectures enabled not only the recognition of multiple target types, including vehicles, pedestrians, cyclists, and motorcycles, but also significantly improved the accuracy of target identification. High-end vehicles began incorporating LiDAR as a safety redundancy measure. At the decision-making level, deep learning neural networks were introduced to dynamically adjust Time-to-Collision (TTC) thresholds based on factors such as driving speed, road conditions, and weather. At the execution level, the system was upgraded to an Electronic Braking System (ESC), reducing response time to under 200 milliseconds and markedly enhancing braking control precision. The third phase constitutes the hyper-fusion perception stage. Driven by advancements in chip computing power, the architecture combining multi-sensor fusion with AI large models has become the primary technical solution researched and developed by automotive manufacturers in recent years. In this stage, vehicles can identify not only traffic participants but also driving environment elements, such as traffic cones, water-filled barriers, and guardrails. The decision-making process utilizes end-to-end large language models, which improve decision accuracy and shorten response times. The increased number of sensors and the application of large models enable vehicles to determine the specific road surface type through semantic understanding of the environment, offering the potential to optimize AEB response strategies for different pavement conditions.

Currently, international standards and those of several countries have been established concerning AEB systems. At the international level, UN R131, "Uniform provisions concerning the approval of motor vehicles with regard to the Advanced Emergency Braking Systems (AEBS)," and UN R152, "Uniform provisions concerning the approval of motor vehicles with regard to the Advanced Emergency Braking System (AEBS) for M1 and N1 vehicle," have been published. China has issued GB 39901, "Technical requirements and test methods for autonomous emergency braking system of light vehicles," and the United States has released FMVSS 127, "Federal Motor Vehicle Safety Standards; Automatic Emergency Braking Systems for Light Vehicles"

These aforementioned regulations are mandatory standards. As they represent fundamental requirements for AEB functionality, the test methods specified primarily focus on the detection of and response to vehicle, pedestrian, and bicycle targets. The standards pertaining to passenger cars also include scenarios to assess the AEB system's susceptibility to false activation. The pass/fail criteria for these tests primarily involve two aspects: first, the evaluation of the timing of collision warnings; and second, the assessment of the vehicle's impact speed with the target object at various initial vehicle speeds[3-6].

In the New Car Assessment Program (NCAP) tests across various countries and regions, the AEB function constitutes a critically important assessment component. Among NCAP testing requirements, the AEB test protocols in Euro-NCAP and C-NCAP are characterized by high stringency and complex scenarios. The Euro-NCAP 2023 version, beyond incorporating traditional test scenarios such as rear-end collisions and scenarios involving vulnerable road users crossing or traveling longitudinally, introduced testing requirements for collision scenarios during vehicle turning maneuvers at intersections involving other vehicles, pedestrians, and motorcycles, as illustrated in Figures 1 and 2. The AEB function accounts for 73.33% of the total score in active safety assessments[7].

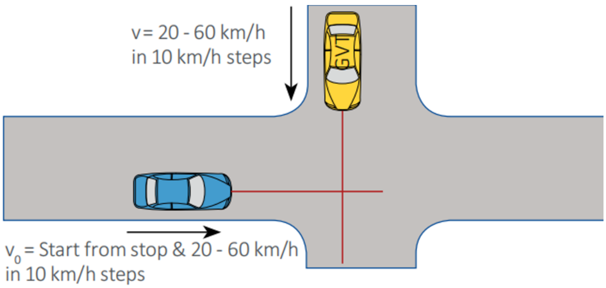

Fig. 1. Car-to-Motorcyclist Front Turn Across Path.

