

Article

A Sustainable Competency Assessment Framework for Automotive Maintenance Technicians: Integrating Maintenance Record Analysis and Expert Consensus

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Abstract

In response to rapid shifts toward electrification, digitalization, and sustainability in the automotive industry, this study developed a sustainability-oriented, evidence-based competency framework for automotive maintenance technicians. Traditional competency frameworks, often derived from manufacturer manuals or curricula, overlook tacit knowledge from real-world maintenance practices, leading to gaps in diagnostic effectiveness, service quality, and resource efficiency. To address this limitation, 8500 maintenance records from 67 service centers (2022–2025) were subjected to quantitative content analysis to identify preliminary competency indicators across five vehicle systems. A three-round Delphi survey involving 24 senior automotive experts was subsequently conducted to validate and prioritize these indicators on the basis of mean importance scores and coefficients of variation (≤ 0.20). The final framework comprised 39 competencies, such as diagnostic proficiency, electronic system integration, system-level troubleshooting, and technical documentation application. Beyond traditional mechanical skills, cross-system diagnostic capability and digital tool proficiency have become essential competencies for modern electric vehicles. By transforming tacit maintenance knowledge into measurable indicators, the developed framework can contribute to supporting workforce sustainability, enhancing repair accuracy, reducing unnecessary part replacement, and improving resource efficiency. It can also inform vocational education, industry certification, and human capital development aligned with Sustainable Development Goals 8, 9, and 12.

Keywords: content analysis; delphi method; vehicle maintenance history; automotive maintenance technician; technical skill framework; sustainable workforce development



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1. Introduction

The global automotive industry has undergone a profound structural transformation driven by decarbonization, electrification, and digitalization. Governments and manufacturers worldwide are actively promoting low-carbon transportation to align with the Sustainable Development Goals of the United Nations, particularly Goals 8, 9, and 12. However, in contrast to the extensive research on electric vehicles and intelligent technologies, the implications of the automotive maintenance and repair service sector for sustainable development have not been systematically examined. Maintenance and repair services play a pivotal role in ensuring efficiency, safety, and environmental performance across the entire vehicle life cycle. Maintenance and repair quality directly shape resource utilization,

material efficiency, and carbon emissions. Inaccurate diagnoses or insufficient technician competence tend to lead to repeated repairs and unnecessary component replacements, thereby increasing costs, waste generation, and the carbon emissions associated with spare-part production and logistics. Therefore, enhancing the diagnostic accuracy and technical competence of technicians is not only a workforce development priority but also a critical strategy for advancing the automotive industry's sustainable transformation. Rapid technological advancement has fundamentally reshaped modern vehicles, which now integrate electric powertrains, advanced driver assistance systems, electronic control units (ECUs), in-vehicle networks [e.g., a controller area network (CAN) bus], and software-based functionalities. Therefore, technician competency requirements have shifted from conventional mechanical repair toward cross-system diagnostics, electronic analysis, and the application of digital tools. This transition highlights the importance of sustainable human capital, that is, a workforce characterized by adaptability and interdisciplinary integration capabilities. Existing competency frameworks for technicians are primarily based on service manuals, vocational education principles, or expert opinions. Although these frameworks offer structured perspectives, they inadequately capture the tacit knowledge embedded in real-world repair practices, particularly under complex and nonstandardized fault conditions. Furthermore, most frameworks lack empirical grounding in real maintenance data and do not incorporate sustainability dimensions such as resource efficiency and life-cycle impacts. Although previous studies have employed content analysis and the Delphi method to construct competency models, research integrating large-scale maintenance data with expert consensus is lacking.

To address the aforementioned gap, the present study developed a sustainability-oriented competency framework for automotive maintenance technicians by integrating maintenance record analysis with a Delphi-based consensus process. Vehicle maintenance records provide objective evidence of the types and frequencies of failures encountered in real-world service practice. Although these records do not directly measure technician competencies, each failure reflects the diagnostic knowledge, repair skills, and technical procedures required for effective resolution. Therefore, maintenance record analysis serves as an empirical starting point for identifying competency requirements, while the Delphi method further validates and refines these competencies through expert consensus. Following this research rationale, the proposed framework was developed through a two-stage process that combined empirical maintenance data with expert validation. In the first stage, 8500 maintenance records collected from 67 service centers between 2022 and 2025 were analyzed to identify common fault types across five major vehicle systems. In the second stage, a three-round Delphi process was conducted in which senior experts refined and validated the preliminary competency indicators, leading to the establishment of a consensus-based competency framework. This study contributes to the literature in three respects. First, it links technician competencies with resource efficiency and life-cycle sustainability, extending the scope of sustainable human capital research. Second, it proposes a competency development approach that integrates empirical maintenance data with expert consensus. Third, it provides an empirical foundation for updating and optimizing vocational education curricula, industry certifications, and workforce development strategies. Rather than seeking to replace foundational training elements—such as routine preventive maintenance, which is already thoroughly established in traditional curricula—this framework serves as a critical supplement to address existing gaps. Standard vocational curricula, often prescribed by educational authorities based on conventional vehicle architectures, frequently lag behind rapid technological advancements and lack coverage of the implicit diagnostic skills and technical competencies required for modern vehicles integrated with advanced sensors and automated systems. By anchoring curriculum re-

finement on recurring field failures and expert consensus, this study offers a targeted mechanism to dynamically enhance existing educational frameworks, ensuring they realign with contemporary industry demands. Amid increasing technological complexity and rising environmental responsibility, establishing a technician competency framework aligned with sustainability principles carries substantial implications for enhancing service quality and reducing resource waste.

