Research and Application of In-Vehicle Odor Testing

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Abstract. In-vehicle odor has become one of the most common complaints among car consumers, and its negative impact on brand loyalty cannot be underestimated. For a long time, the evaluation of in-vehicle odor has mainly relied on the subjective sniffing method by professional evaluators. However, this traditional method has many inherent drawbacks: it is highly dependent on the professional quality and experience of personnel, the evaluation results are strongly subjective due to individual differences, the repeatability of test data is poor, the efficiency of handling a large number of test tasks is low, the potential occupational hazards to evaluators are not clearly defined, and there is a serious shortage of high-level "golden-nose" odor evaluators who can provide authoritative evaluations.

Against this background, objective odor-measuring equipment has become an important solution. It aims to reduce the limitations of human-based evaluation and improve consistency and efficiency. At present, this type of equipment can be grouped into three main categories according to its working principle.The first category measures total volatile compounds (TVOCs). It reflects the overall concentration of volatile substances inside the vehicle, but does not distinguish individual components.The second category uses multiple sensors or detectors. Different sensors respond to different gases, and their combined signals form a multi-dimensional odor profile.The third category relies on substance separation technology. It separates mixed gases and performs qualitative and quantitative analysis at the molecular level. This approach identifies specific odor-causing substances and measures their concentrations.

The fundamental difference between these three types of equipment lies in the richness and precision of the detection data they can obtain. The more detailed and comprehensive the data, the more accurate and reliable the subsequent odor evaluation results will be. At present, relevant products of these three categories have been gradually launched on the market, and each category has shown different application characteristics and market acceptance in various fields such as automotive manufacturing, environmental monitoring, and food safety.

With ongoing progress in sensor materials, separation techniques, and intelligent algorithms, these technologies are expected to become more specialized. At present, most objective odor studies focus on odor intensity, because it is easier to measure and correlate with physical or chemical parameters. In contrast, odor pleasantness and persistence are more difficult to quantify. Pleasantness depends heavily on human perception, while persistence involves changes over time. Further development in these areas will require improvements in detection sensitivity as well as the accumulation of large experimental datasets to support model development and validation.

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1 Introduction

In recent years, growing public attention to personal health and living quality has brought renewed scrutiny to the issue of in-vehicle odor. What was once considered a minor comfort-related concern has increasingly been framed as a matter of health and safety within the automotive industry. Reports and consumer feedback indicate a steady rise in complaints associated with unpleasant interior smells, many of which are rooted in underlying concerns about potential health risks [1]. Prolonged exposure to noticeable in-vehicle odors often leads occupants to question whether such environments may contribute to respiratory irritation, allergic responses, or even longer-term chronic conditions [2].

A large number of scientific studies have confirmed that many harmful gases often exist in the in-vehicle air, such as formaldehyde, benzene, toluene, and xylene. When the concentration of these substances in the air inside the vehicle exceeds the standard limit, it may cause varying degrees of damage to key organs such as the respiratory system and the nervous system in the human body. Figure 1 shows the path by which the main harmful components in the vehicle affect human health. As shown in the figure, when substances such as benzene and formaldehyde enter the human body, they will activate a series of biological reactions, such as the activation of cysteine protease-3, an increase in reactive oxygen species (ROS), and damage to hematopoietic cell function. These changes may eventually lead to cell apoptosis and further cause problems with organ functions.

Long-term exposure to pollutants does indeed have a significant correlation with diseases. This conclusion has been strongly supported by clinical research and environmental epidemiological investigations. Lu found that long-term contact to volatile organic compounds (VOCs) is an important risk factor for chronic obstructive pulmonary disease (COPD) [3]. Liu pointed out that continuous inhalation of VOCs will have a similar anesthetic inhibitory effect on the central nervous system, causing drowsiness and weakness [4].