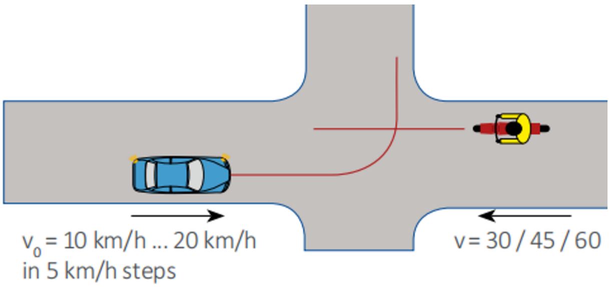

Fig. 2. Car-to-Motorcyclist Front Turn Across Path

The test scenarios in the NCAP 2024 edition are more representative of actual traffic conditions in China. In intersection scenarios, a stationary vehicle parked on the right side creates an occlusion. In highway scenarios, the preceding vehicle performs an emergency avoidance maneuver. The protocol also includes ten false activation test scenarios, aimed at improving the accuracy of AEB risk identification, as shown in Figures 3 and 4. The AEB function now accounts for 77.08% of the total active safety score.

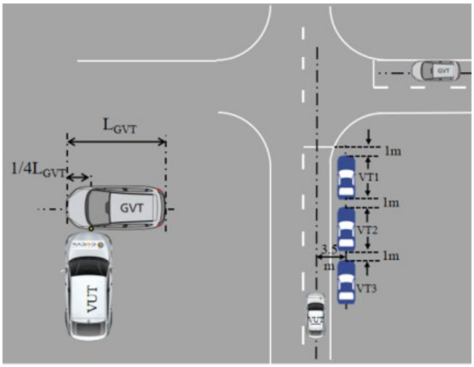

Fig. 3. Car-to-Car Straight Crossing Path with Obstruction.

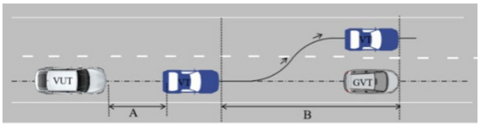

Fig. 4. High Speed Car to Car Rear.

Whether in mandatory standards or NCAP test protocols, the assessed metrics primarily focus on collision speed and warning TTC (Time-to-Collision). These evaluation indicators are predominantly oriented towards the final safety outcome, lacking a comprehensive assessment of the braking process itself. Furthermore, these tests simulate traffic accidents on urban roads and highways, characterized by high road adhesion coefficients where achieved braking deceleration typically exceeds 6 m/s^2[8]. In recent years, the number of underground garages in China has increased rapidly[9]. With all newly produced light-duty vehicles in China required to be equipped with AEB systems by 2028, there is an urgent need to establish dedicated test methods to evaluate AEB system performance on epoxy flooring surfaces, thereby mitigating traffic accidents in underground garage scenarios.

3 Construction of Test Scenarios for AEB in Underground Garages

3.1 Test Scenarios

Based on the architectural characteristics of underground garages and the types of traffic participants involved, three scenarios with higher occurrence frequencies were extracted from underground garage traffic accident statistics for testing purposes[10]. The test site adopts a smooth epoxy floor pavement in an underground garage, with an illumination level of 50–100 lux. The initial steady vehicle speed has an error of 0–1 km/h, and the speed must be stabilized at least when TTC = 4 s. All targets comply with the requirements of ISO 19206.

The preceding vehicle braking scenario is illustrated in Figure 5. In this scenario, the test vehicle and the preceding vehicle travel at a constant speed of 20 km/h, maintaining an inter-vehicle distance of 12 m. The preceding vehicle then decelerates at -2 m/s^2 until coming to a complete stop. To assess the false activation tendency of the AEB system, a variant of this scenario is also implemented: the target vehicle decelerates to 10 km/h, maintains this speed for 2 seconds, and subsequently accelerates back to 20 km/h.

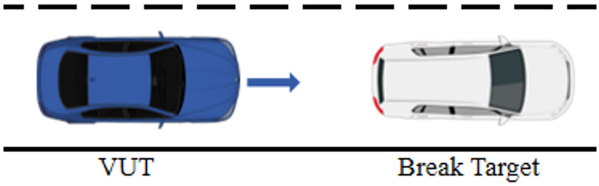

Fig. 5. Car-to-Car Rear Braking.