2. Literature Review

2.1. Sustainable Development Trends in Automotive Technology

With continuous technological advancements, automotive systems have transformed from conventional mechanical structures into integrated platforms combining automation, digitalization, and electrification. With regard to automation and digitalization, modern vehicles typically incorporate multiple sensors, ECUs, and tightly coupled subsystem architectures. Automotive control systems have evolved from mechanical control mechanisms to distributed ECUs and subsequently to centralized computing architectures powered by high-performance central processors. This progression has enabled a shift from hardware-defined vehicles to a software-defined vehicle paradigm [1,2]. Furthermore, automotive electrification represents a system-level engineering transformation. Its key features include the replacement of internal combustion engines with electric motors, the use of electrochemical energy storage technologies (e.g., battery systems), and the incorporation of intelligent energy management systems [3]. Automation and digitalization have enhanced vehicle controllability and safety while optimizing powertrain efficiency, thereby improving energy conservation and reducing carbon emissions. Electrification has advanced energy transition and intelligent management, thus contributing to energy savings and carbon emission reduction. In summary, the technological transformation of the automotive industry is a crucial part of the global trajectory of sustainable development.

2.2. Human Capital in Maintenance Services and Sustainable Development

Within the automotive industry, market value reflects the combined influence of tangible resources and intangible human capital. Systematic assessment, planning, and implementation of training needs can enhance technician performance and strengthen the competitiveness of automotive service enterprises [4]. Automotive maintenance technicians are vital human capital in the automotive service sector. With the advancement of sustainable automotive technologies, vehicle systems have become increasingly complex, and technological updates have accelerated. Consequently, the competencies required by technicians have shifted from traditional repair skills toward cross-system diagnostic and data analysis capabilities. Insufficient technical competence may hinder effective fault resolution, resulting in service failures, repeated repairs, and resource waste, which compromise service quality and sustainable development. Empirical evidence indicates that inadequate training or diagnostic capability among technicians increases the recurrence rate of post-service faults, reduces system reliability, and raises maintenance costs [5]. Deficiencies in technical skills or inadequacies in quality management may lead to rework and inefficiencies in maintenance processes, thus reducing resource efficiency and customer satisfaction [6]. Service quality problems are also a primary source of customer complaints. Erroneous repair practices, such as unnecessary component repair or overservicing, reflect insufficient on-site competence and contribute to diminished asset sustainability as well as increased resource consumption and costs [7,8]. Moreover, inappropriate maintenance practices exacerbate resource waste. When such practices involve waste generation and emissions, they may increase hazardous emissions and occupational exposure risks. These challenges underscore the importance of strengthening technical competence among

technicians and enhancing service quality [9]. In summary, strengthening technicians' competencies and supporting their continuing professional development are critical for enhancing organizational performance and advancing sustainable development.

2.3. Evaluation Indicators of Technical Competencies for Maintenance Technicians

The fault diagnosis process typically comprises three stages: fault detection, localization, and isolation. In traditional automotive repair settings, technician competence is primarily assessed on the basis of original equipment manufacturer (OEM) manuals. However, these manuals mainly provide guidance on repair procedures and component replacement and lack comprehensive, systematic diagnostic logic. Consequently, they offer limited support for the holistic evaluation of technician competence [10,11]. Certain forms of tacit knowledge require years of accumulated experience to master and cannot be fully codified in technical manuals. As vehicle digitalization and intelligence continue to advance, system architectures are becoming increasingly complex and cross-system integration is expanding, further exacerbating this limitation [12–14]. Moreover, fault causes may arise from abnormal environmental conditions, improper operation, non-OEM components, modifications, accidents, or maintenance errors. OEM manuals cannot cover all possible scenarios, providing limited guidance for intermittent or nontypical faults [15].

Qualitative studies have suggested that methods such as content analysis, the Delphi method, and focus group interviews can facilitate the development of maintenance and repair skill evaluation indicators. Yu et al. [16] assessed the competencies of electric vehicle maintenance technicians by integrating the literature and standards analysis with three rounds of expert surveys, developing a framework comprising four core competencies, 24 subcategories, and 106 competency indicators. Fatah et al. [17] employed a modified Delphi technique to leverage expert opinions in the development of competency indicators for automotive body repair instructors. Arasinah and Sariati [18] combined curriculum and occupational standards analysis with three rounds of expert surveys to define core competency dimensions and detailed skills in the field of automotive technology. Moreover, Shyr [19] developed competency indicators for mechatronics through content analysis, supplemented their framework with focus group interviews, and then applied the Delphi method to refine their indicator set.