In addition to the risks brought by long-term exposure, many consumers will immediately experience uncomfortable reactions when they smell a distinct odor in the vehicle, such as coughing, sneezing, dry and itchy eyes, dizziness, or nausea. Many people will directly associate this discomfort with the air quality inside the vehicle [5]. This will have a negative impact on the car brand, especially when the vehicle odor problem is not resolved in a timely manner. The odor problem will directly affect the purchasing decisions of consumers, as those who have had a bad experience are unlikely to consider this brand again. On the other hand, if the odor problem persists for a long time, the brand image will be gradually weakened, and consumers' purchase intention will naturally decrease [6].

For this reason, consumers' expectations of car manufacturers are becoming increasingly specific: during the design phase of car interiors, materials that are environmentally friendly, have low volatility and low odor should be given priority for use. At the same time, a systematic indoor air quality control system should be established, such as conducting strict inspections before delivery and controlling the odor well.

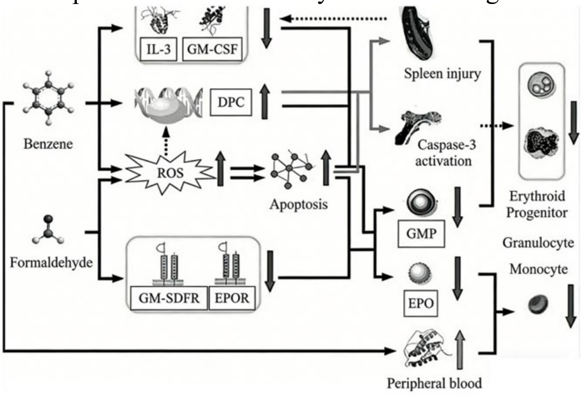

Fig. 1. Hazards of Harmful Components in In-Vehicle Air to Human Health

2 Existing Evaluation Methods

To put it simply, odor is a sensory experience that arises from the stimulation of olfactory system by chemical substances in the air. An odor can be caused by a single chemical substance alone, or formed by several substances mixed together in a certain proportion and working together.

In terms of odors, gas analysis has gradually developed into a relatively mature discipline over the years. Industries such as perfumery, food, and cosmetics have long accumulated a considerable amount of research experience and methods [7]. Take osmanthus for example. Its distinctive fragrance is not supported by a single compound, but mainly by three key odor substances: linalool, furan-type linalool oxides, and β-viridone. Main substance composition of wweet osmanthus fragrance is shown in Figure 2 [8]. Each of these ingredients possesses unique odor characteristics, and the well-known aroma of osmanthus is formed when they combine and work together.

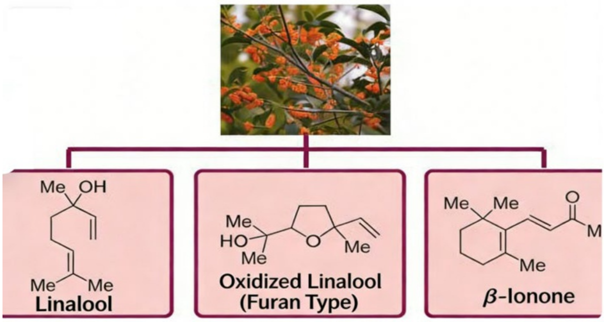

Fig. 2. Main Substance Composition of Sweet Osmanthus Fragrance

In contrast, the composition of interior vehicle odors is much more complex. Various complex materials are used in automotive interiors, which can release volatile organic compounds. The way these compounds are released varies with changes in environmental conditions. The odor components themselves fluctuate greatly, making control even more difficult[9]. However, speaking of this, the odor analysis methods accumulated in the fragrance and food industries are still of reference value for studying interior vehicle odors, especially in finding key odor substances and screening interior materials. But unlike directly measuring volatile organic compounds with instruments, how to evaluate interior vehicle odors now mainly relies on artificial olfactory perception, which is commonly referred to as the "human nose method". The specific process is illustrated in Figure 3. This method essentially represents a subjective evaluation that simulates the perception of a real human body. Professional-trained olfactory assessors use their own olfactory system as a “detector” to capture and analyze the complex odors in the air, which are composed of various volatile organic compounds. When human beings inhale odor molecules, the odor molecules bind to the receptor proteins on the olfactory nerve cells, converting into electrical signals that are transmitted to the brain. The brain then retrieves the memory bank and completes the decoding of the odor.