The intersection vehicle crossing scenario is depicted in Figure 6. In this configuration, the test vehicle proceeds at a constant speed of 20 km/h, while the target vehicle travels perpendicular to the test vehicle's path at 15 km/h. The test vehicle's lateral views are obstructed by pillars and stationary vehicles. To evaluate the AEB system's propensity for false activation, a variant of this scenario is employed: the target vehicle decelerates at 2 m/s^2 until coming to a complete stop, positioned 1 meter from the outermost edge of the test vehicle's path upon cessation.

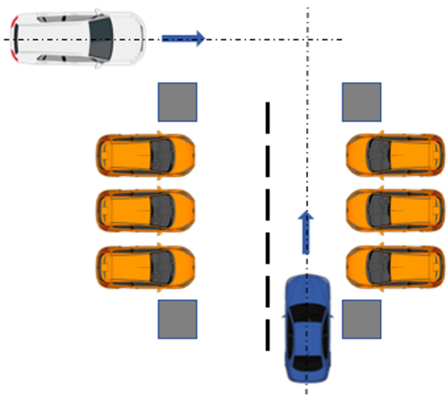

Fig. 6. Underground Garage Car-to-Car Straight Crossing Path.

The pedestrian crossing scenario is illustrated in Figure 7. In this configuration, the test vehicle travels straight at a constant speed of 20 km/h, while a pedestrian alights from a vehicle and crosses the path at 5 km/h, with the collision point positioned at onequarter of the test vehicle's width. To evaluate the AEB system's susceptibility to false activation, a variant of this scenario is implemented: the target pedestrian decelerates at 1.3 m/s^2 until coming to a complete stop, positioned 1 meter from the outermost edge of the test vehicle's path upon cessation.

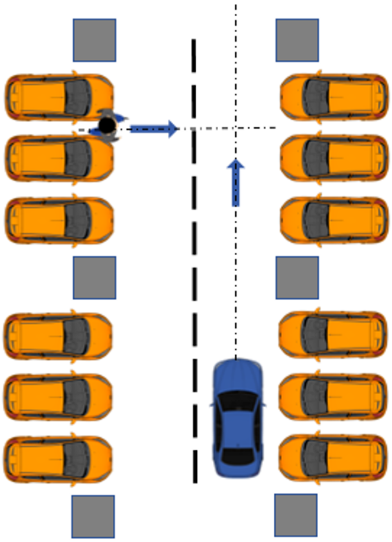

Fig. 7. Underground Garage Car-to-Pedestrian Farside Adult.

Based on the typical layout characteristics of underground garages, three vehicles are parked between two pillars. Each pillar has a width of 0.6 m, and the spacing between pillars is 6.75 m. The test vehicle travels in the center of the right lane on a two-lane road, with each lane measuring 3 m in width[11].

3.2 Test Equipment

To ensure the reproducibility and consistency of the evaluation protocol, it is essential to maintain consistent environmental and pavement conditions that may influence system performance. Additionally, high-precision test equipment is required to measure critical kinematic data throughout the testing process.

Driving Robot: Capable of high-precision control over vehicle steering, throttle, and braking inputs.

High-Precision Gyroscope: Provides accurate positioning capabilities, measuring parameters such as position, velocity, and acceleration.

Indoor Positioning Equipment: As underground garages are indoor environments where high-precision gyroscopes cannot receive satellite signals, indoor positioning devices are necessary to provide position data.

Soft Target: A surrogate representing real targets, featuring radar, infrared properties, and a profile similar to those of pedestrians or vehicles.

4 Evaluation Model for AEB System Testing in Underground Garage Scenarios

This paper employs the Analytic Hierarchy Process (AHP) to decompose evaluation indicators and assign weights, considering both system characteristics and driver usage perspectives. Through real-vehicle testing, a comprehensive scoring of AEB performance in underground garage scenarios is conducted. The proposed evaluation model is illustrated in Figure 8.