Beyond their traditional role in supporting equipment maintenance, maintenance records have increasingly been recognized in reliability engineering and prognostics and health management (PHM) research as valuable operational data that reflect recurring failure modes, maintenance priorities, and system health conditions. Jardine et al. emphasized that condition-based maintenance relies on historical operational data to support diagnostic reasoning and maintenance decision-making [20]. Likewise, Lee et al. described PHM as an integrated framework that combines diagnostics, prognostics, and maintenance knowledge to improve system reliability through the effective use of operational data [21]. Furthermore, studies on maintenance data quality have noted that maintenance records may contain incomplete or inconsistent information, highlighting the importance of expert validation and complementary data verification procedures when such records are used for analytical purposes [22]. Therefore, although maintenance records do not directly measure technician competencies, they provide an objective empirical basis for identifying recurring maintenance demands, while expert consensus can further validate and refine competency indicators.

3. Methodology

This study adopted a two-stage research design. In the first stage, maintenance records from vehicle repair centers were subjected to statistical analysis to extract preliminary indi-

cators. These records were selected as the primary data source to reflect actual vehicle usage conditions and common problems encountered by vehicle owners. In the second stage, experts in automotive maintenance and repair were invited to validate the preliminary competency indicators, evaluate their importance, and identify additional competencies not directly reflected in maintenance records, such as diagnostic reasoning, technical documentation usage, and emerging technology skills. Through this Delphi-based refinement process, the preliminary indicators were further refined and supplemented to complement existing technical competency assessments by incorporating practical competencies identified from real-world maintenance experience and expert consensus.

3.1. Preliminary Indicator Extraction

Content analysis involves systematically encoding, classifying, and examining textual, visual, or symbolic data to identify the characteristics and trends of phenomena [23–25]. This study applied content analysis to maintenance records from automotive repair facilities, focusing on problems that had been diagnosed and repaired across five major vehicle systems. The analysis involved recording frequency counts and conducting preliminary classification of fault types. By examining problems that are difficult to capture in traditional technical manuals and deriving preliminary indicators from categorized historical maintenance records, experts can avoid excessive divergence in the absence of baseline references. The preliminary indicators were then reviewed and assessed by experts in automotive maintenance and repair. While individual maintenance records may occasionally exhibit diagnostic inaccuracies or human errors inherent in real-world field operations, the primary objective of this study was not to isolate the precise root causes of discrete vehicle failures. Instead, it aimed to identify macro-level technical competencies required for automotive maintenance by analyzing a vast corpus of empirical data. The dataset comprises approximately 8500 completed maintenance cases collected from 67 authorized service centers over multiple years. Through this large-scale data aggregation, the statistical impact of isolated diagnostic anomalies is substantially diluted. Furthermore, because the competency indicators were derived from frequently recurring maintenance tasks and subsequently validated through three rounds of rigorous Delphi consultations with experienced experts, the potential influence of occasional recording errors was effectively minimized, ensuring the robustness of the finalized framework.

3.2. Indicator Validation and Importance Assessment

Content analysis typically relies on coders to perform data coding and classification, followed by reliability testing. However, previous studies have identified several limitations of this approach. First, coders are often research assistants or trained personnel who lack domain-specific expertise, which may result in misinterpretation of meaning and context, leading to classification bias and compromised interpretive validity. Second, although coder training requires substantial time and cost, it cannot fully compensate for deficiencies in domain knowledge. Third, content analysis generally does not incorporate expert feedback mechanisms for refining results; consequently, interpretive bias may arise, further weakening research validity [24–27]. To address these limitations, the Delphi method was applied in the second stage of this study. Experts in automotive maintenance and repair were invited to validate the derived indicators and assess their importance. This process allowed the indicator set to be refined, thereby enhancing the effectiveness and accuracy of the content analysis. Furthermore, regarding the specific operational criteria within this content analysis stage, although vehicle mileage and failure-life-cycle characteristics (e.g., the classical bathtub curve) significantly influence specific failure mechanisms, detailed mileage data were unavailable in this study due to data privacy policies and system

limitations within the service networks. Moreover, the primary objective of this research was to establish a macro-level technician competency framework associated with systemic maintenance tasks, rather than to analyze discrete component reliability. Therefore, the maintenance records were aggregated and analyzed based on fault occurrences across major vehicle systems instead of mileage intervals.

3.2.1. Selection of Domain Experts

Domain experts are individuals who possess both specialized knowledge and practical experience related to a research topic. Experts can perform multiple roles, including providing critical information, evaluating trends and potential developments, facilitating consensus, and enhancing the legitimacy of decision-making. Such individuals should demonstrate strong professional judgment, high participation motivation, sufficient time commitment, and effective written communication skills [28,29]. No unified standard exists regarding the appropriate sample size for expert panels. An insufficient number of experts may limit the representativeness of judgments, whereas a large panel can enhance diversity but also increase analytical burden. For small-scale studies or panels with relatively homogeneous backgrounds, a range of 8–20 experts is recommended [29–31]. By contrast, studies involving larger samples or more diverse backgrounds should include 20–30 or more experts to strengthen group representativeness and enhance research validity, stability, and replicability [32].

Given the high complexity of automotive systems, this study placed particular emphasis on multidisciplinary system expertise in expert selection. The selection criteria required a minimum of 5 years of practical experience in automotive maintenance and repair facilities as well as prior service in a technical managerial position at or above the chief technician level. In addition to technical expertise, communication and collaboration abilities were considered essential for facilitating the Delphi consultation process. Experts were primarily selected from technical managers and chief technicians employed at authorized automotive service centers. In Taiwan's automotive service industry, these professionals not only perform managerial responsibilities but also remain actively involved in frontline vehicle diagnosis and repair, supervise maintenance quality, and provide technical guidance and mentoring to junior technicians. Consequently, they possess extensive practical maintenance experience together with comprehensive knowledge of technician competency requirements across different skill levels, making them well qualified to serve as experts in this Delphi study. Considering the broad scope of automotive-system-related problems, this study aimed to recruit 20–30 experts with diverse system specializations to ensure comprehensive coverage.