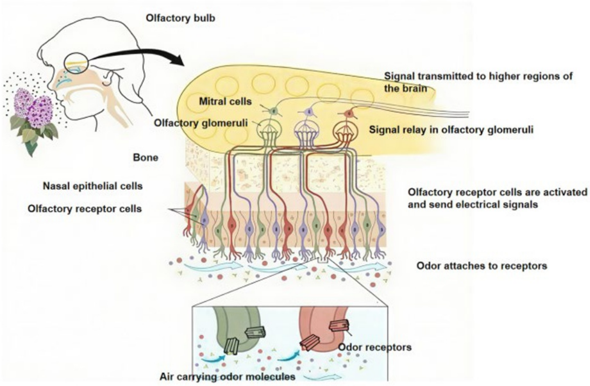

Fig. 3. Olfactory Perception Mechanism of Odors

Due to the varying sensitivity of each person's sense of smell, different individuals may have different evaluations of the same odor in terms of type, intensity, or pleasantness. Because of this variability, the training and experience of professional evaluators play a crucial role in ensuring the reliability of subjective odor evaluations. [10].

In the current subjective evaluation methods for in-vehicle odor, the most widely used is the 6-level odor intensity classification method. This method classifies odor intensity from Level 1 (imperceptible) to Level 6 (intense odor). Due to its simplicity, intuitiveness, and strong operability, this classification method has been adopted by most automakers and related testing institutions in the automotive industry. The specific classification criteria are shown in Table 1. In addition to the 6-level system, there are also other classification methods such as the 10-level system (which provides more detailed intensity grading) and the 5-level system (which simplifies the grading standards) in practical applications, but their application scope and popularity are far less than the 6-level system.

Table 1. Classification Method for Odor Character and Odor Intensity

Level	Evaluation Criterion
1	Imperceptible: No odor can be detected even by sensitive individuals under standard test conditions.
2	Slightly perceptible: Only individuals with extremely sensitive olfaction can detect a faint odor, and it is difficult to determine the specific type of odor.
3	Perceptible: Most people can clearly detect the odor, and can roughly judge the type of odor (such as fruity, floral, or pungent).
4	Easily perceptible: The odor is obvious and can be clearly identified in terms of type; it will not cause obvious discomfort but can attract people's attention.
5	Strong odor: The odor is intense, and its type is very clear; it may cause mild discomfort to some people, such as slight dizziness or eye irritation.
6	Intense odor: The odor is extremely strong and pungent; it can cause obvious discomfort to most people, such as severe coughing, tearing, or nausea, and may even affect normal breathing.

In addition to odor intensity, the comprehensive description of odor also includes two important dimensions: pleasantness and persistence [11]. Odor pleasantness refers to the subjective emotional feelings and satisfaction that people generate when perceiving a certain odor, which is a highly personalized evaluation index. It is not only related to the chemical properties of the odor-causing substances themselves, but also closely related to factors such as individual olfactory preferences, cultural backgrounds, and emotional states at the time of perception. Some people may find the smell of gasoline pleasant (related to their occupation or hobbies), while most people may find it pungent and unpleasant. Similarly, the smell of traditional Chinese medicine may be acceptable to some people but difficult to tolerate for others.

Persistence, on the other hand, mainly describes the adaptation of the human olfactory system to odors, that is, the change law of human sensitivity to a certain odor over time. After being continuously exposed to a specific odor for a period of time, the human body's olfactory receptors will gradually adapt to the odor molecules, resulting in a decrease in sensitivity to this odor—this phenomenon is called olfactory desensitization. The evaluation of persistence is usually carried out by grading according to the time it takes for olfactory desensitization to occur or the time it takes for the odor to dissipate. The specific grading standards are shown in Table 2. This index is particularly important for in-vehicle odor evaluation because it can reflect the duration of the odor in the vehicle and the difficulty of eliminating it, providing an important reference for consumers to use the vehicle and automakers to improve odor.