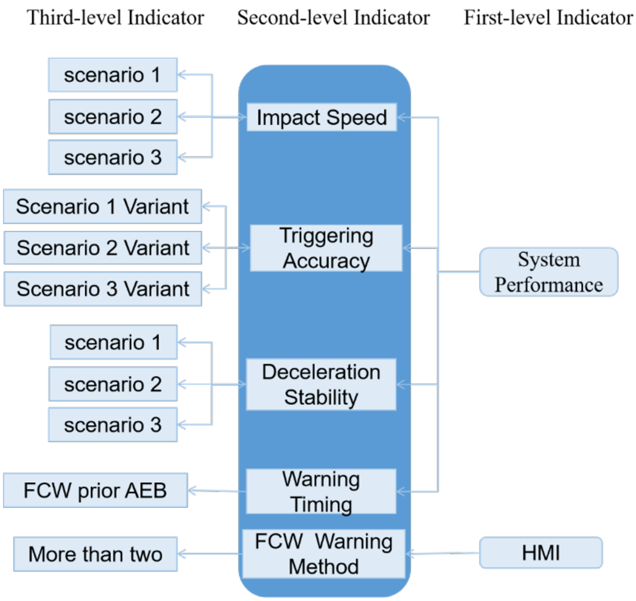

Fig. 8. Evaluation model diagram.

Using the Analytic Hierarchy Process (AHP), the indicators of the evaluation system are hierarchically decomposed based on the functional characteristics of AEB. The objective evaluation of the AEB system is primarily divided into two first-level indicators: system performance and human-machine interaction. From the perspective of collision risk mitigation, the second-level indicators for system performance evaluation are further categorized into collision speed, activation accuracy, deceleration stability, and warning timing. In terms of human-machine interaction, the warning method serves as the primary safety indicator.

Collision speed directly indicates the extent of injury or vehicle damage following a collision. Activation accuracy fosters driver trust in the AEB system, preventing drivers from permanently disabling the system due to false activations. If the warning timing occurs later than the AEB activation moment, its role as an alert is negated. Deceleration stability is a specialized evaluation indicator for AEB systems operating in underground garage conditions. On epoxy-coated surfaces in underground garages, characterized by a low adhesion coefficient, even with Anti-lock Braking System (ABS) intervention, the vehicle may experience wheel slip under high deceleration demands, leading to a loss of control risk. If wheel slip occurs, the expected deceleration effect cannot be achieved, thereby increasing the severity of collision risk.

Collision speed, activation accuracy, deceleration stability, and warning timing are evaluated through the three test scenarios selected based on the aforementioned characteristics of underground garages. The test results form the third-level indicators.

In this model, the weight values of the evaluation indicators are determined using the Analytic Hierarchy Process (AHP). AHP decomposes complex problems into their constituent factors and organizes these factors into a hierarchical structure based on their dominance relationships. By comparing the effectiveness of AEB in preventing vehicle collisions, a pairwise comparison method is employed to establish the relative importance of each factor within the hierarchy. Experts in intelligent driving assessment assign scores to each indicator, thereby determining the weights of evaluation indicators at the same hierarchical level. The specific weight configuration is presented in Table 1. In the Analytic Hierarchy Process (AHP), the pairwise comparison matrix is a positive reciprocal matrix derived from experts' pairwise comparisons of the relative importance of indicators, using the 1–9 scale method. A scale of 1 indicates that two indicators are equally important; 3 indicates that the former indicator is slightly more important than the latter; 5 indicates that the former is obviously more important; 7 indicates that the former is strongly more important; and 9 indicates that the former is extremely more important. Values of 2, 4, 6, and 8 represent intermediate degrees of importance, and reciprocals correspond to reverse comparisons. Consistency testing is not required for indicators with only 1 or 2 subordinate sub-indicators. The comparison matrix for the first-level indicators is as follows:

$$A = \begin{bmatrix} 1 & 4 \\ 1/4 & 1 \end{bmatrix} \tag{1}$$

The comparison matrix for the second-level indicators is as follows:

$$B = \begin{bmatrix} 1 & 2 & 2 & 5 \\ 1/2 & 1 & 1 & 3 \\ 1/2 & 1 & 1 & 3 \\ 1/5 & 1/3 & 1/3 & 1 \end{bmatrix} \tag{2}$$