3.2.2. Expert Questionnaire Design

The Delphi method typically involves 2–4 rounds of expert surveys. In the first round, an open-ended questionnaire is used to collect expert opinions. In the second round, a structured scale (e.g., a Likert scale) is employed for evaluation. If consensus is not achieved, a third round is conducted, where experts revise items on the basis of prior results and provide statistical summaries and feedback. This stage enables experts to reconsider their responses according to group opinions and facilitates the formation of consensus [28,29,33,34]. If a fourth round is required, it follows the third; revisions and synthesis are based on the third-round results.

In this study, the first round of the Delphi method involved administering an open-ended questionnaire to experts to assess the appropriateness of competencies identified in the first research stage and identify any critical competencies that were not captured. This approach incorporated empirical data, reduced response dispersion, and improved survey

efficiency. As noted in Section 3.1, indicators derived from historical maintenance data provided a reference and limited excessive divergence. From the second round onward, a Likert scale was employed for evaluation. Scale selection influences response quality; overly limited scales constrain information, whereas excessively broad scales increase respondent burden and reduce willingness to respond. Most studies adopt 5- or 7-point scales, whereas 9–11-point scales are suitable for contexts requiring high expertise and fine discrimination [35,36].

Given the high level of specialization involved in automotive system repair and the participation of senior technical experts, this study adopted a 10-point Likert scale to enhance the discrimination of indicator importance. Ratings ranged from 1 (*not important at all*) to 10 (*extremely important*). Each item included a comment field to allow experts to provide additional explanations, thereby promoting communication and facilitating convergence of opinions.

3.2.3. Expert Survey

Delphi studies typically achieve consensus and convergence within three rounds. When results remain unstable or specific research requirements arise, a fourth round may be introduced to confirm and refine the findings, with experts reviewing categorized maintenance data and indicating additions or items for removal [28,29,31,37,38].

In this study, the expert survey was designed to span 2–4 rounds. In the first round, an open-ended questionnaire was used to collect expert opinions on the competencies identified in the first stage of the research and any missing competencies, thereby establishing a basis for the development of competency indicators. The collected responses were then consolidated into a set of competency indicators, which informed the design of a structured questionnaire in the second round. If a high level of consensus was achieved for all competency indicators in the second round, the survey was concluded. If consensus was not achieved for certain indicators, a third round was conducted, focusing exclusively on indicators that had moderate consensus or were newly proposed. The experts then revised the questionnaire on the basis of prior results and provided statistical summaries and feedback. All responses were collected anonymously to promote convergence of expert opinions. If consensus was still not achieved after the third round, a fourth round was conducted using the same procedure to achieve a high level of consensus for all competency indicators.

3.2.4. Assessment of Competency Importance and Consensus Testing

The Delphi method relies on group judgments by experts for decision-making. Survey results are typically analyzed using measures of central tendency (e.g., mean, median, and mode) to assess the importance of each item, whereas measures of dispersion [e.g., coefficient of variation (CV), percentage agreement, and interquartile range] are used to evaluate the level of consensus. When the survey involves ranking tasks, Kendall's *W* is commonly employed to test the stability of expert opinions; when items are independent, the CV is generally applied [29,39]. In the present study, the mean value was used to assess the importance of an indicator. Moreover, because the indicators were independent, the CV was adopted to evaluate consensus. A lower CV reflects a higher level of agreement among experts, and a decreasing CV across Delphi rounds indicates a shift toward convergence. Although no universally accepted threshold exists for the CV, values between 0.2 and 0.3 have been widely adopted as a basis for determining consensus, with Kendall's *W* sometimes used for further verification. In this study, CV values of ≤ 0.2 , 0.21–0.3, and > 0.3 were considered to indicate high consensus, moderate consensus, and lack of consensus, respectively.

3.3. Identification of Competency Indicators for Maintenance Technicians

Competency indicators with a CV above 0.3 were excluded during each survey round. After the third round, any indicators with a CV of 0.21–0.3 had also been removed. The final competency indicators satisfied two criteria: they had a CV of ≤ 0.2 (indicating high consensus) and a mean importance score of ≥ 7.0 . These indicators were regarded as highly critical and indispensable, serving as the basis for evaluating the competencies of automotive maintenance technicians (Figure 1).