Table 2. Persistence Evaluation Table

Grade	Description
5	Very persistent. After attempting to ventilate the vehicle for more than 5 minutes, the odor still does not dissipate.
4	Persistent, but the odor can dissipate within less than 5 minutes of active ventilation.
3	Transient presence of odor. However, without any specific elimination measures, it disappears after more than 5 minutes.
2	Transient presence of odor. However, without any specific elimination measures, it disappears within less than 5 minutes.
1	No "odor" of anything is detected or captured, and it remains imperceptible continuously.

3 Existing Problems

Subjective evaluation can describe in-vehicle odor from several dimensions, including intensity, pleasantness, and persistence. It is easy to operate and relatively low in cost. However, because it depends entirely on human perception, it has clear limitations. These limitations affect the accuracy, consistency, and credibility of the results.

One major problem is the strong dependence on individual evaluators. Odor judgment is closely related to personal sensory sensitivity and experience. People differ in olfactory sensitivity, prior exposure to odors, and understanding of evaluation standards. As a result, the same sample may receive different scores from different evaluators. One person may describe it as “easily perceptible,” while another may consider it only “slightly perceptible.” Even the interpretation of grading terms is not fully consistent. These differences make it difficult to achieve comparability between laboratories or between different test batches. It is therefore challenging to establish a fully standardized and enforceable testing system.

Another issue is poor repeatability. Subjective results are easily influenced by external and internal factors. Environmental conditions such as temperature, humidity, airflow, and background odors can affect perception. At the same time, the evaluator’s physical condition, fatigue level, emotional state, clothing odor, and even recently consumed food can influence judgment. Because of these factors, the same evaluator may give different scores to the same sample at different times. This instability reduces the scientific reliability of the results.

Test efficiency is also limited. Each evaluator can only assess a small number of samples per day. Rest periods are necessary to avoid olfactory fatigue. With the increasing number of regulatory requirements and consumer complaints, the demand for odor testing has grown rapidly. Subjective evaluation methods struggle to meet large-scale testing needs. In addition, some odor-causing substances, such as benzene, formaldehyde, and naphthalene, are toxic or carcinogenic. Long-term exposure during repeated testing may pose health risks to evaluators. At present, industry-wide standards for occupational protection in this field are still insufficient.

Finally, there is a shortage of highly trained professional evaluators. Accurate odor assessment requires strong olfactory sensitivity, extensive training, and consistent application of grading standards. Such “golden-nose” experts are rare. Their training takes years and involves significant cost. Health risks associated with repeated exposure to chemicals further discourage people from entering this profession. This shortage limits the sustainable development of subjective in-vehicle odor evaluation.

4 Principles and Classification of Odor Objectification Currently

Odor evaluation mainly relies on the subjective assessment of professional evaluators. This method has problems such as limited test throughput and unclear occupational hazards [12]. The industry is seeking equipment that can replace humans with machines for odor evaluation. The main purpose of odor objectification equipment is to replace manual work in assessing in-vehicle odors. In addition, it also has functions such as quantitative analysis and traceability of odor-causing substances to better solve in-vehicle odor problems.

Based on the differences in the testing principles of system or instrument hardware, the current odor objectification equipment on the market can be divided into three categories, as shown in Figure 4:

Sensors or detectors that quantify total volatile substances, establishing the relationship between odor levels and total volatile substance concentrations; Array-based equipment that generates multi-dimensional concentration signals using multiple sensors or detectors, which is equivalent to classifying and describing gases separately, and establishing the relationship between odor levels and multi-dimensional concentrations; Equipment that achieves qualitative and quantitative analysis of substances at the molecular level through material separation, establishing the relationship between odor levels and the concentrations of all contained volatile substances, where each concentration corresponds one-to-one with a CAS number. Each category essentially corresponds to a way of describing mixed gases. For example: The first type of equipment measures the total amount of volatile substances, which is equivalent to describing a chemical product as a reagent—this description is correct but not accurate; The second type classifies substances first, and the classification method varies depending on the combination of detectors used (e.g., classification by functional groups, describing a reagent as an alcohol); The third type also classifies substances first, but the classification is more detailed, reaching the molecular level, and describes substances according to their molecular structures (e.g., describing a reagent as analytical-grade 2-ethylhexanol).