The maximum eigenvalue of B is 4.0107, the consistency index is CI = 0.0036; the average random consistency index is RI(4) = 0.90; the consistency ratio is 0.04 < 0.1, which satisfies the consistency requirement.:

$$CR = \frac{CI}{RI} = \frac{0.0036}{0.90} = 0.04 \tag{3}$$

Among the third-level indicators, the comparison matrix for impact speed, triggering accuracy, and deceleration stability is denoted as C:

$$C = \begin{bmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 1/2 \\ 3 & 2 & 1 \end{bmatrix} \tag{4}$$

The maximum eigenvalue of C is 3.0092, the consistency index is CI = 0.0046; the average random consistency index is RI(3) = 0.58; the consistency ratio is 0.0079 < 0.1, which satisfies the consistency requirement.

$$CR = \frac{CI}{RI} = \frac{0.0046}{0.58} \approx 0.0079 \tag{5}$$

The principal eigenvector corresponding to each comparison matrix is computed using the eigenvalue method, followed by normalization of the eigenvectors to derive the normalized weights of indicators at each hierarchical level. For ease of practical application, the normalized weights are further converted into integer weight ratios. The final weight configuration is presented in Table 1.

Table 1. Model Weighting.

<table>
<tr><th colspan="2">First-level Indicator</th><th colspan="2">Second-level Indicator</th><th colspan="2">Third-level Indicator</th></tr>
<tr><th>item</th><th>weight</th><th>item</th><th>weight</th><th>item</th><th>weight</th></tr>
<tr><td rowspan="11">System Performance</td><td rowspan="11">4</td><td rowspan="3">Impact Speed</td><td rowspan="3">5</td><td>Scenario 1</td><td>1</td></tr>
<tr><td>Scenario 2</td><td>2</td></tr>
<tr><td>Scenario 3</td><td>3</td></tr>
<tr><td rowspan="3">Triggering Accuracy</td><td rowspan="3">3</td><td>Scenario 1 Variant</td><td>1</td></tr>
<tr><td>Scenario 2 Variant</td><td>2</td></tr>
<tr><td>Scenario 3 Variant</td><td>3</td></tr>
<tr><td rowspan="3">Deceleration Stability</td><td rowspan="3">3</td><td>Scenario 1</td><td>1</td></tr>
<tr><td>Scenario 2</td><td>2</td></tr>
<tr><td>Scenario 3</td><td>3</td></tr>
<tr><td>Warning Timing</td><td>1</td><td>FCW prior AEB</td><td>1</td></tr>
<tr><td>HMI</td><td>1</td><td>AEB Warning Method</td><td>1</td><td>FCW Warning Method</td><td>1</td></tr>
</table>

Each level of indicators is evaluated on a 100-point scale. To facilitate pairwise comparisons during the Analytic Hierarchy Process, the weighted average scores are subjected to linear normalization, as shown in Equation (6).

$$y_j = \frac{\sum_{i=1}^{n} x_{ji}\alpha_{ji}}{100\sum_{i=1}^{n} \alpha_{ji}} \tag{6}$$

In the formula, α_{ji} represents the weight of the i-th indicator at the current level under the j-th higher-level indicator, and x_{ji} represents the score of the i-th indicator at the current level under the j-th higher-level indicator. The result calculated by the formula yields the score for the j-th higher-level indicator.