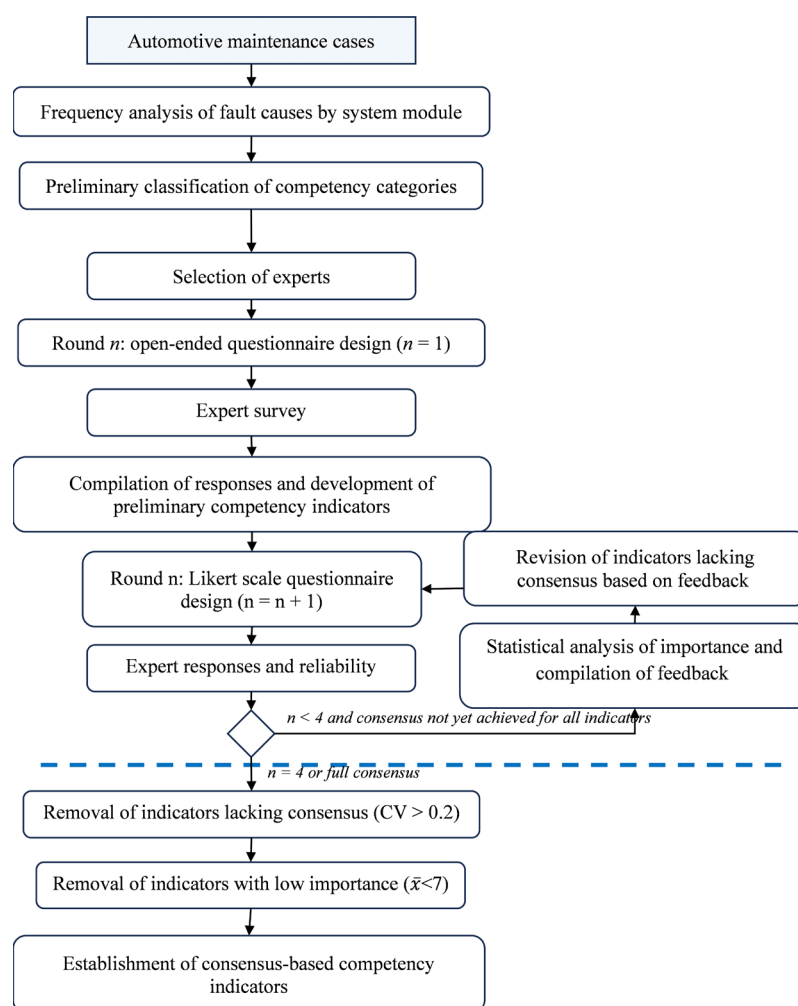


Figure 1. Process for establishing competency indicators for automotive maintenance technicians.

3.4. Use of Generative AI for Literature Identification

During the literature identification process, ChatGPT (GPT 5.5, OpenAI, San Francisco, CA, USA) was used solely to assist in identifying potentially relevant publications and references related to automotive maintenance technician competencies, maintenance record analysis, and the Delphi method. The tool was not used to conduct the literature review, determine the inclusion or exclusion of sources, generate research data, perform statistical analysis, interpret the findings, or formulate the conclusions. All references suggested by the tool were independently searched, screened, verified, and evaluated by the authors before being cited in this study.

4. Empirical Results

4.1. Case Data Collection and Preliminary Analysis

The maintenance records collected in this study were derived from service histories of passenger vehicles of a certain brand in Taiwan and obtained from 67 local repair facilities. The dataset covered the period from September 2022 to May 2025 and comprised 8500 diagnostic and repair records documented through the maintenance record system. The collected data were related to five major automotive systems: engine control, electrical, body, chassis, and transmission systems. An initial statistical analysis was conducted to examine the frequency of maintenance events across these five systems. As presented in Table 1, the engine control system accounted for the highest number of cases (3510 cases, 41.29%), followed by the electrical system (2013 cases, 23.68%), body system (1620 cases, 19.06%), chassis system (832 cases, 9.79%), and transmission system (525 cases, 6.18%). Based on technicians' descriptions of fault conditions, the research team conducted a content analysis of the 8500 maintenance records. Fault records describing the same or substantially similar maintenance problems were consolidated into representative fault categories within each vehicle system to standardize heterogeneous maintenance records, and the occurrence frequency of each category was calculated. This initial categorization was performed by the research team. During the first round of the Delphi process, the experts reviewed the preliminary fault categories and, where necessary, refined or revised the categorization before proceeding with the development of competency indicators. They also identified and supplemented additional competencies not explicitly reflected in the maintenance records. The analysis identified 12 major fault types for the engine control system. For example, "engine idle vibration with a tendency to stall" occurred 512 times (14.6%) and "unstable idling" occurred 264 times (7.5%). Moreover, 26, 24, 10, and 12 fault types were identified for the electrical, body, chassis, and transmission systems, respectively; the 84 fault types across the five systems served as the basis for designing expert questionnaire surveys.

Table 1. Summary of maintenance cases by system.

No	System	Number of Maintenance Cases	Percentage (%)	Number of Fault Types
1	Engine control system	3510	41.29	12
2	Electrical system	2013	23.68	26
3	Body system	1620	19.06	24
4	Chassis system	832	9.79	10
5	Transmission system	525	6.18	12
	Total	8500	100	84

4.2. Selection of Experts

This study selected 24 experts with professional backgrounds in automotive maintenance and repair on the basis of predefined criteria. The final panel comprised 4 service center managers, 7 regional chief technicians, and 13 senior chief technicians. Among the 24 experts, 23 held academic degrees in automotive engineering or related fields. One expert lacked formal academic training in automotive maintenance but accumulated extensive practical experience through apprenticeship and subsequently advanced to the position of regional chief technician; this individual was therefore included in the study. The selected experts had an average experience of 17 years in automotive maintenance and repair. Their core expertise covered the five considered automotive systems, with 4–5 experts specializing in each system.