The main difference between the above principles lies in the richness of data detected by the detectors. The latter categories of equipment can detect more types of substances, providing more dimensions for subsequent simulated intelligent calculations, thereby achieving higher accuracy, as shown in Figure 5.

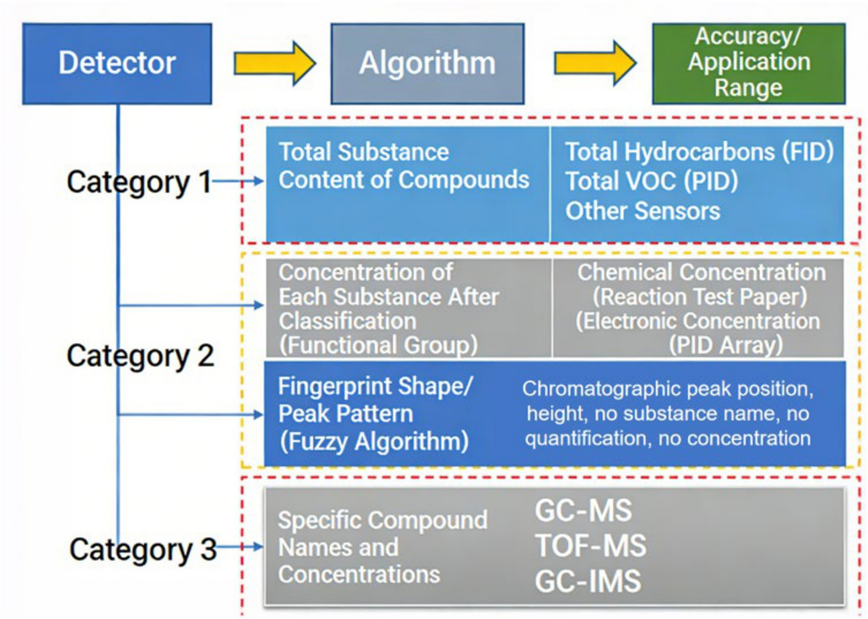

Fig. 4. Classification Diagram of Odor Objectification Equipment

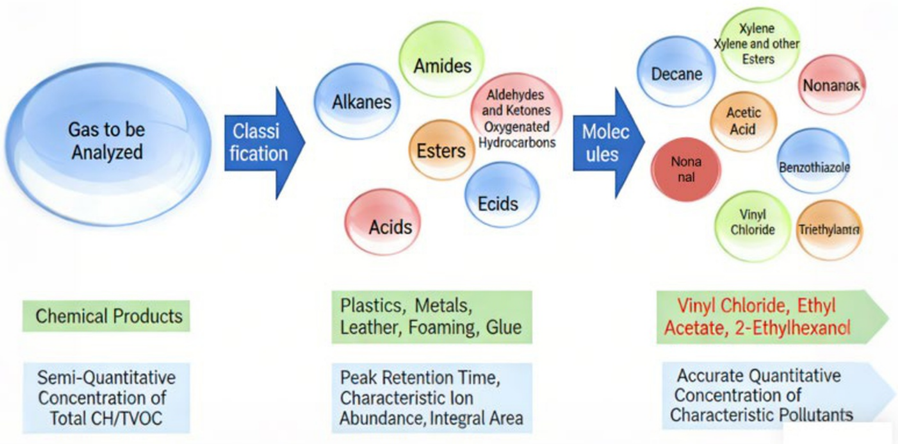

Fig. 5. Schematic Diagram of Descriptions from Different Dimensions

After collecting the relevant parameters, the hardware needs to call the database for calculation, as shown in Figure 6. There are differences in the size and completeness of the database corresponding to each detection method, and the differences in data volume lead to corresponding differences in the subsequent algorithms.