The scoring rate for collision speed is calculated based on the deceleration percentage at the moment of collision or when the vehicle is brought to a stop by the AEB function. For false activation scenarios, no activation of AEB or FCW results in a score of 100%; FCW activation alone results in 50%; and AEB activation results in 0%. In terms of deceleration stability, if wheel slip occurs, the score is 0%; if no slip occurs, the score is 100%. Regarding warning timing, an earlier warning allows for earlier driver intervention, whereas a delayed warning may necessitate greater braking force from the driver. For warning timing calculation, if the FCW TTC (Time-to-Collision) is earlier than 1.7 seconds, the score is 100%; if it falls between 1.7 and 0.8 seconds, the score is 50%; and if it is less than 0.8 seconds, the score is 0%. For warning methods, if at least two of the following—acoustic, optical, or haptic warnings—are provided, the score is 100%; otherwise, the score is 0%.

5 Model Application Case Study

To validate the effectiveness of the proposed AEB evaluation system for underground garages, three vehicles equipped with the AEB system were randomly selected and tested according to the model established in this study. Upon AEB activation, the driving robot ceased controlling the accelerator pedal and did not intervene with the AEB system.

For this real-vehicle verification, 3 test vehicles were selected, and each test scenario was repeated 5 times. The initial vehicle speed was uniformly set to 20 km/h, and the test road surface adopted an epoxy floor with a low adhesion coefficient. To evaluate the performance stability of the tested vehicles, the collision speed test data of each vehicle in each scenario was screened. Test points with a pairwise speed difference not exceeding 5 km/h were selected as valid data. The average value of the valid data was calculated and used as the final collision speed test result of the vehicle in the corresponding scenario, Figure 9 illustrates the impact speed during the test. For the remaining test items, only the test points that exhibit stable performance were selected for statistical analysis.

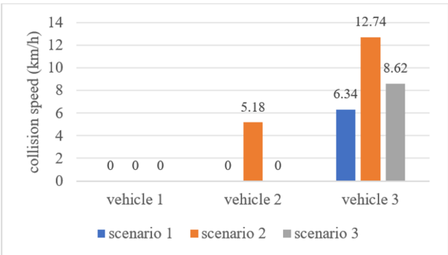

Fig. 9. Impact Speed of Test Vehicle

Vehicle 1 triggered the FCW function in Scenario 2. Vehicle 2 triggered the collision warning in the pedestrian crossing scenario. Vehicle 3 activated the AEB function in Scenario 3. These results are presented in Table 2.

Table 2. False Positive Test Results

scenario Result Vehicle	vehicle 1	vehicle 2	vehicle 3
scenario 1	No Trigger	No Trigger	No Trigger
scenario 2	FCW	FCW	No Trigger
scenario 3	No Trigger	FCW	AEB

In terms of deceleration stability, the AEB system of Vehicle 1 requested relatively lower acceleration, and no wheel slip occurred. Vehicle 2 experienced slight wheel slip. Vehicle 3, however, maintained the same acceleration request as used on urban roads, resulting in severe wheel slip in the underground garage environment. This failure to maintain stable deceleration led to a collision. The deceleration curve of Vehicle 3 is shown in Figure 10