4.3. Design of the First-Round Questionnaire and Expert Survey

The open-ended questionnaire used in the first round of the Delphi method was developed on the basis of the 84 fault types identified through maintenance record analysis. This questionnaire was used to collect expert opinions on the repair techniques required for each type of recognized fault, evaluate the suitability of these techniques as competency indicators, and identify critical competencies not captured in the maintenance records.

On the basis of the expert feedback, fault items were merged, eliminated, and added. First, items that corresponded to the same system and fault type and required identical technical competencies were consolidated to improve indicator consistency. For example, multiple engine-related idling abnormalities were merged into a single indicator because they required the same diagnostic capability. Second, fault items with occurrence rates below 3% were excluded. These items typically reflected exceptional conditions and did not adequately represent the core competencies of general technicians; therefore, they were not included in the indicator system. Finally, given the high reliance of modern vehicles on electronic and diagnostic systems, additional competencies were incorporated, including diagnostic equipment (e.g., automotive diagnostic system) operation, fault code interpretation, and technical documentation review. These additions ensured a more comprehensive representation of the digital competencies required in practical maintenance work. Importantly, these expert-added competencies do not diminish the value of maintenance record analysis. Rather, they illustrate the complementary roles of the two research stages: maintenance records provided an objective, practice-based foundation for identifying competencies associated with frequently encountered service tasks, whereas the Delphi process enabled experts to identify essential competencies that are less visible in maintenance records but remain critical for effective diagnosis and repair in modern vehicles. Together, these two stages produced a more comprehensive and practically relevant competency framework. Following the aforementioned procedures, 37 fundamental maintenance skills across the five major automotive systems were identified as required competencies for maintenance technicians. The consolidated results are presented in Table 2.

Table 2. Summary of expert feedback obtained from the first-round questionnaire.

System	Total Number of Fault Types	Numbers of Fault Types Before and After Merging		Number of Eliminated Fault Types	Number of Added Fault Types	Number of Retained Fault Types	Final Number of Fault Types
		Before Merging	After Merging				
Engine control system	12	6	2	3	4	3	9
Electrical system	26	12	3	14	5	0	8
Body system	24	13	3	11	3	0	6
Chassis system	10	7	2	3	5	0	7
Transmission system	12	6	2	6	5	0	7
Total	84	44	12	37	22	3	37

4.4. Design of the Second-Round Questionnaire and Expert Survey

To explore expert consensus, this study designed a second-round questionnaire on the basis of the 37 competency indicators compiled in the first round, with a 10-point Likert scale used to assess the importance of each indicator. Each questionnaire item included an open-ended comment field to allow experts to provide additional explanations.

The results indicated that 29 of the 37 competency indicators met the consensus criterion ($CV \leq 0.20$). The eight indicators for which consensus was not reached were revised in accordance with the expert feedback. First, the skill of refrigerant replacement in the body system was removed because it failed to meet the criteria for both mean importance score (6.92) and CV (0.39). In addition, most experts considered it a non-core competency. Second, several experts suggested including competencies related to the electronic control system, such as diagnostic and troubleshooting skills for the anti-theft control circuit in the body control module (BCM), the supplemental restraint system (SRS) control circuit, and the CAN communication circuit. These competency indicators were incorporated for evaluation in the third round. Third, additional opinions were collected on the seven remaining indicators for which consensus had not yet been reached. Experts assigning high scores tended to provide less detailed explanations, whereas those assigning relatively low scores offered more extensive feedback. To facilitate the formation of consensus, experts who assigned high scores were invited to provide supporting rationales, which were shared anonymously with all participants to strengthen communication and promote convergence of opinions.

4.5. Third-Round Expert Survey

The third-round expert survey focused only on the competency indicators for which consensus was not reached in the second round and the newly proposed indicators. On the basis of the results of the second round, seven existing and three new competency indicators were considered in the third round. One indicator for which consensus could still not be reached (failing to meet the criteria for mean importance score and CV) was excluded; thus, the third-round questionnaire comprised nine competency indicators. To facilitate experts' understanding of the second-round results and the opinions of other experts, a summary of the second-round findings was presented to the experts (Appendix A). The summary included the mean scores, standard deviations, and consensus levels for each competency indicator as well as anonymized expert feedback. In the third-round survey, consensus was achieved for all nine considered indicators ($CVs < 0.20$). Thus, consensus was reached for 39 competency indicators across the second and third rounds; consequently, a fourth survey round was not conducted.

4.6. Importance and Consensus Levels of Competency Indicators for Maintenance Technicians

After the three rounds of expert surveys, 39 skill indicators exhibited a mean importance score exceeding 7.0 and a CV below 0.20 (Tables 3–7), suggesting that these indicators had high importance and a high consensus level. Accordingly, the 39 indicators were considered crucial competency evaluation criteria for automotive maintenance technicians.

Table 3. Analysis of expert opinions regarding the engine control system (rounds 2 and 3).