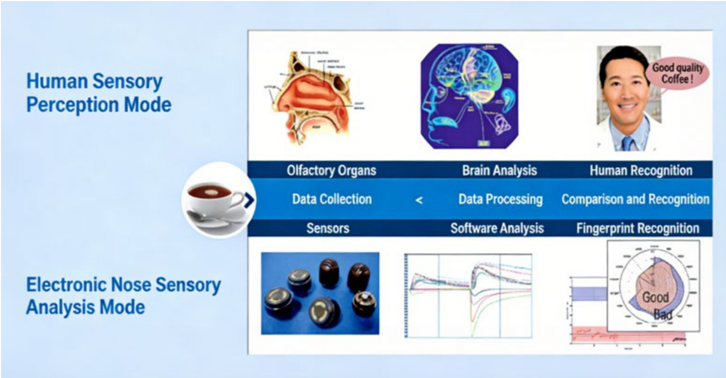

Fig. 6. Schematic Diagram of Odor Objectification Analysis Principle

5 Application Status

Currently, there is a batch of products on the market promoted and sold with odor objectification functions. According to product categories and application scenarios, the specific application status is as follows:

Equipment with sensors or detectors for quantifying total volatile substances Common detectors include PID (Photoionization Detector), metal oxide sensors, FID (Flame Ionization Detector), etc. This type of equipment is applied in fixed-site environmental and odor detection, with application scenarios mainly characterized by: relatively simple gas components or a small number of components, fixed proportion of components in the mixed gas, and proportional concentration increase among different substances. A typical product of this category is the XP-329IIIR Portable Odor Sensor from New Cosmos Electric Co., Ltd. of Japan.

Equipment based on multiple sensors or detectors Ordinarily, it is a system composed of multiple odor sensors. Each sensor is sensitive to specific gases, enabling the detection and identification of different odors accordingly. Meanwhile, these sensors can work synergistically to detect and identify complex odors. Commonly used sensors include Metal Oxide Semiconductor (MOS) sensors, Conductive Polymer Sensors (CPS), mass sensors (e.g., Quartz Crystal Microbalance, QCM), optical fiber gas sensors, Surface Acoustic Wave (SAW) sensors, Photoionization Detectors (PID), and nanomaterial-based sensors. Many devices also adopt detectors such as GC-FID, but they are mainly used to obtain odor characteristics rather than for qualitative and quantitative analysis, so such devices can also be classified into sensor array equipment. Representative brands and models include AQM-836S from AQM, FOX4000 from AlphaMOS, PEN 3 Series from AIRSENSE, Cyranose 320 from Cyranosciences, and SuperNose 1 from ISENSO. This technology has been widely applied in various fields, including environmental monitoring, food safety, and medical diagnosis.

Equipment achieving qualitative and quantitative analysis of odorant molecules in mixed gases emitted by samples through substance separation It mainly relies on full separation of mixed gases to obtain the qualitative name of each substance, which further serves as the basis for quantitative analysis. It studies the odor laws of individual substances (as shown in Figure 7) and thoroughly explores the coupling laws between substances. Based on these studies, it learns from the samples to be tested and forms an odor objectification method. This type of equipment incorporates qualitative and accurate quantitative analysis. After calibration, hardware of different batches can achieve the transfer of relevant models, allowing different devices to implement the same standard. Thus, the evaluation indicators are transferable, truly realizing odor objectification. Due to the reliance on chemical quantification, integration of intelligent algorithms and sensor technology, there are relatively few related products. The Intelligent Olfaction System developed by China Automotive Components Technology (Tianjin) Co., Ltd. falls into this category. The company has conducted in-depth research on the special composition of automotive interior air, integrating a comprehensive database of in-vehicle odorants and specially adjusted detection technologies. For example, the relevant detection hardware can screen out non-odor substances and mainly test odorants among in-vehicle volatile substances (as shown in Figure 8). This method can simultaneously test more than 200 odor-related factors. By adding coupling laws and databases, it not only realizes the grade evaluation of in-vehicle odors but also achieves the traceability of odorants and key assemblies. Additionally (as shown in Figure 9), the system controls the consistency of product odors through a multi-substance concentration control method.