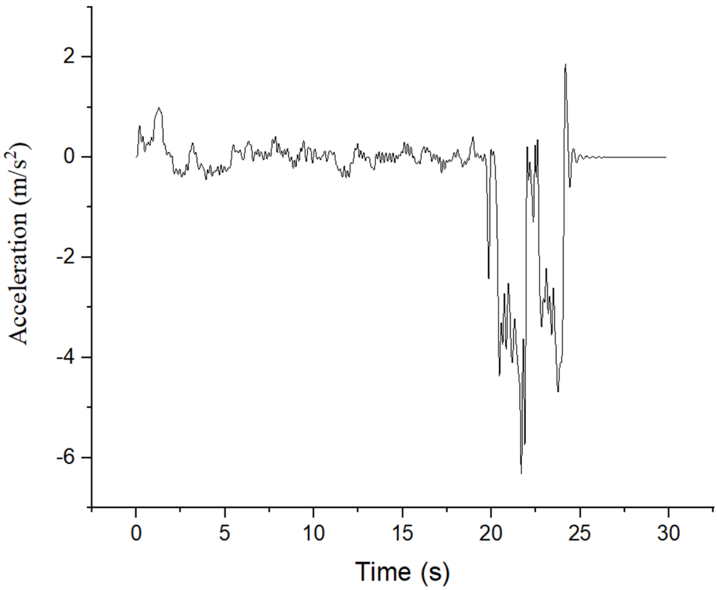

Fig. 10. Skid-Induced Deceleration Profile

The warning timing for Vehicle 1 occurred later than the AEB activation moment. For both Vehicle 2 and Vehicle 3, the warning timing preceded AEB activation by more than 0.8 seconds, with minimum warning TTC values of 1.2 seconds and 1.5 seconds, respectively. All three vehicles utilized both acoustic and optical warnings as the AEB warning methods.

According to the evaluation model, the final test scores for the three vehicles are as follows: Vehicle 1 achieved a comprehensive score of 0.90, Vehicle 2 scored 0.65, and Vehicle 3 scored 0.51. Based on the comprehensive scores, the system performance of Vehicle 1 is superior. A comparison of the secondary indicators reveals that the primary discrepancy in scores stems from whether wheel slip occurred on the epoxy flooring material, which subsequently affected braking effectiveness and led to differences in collision speed scores, as illustrated in Figure 11.

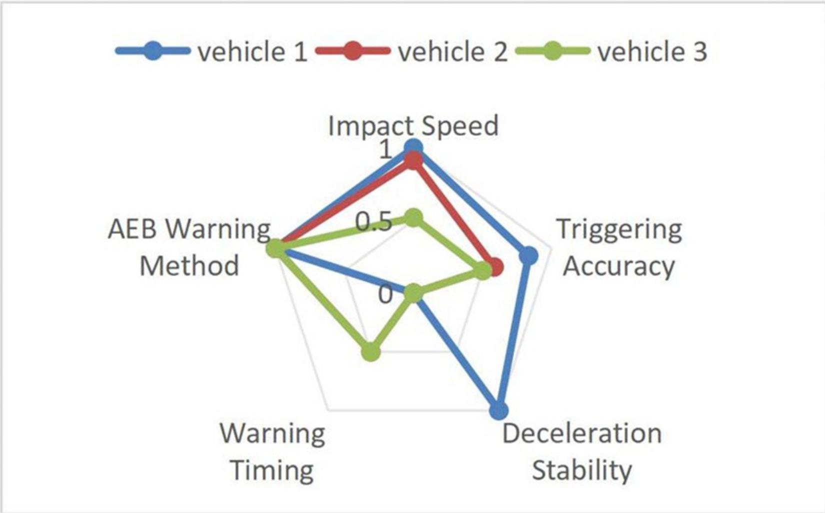

Fig. 11. Comparison of Second-Level Indicator Results

6 Conclusion

This paper introduces the objectives of AEB testing and evaluation in underground garages, reviews existing AEB standards and NCAP assessment protocols, and proposes a tailored evaluation model for AEB systems in underground garage environments. The model employs the Analytic Hierarchy Process (AHP) to scientifically assign weights to each indicator, enabling comprehensive and quantifiable assessment of AEB system functionality in underground garage settings. Furthermore, horizontal comparison of second-level indicators facilitates precise identification of system deficiencies, assisting function developers in pinpointing problematic categories and implementing timely improvements. The evaluation system proposed in this paper serves as a scenario supplement and indicator extension to existing AEB regulations and New Car Assessment Programs (NCAPs). It covers indoor scenarios with low road adhesion coefficient, introduces additional evaluation of braking process and stability, and enables the identification of performance weaknesses for targeted optimization.In an era of rapid technological advancement, the proposed evaluation framework can be updated to accommodate evolving technologies. This evaluation system can also be extended to the assessment of other intelligent driving systems.

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