Competency Indicator	Round 2				Round 3			
	Total Score	Mean	Standard Deviation	Coefficient of Variation (CV)	Total Score	Mean	Standard Deviation	CV
Automotive diagnostic system operation	222	9.25	1.22	0.13	-	-	-	-
Service manual consultation	216	9.00	1.38	0.15	-	-	-	-
Fault code interpretation	219	9.13	1.23	0.13	-	-	-	-
Ability to handle scenarios where the engine fails to fire	224	9.33	1.24	0.13	-	-	-	-
Ability to handle scenarios where the engine fails to start	221	9.21	1.53	0.17	-	-	-	-
Ability to handle scenarios where the engine exhibits idle vibration and a tendency to stall	211	8.79	1.82	0.21	218	9.08	0.93	0.10
Ability to handle scenarios where engine acceleration is insufficient	216	9.00	1.69	0.19	-	-	-	-
Measurement of major engine parameters	207	8.63	1.93	0.22	213	8.88	1.12	0.13
Engine electrical circuit diagnostics	223	9.29	1.00	0.11	-	-	-	-

Table 4. Analysis of expert opinions regarding the transmission system (rounds 2 and 3).

Competency Indicator	Round 2				Round 3			
	Total Score	Mean	Standard Deviation	CV	Total Score	Mean	Standard Deviation	CV
Automotive diagnostic system operation	228	9.50	1.06	0.11	-	-	-	-
Service manual consultation	211	8.79	1.82	0.21	227	9.46	0.88	0.09
Fault code interpretation	222	9.25	0.94	0.10	-	-	-	-
Insufficient transmission acceleration	197	8.21	1.77	0.22	205	8.54	1.02	0.12
Measurement of major transmission parameters	199	8.29	0.55	0.07	-	-	-	-
Transmission electrical circuit diagnostics	219	9.13	1.03	0.11	-	-	-	-
Transmission disassembly and reassembly	173	7.21	2.26	0.31	188	7.83	1.05	0.14

Table 5. Analysis of expert opinions regarding the body system (rounds 2 and 3).

Competency Indicator	Round 2				Round 3			
	Total Score	Mean	Standard Deviation	CV	Total Score	Mean	Standard Deviation	CV
Automotive diagnostic system operation	215	8.96	1.54	0.17	-	-	-	-
Service manual consultation	216	9.00	1.56	0.17	-	-	-	-
Fault code interpretation	221	9.21	1.32	0.14	-	-	-	-
Measurement of major air-conditioning (AC) parameters	211	8.79	1.44	0.16	-	-	-	-
AC control circuit diagnostics	211	8.79	1.64	0.19	-	-	-	-
Refrigerant replacement	156	6.50	2.54	0.39	-	-	-	-
Diagnostics for the anti-theft control circuit in the Electronic Time and Alarm Control System	-	-	-	-	205	8.54	1.02	0.12
Diagnostics for the supplemental restraint system's control circuit	-	-	-	-	189	7.88	0.68	0.09
Diagnostics for the controller area network communication circuit	-	-	-	-	227	9.46	0.83	0.09

Table 6. Analysis of expert opinions regarding the chassis system (rounds 2 and 3).

Competency Indicator	Round 2				Round 3			
	Total Score	Mean	Standard Deviation	CV	Total Score	Mean	SD	CV
Automotive diagnostic system operation	224	9.33	1.24	0.13	-	-	-	-
Service manual consultation	224	9.33	1.24	0.13	-	-	-	-
Fault code interpretation	226	9.42	1.44	0.15	-	-	-	-
4WD system diagnostics	187	7.79	1.93	0.25	203	8.46	0.72	0.09
Anti-lock braking system and active stability control system diagnostics	192	8.00	0.66	0.08	-	-	-	-
Measurement of major chassis-related parameters	207	8.63	1.66	0.19	-	-	-	-
Chassis control circuit diagnostics	210	8.75	1.29	0.15	-	-	-	-

Table 7. Analysis of expert opinions regarding the electrical system (rounds 2 and 3).

Competency Indicator	Round 2				Round 3			
	Total Score	Mean	Standard Deviation	CV	Total Score	Mean	Standard Deviation	CV
Automotive diagnostic system operation	218	9.10	1.45	0.16	-	-	-	-
Service manual consultation	224	9.33	0.92	0.10	-	-	-	-
Fault code interpretation	224	9.33	1.13	0.12	-	-	-	-
Lighting system diagnostics	193	8.04	1.71	0.21	210	8.75	0.85	0.10
Central locking system diagnostics	214	8.92	1.32	0.15	-	-	-	-
Power window system diagnostics	212	8.83	1.43	0.16	-	-	-	-
Measurement of major electrical component parameters	208	8.67	1.61	0.19	-	-	-	-
Electrical control circuit diagnostics	229	9.54	0.78	0.08	-	-	-	-

4.7. Validation of the Consensus on Competency Indicators for Maintenance Technicians

This study evaluated the overall level of expert consensus for the questionnaire and compared the improvements between the second and third survey rounds. The relevant results are summarized in Table 8. The average mean importance score across all competency indicators increased from 8.82 in Round 2 to 8.95 in Round 3, whereas the standard deviation of the mean importance score decreased from 1.61 to 1.29. Moreover, the average CV decreased from 0.29 to 0.18, reflecting an overall shift from moderate consensus to high consensus. Thus, the third-round survey substantially improved the consistency of expert opinions. Further gains from conducting a fourth round were expected to be limited. Therefore, expert opinions were considered to have stabilized. Because all competency indicators achieved the predefined consensus criterion ($CV \leq 0.20$) in the third round, the stopping criterion established in the methodology was satisfied. Under these conditions, an additional Delphi round was considered unlikely to produce meaningful changes in expert ratings or the overall competency framework.