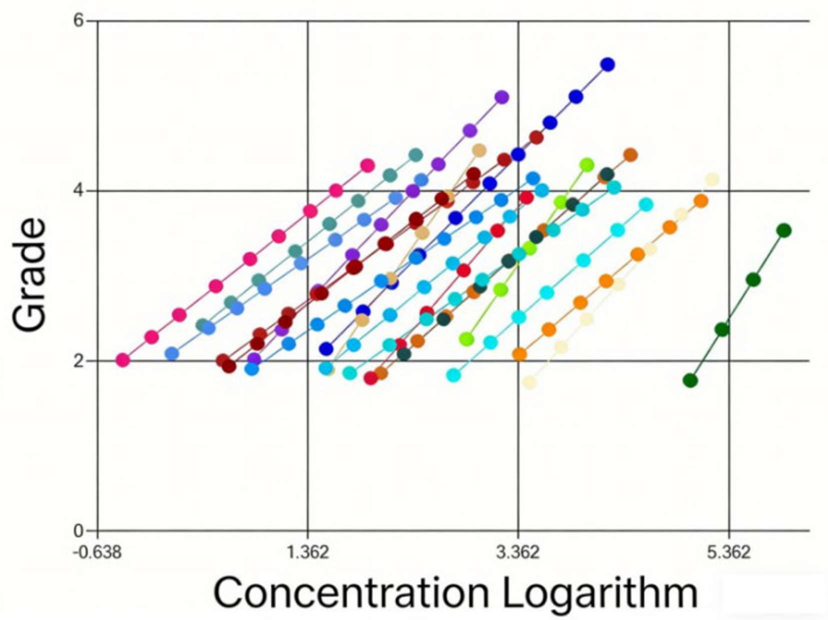

Fig. 7. Odor Laws of Odorants in the Intelligent Olfaction System

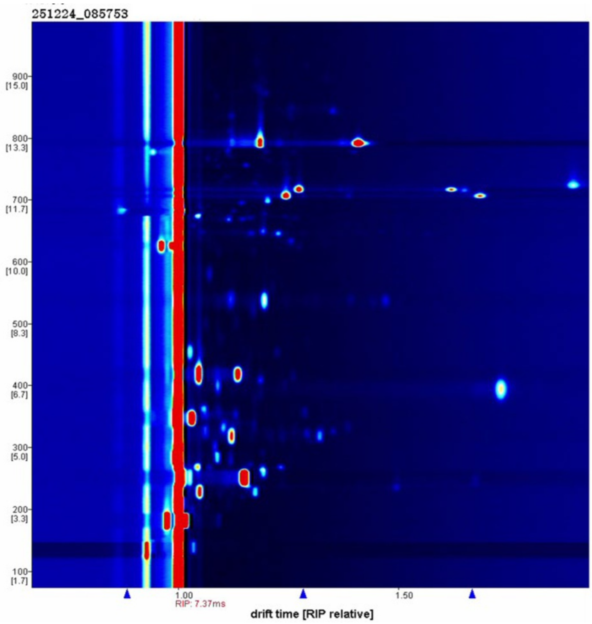

Fig. 8. Odorant Test Spectrum of the Intelligent Olfaction System

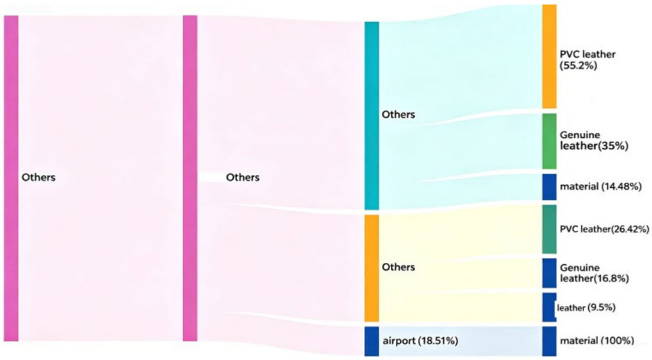

Fig. 9. Traceability Analysis of Odor Substances by Intelligent Olfaction System

6 Future Development Trends

Devices that measure total volatile compounds (TVOCs) are likely to find broader use in other industries as sensor accuracy improves. However, their principle is simple. They only measure the total concentration of volatile substances and cannot distinguish individual components. Because of this limitation, their role in automotive odor evaluation will remain limited.

Devices based on multiple sensors or detector arrays are expected to benefit from advances in semiconductor and nanotechnology. As technology improves, the detection limits of individual sensors will become lower. The variety of sensors that respond to different substances will increase. In addition, more sensors can be integrated into a single device. These systems also respond quickly and are suitable for rapid modeling. For this reason, they are widely used in areas such as food flavor analysis and environmental monitoring. Many electronic nose manufacturers focus on this type of product.

In the automotive field, such devices may become more practical under certain conditions. One condition is that detection limits reach the ppb level for key target substances. Another is that the odor composition of the tested material is relatively simple, such as single-material samples or materials with stable composition. Although these systems can identify odor problems, they still face difficulties in traceability and consistency control.

Devices that use substance separation technology operate at the molecular level. They separate mixed gases and perform both qualitative and quantitative analysis of specific odorants. This approach provides higher accuracy and represents a more advanced technical pathway. However, it also requires extensive work. Each target substance must be identified and quantified, and its odor characteristics must be studied. The chemical composition of samples varies across industries, so dedicated databases and quantitative models must be developed for different applications. If rapid identification and trace-level quantification become technically feasible, this category of equipment will likely play a central role in future odor research.

Currently, most odor evaluation systems are mainly used to assess odor intensity. Odor pleasantness and duration remain difficult to quantify. Their evaluation results are closely related to human subjective perception and change dynamically over time, leading to strong subjectivity in test results, which are difficult to verify through experiments.

In recent years, with the advancement of sensing technology and computing capabilities, methods for predicting odors based on molecular structures have gradually emerged. At the same time, the performance of sensors and related detection equipment is constantly improving. In the future, acquiring multi-dimensional signals through multi-modal fusion sensors and combining big data and artificial intelligence models for signal analysis is expected to achieve more comprehensive odor prediction and evaluation.

7 Conclusions

The evaluation of interior odors is currently receiving increasing attention in the automotive industry. However, the current methods have a significant drawback - the results largely depend on the personal perception of the evaluators, which is highly subjective. Moreover, the results obtained by different people or in different tests often vary greatly. Due to this, objective detection technologies have developed rapidly in recent years and have begun to be widely used.

The objective instruments currently available on the market for odor evaluation can be broadly classified into three categories: The first type is mainly used to measure the overall concentration of total volatile organic compounds (TVOCs); the second type relies on sensor arrays to classify and identify odors; and the third type utilizes material separation technology to isolate and analyze the components of odors at the molecular level for qualitative and quantitative analysis. The main difference among these instruments lies in the level of detail and accuracy of the information they can obtain, which directly determines where they can be used and the reliability of the results.

In the future, a TVOC detection device that only provides a total concentration value will still have many limitations when used in a car. Sensor arrays of this type of equipment are expected to be improved in terms of sensitivity and integration in the future, and are more suitable for quickly screening materials with relatively simple odor components. The technology of substance separation, although with a complex process and high cost, can precisely identify the source of the odor and achieve true "speaking based on components", so it is also regarded by many as a key direction for achieving objective odor evaluation.

At present, our research on odors mostly remains at the level of “intensity”. As for subjective indicators such as how pleasant the odor is and how long it can last, quantifying and measuring them is quite challenging. The related detection technologies and theoretical systems also need to be gradually explored and improved. Overall, better integration of high-precision chemical analysis and intelligent algorithms will be an important direction for solving the odor problem inside cars and improving the quality of automobiles in the future.

Definitions/Abbreviations

Abbreviation	Definition
VOCs	Volatile Organic Compounds
PID	Photoionization Detector
FID	Flame Ionization Detector
MOS	Metal Oxide Semiconductor
QCM	Quartz Crystal Microbalance
SAW	Surface Acoustic Wave
TVOC	Total Volatile Organic Compounds
ppb	parts per billion
CAS	Chemical Abstracts Service

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