Table 8. Overall consensus of expert opinions and trend analysis.

Measure	Round 2	Round 3	Improvement
Average mean importance ($\bar{x}$)	8.82	8.95	0.13
Standard deviation (s) of the mean importance	1.61	1.29	0.32
Average CV ($\bar{x}/s$)	0.29	0.18	0.11
Consensus level	Moderate ($2 < CV < 3$)	High ($CV < 2$)	

5. Discussion

5.1. Identification of Core Competency Indicators

This study employed a two-stage design, integrating quantitative content analysis of maintenance records with a structured Delphi method to develop core competency indicators for automotive maintenance technicians. In the first stage, 8500 maintenance records from 67 service centers, collected between 2022 and 2025, were analyzed to identify

common faults across five major vehicle systems. A total of 84 fault types were identified, reflecting practical demands and technical challenges in automotive maintenance.

Following preliminary data organization, an open-ended questionnaire was used in the first round of a Delphi survey to assess the appropriateness of the technical competencies required for each fault category as potential competency indicators. On the basis of expert feedback, categories were consolidated, low-frequency fault types were removed, and critical competencies not directly captured in the maintenance records—such as diagnostic tool operation and technical documentation usage—were incorporated. This process yielded a set of 37 preliminary competency indicators across the five major systems. In the second round, experts evaluated the importance of each competency indicator by using a 10-point Likert scale. Of the 37 examined indicators, 29 met the consensus criterion of $CV \leq 0.20$, whereas eight did not. Under the guidance of expert suggestions, one low-importance indicator that did not exhibit consensus was eliminated, and three new competencies related to electronic control systems were added. The third round focused exclusively on the remaining seven indicators that did not exhibit consensus and the three newly added indicators, ultimately confirming that all indicators met the consensus standard. Through three rounds of the Delphi process, a final framework comprising 39 competency indicators across the five major vehicle systems was established. Each indicator satisfied the criteria for high importance (mean ≥ 7.0) and high consensus ($CV \leq 0.20$), reflecting their high value in automotive maintenance.

Overall, the competency framework developed in this study demonstrates that integrating large-scale maintenance records with expert consensus provides a practical and robust approach for identifying competency requirements in automotive maintenance. Although the source records were derived from routine service operations rather than controlled experimental settings, meaning occasional diagnostic or recording inaccuracies cannot be completely excluded, the primary objective of this study was to identify recurring competency requirements rather than evaluate the diagnostic accuracy of individual maintenance cases. Because the analysis relied on the substantial volume of this multi-center dataset, the competency indicators were successfully derived from macro-level, recurring maintenance patterns rather than isolated anomalies. Therefore, occasional diagnostic or recording errors are highly unlikely to substantially influence the overall analytical findings. Moreover, the competency indicators were subsequently refined and validated through three rounds of Delphi consultation with experienced experts, further mitigating the potential influence of isolated recording errors and ensuring the empirical robustness of the finalized framework.

5.2. Evolution of Technical Competency Requirements

The results indicate a substantial transformation in the competency structure of modern automotive maintenance technicians. Traditional mechanical repair skills remain essential; however, the importance of system-level diagnostics and electronic system analysis has gradually increased. Across all vehicle systems, three competencies—operation of diagnostic tools (automotive diagnostic system), fault code interpretation, and use of service manuals—received considerably high ratings, demonstrating that digital diagnostic proficiency has become a core requirement in the field. With vehicles increasingly integrating ECUs, sensor networks, and software-based control architectures, technicians must possess the ability to interpret diagnostic data and analyze system interactions rather than relying solely on mechanical troubleshooting. In addition, newly identified competencies related to CAN communication systems, SRS control circuits, and BCM safety systems reflect the growing complexity of vehicle electronic architectures. These skills were not captured directly through maintenance record analysis but were recognized by experts as

essential for contemporary technicians. These findings are consistent with those of prior research, which has emphasized that modern vehicle maintenance requires cross-system diagnostic reasoning and the integration of interdisciplinary knowledge rather than simply traditional single-component repairs.

Although several of the highest-rated competencies were identified through expert consensus rather than directly from the maintenance records, this does not diminish the value of maintenance record analysis. Instead, the findings highlight the complementary roles of empirical maintenance data and expert knowledge in competency development. Maintenance records provided an objective foundation by identifying the vehicle systems and fault types most frequently encountered in real-world service practice, thereby defining the core technical domains requiring competence. The Delphi process subsequently enabled experts to identify additional competencies, particularly those related to advanced diagnostics and emerging vehicle technologies, that are essential for effective maintenance but are not explicitly reflected in maintenance records. Consequently, the final competency framework integrates both evidence from maintenance practice and expert judgment, resulting in a more comprehensive representation of the competencies required of contemporary automotive maintenance technicians.

5.3. Implications for Sustainable Automotive Maintenance

In addition to indicating crucial technical competencies for automotive maintenance technicians, the findings of this study have vital implications for the sustainable operation of automotive repair services. Accurate fault diagnosis and efficient maintenance directly contribute to sustainability by preventing unnecessary part replacements, reducing material waste, and enhancing resource utilization over the vehicle's life cycle. Conversely, insufficient diagnostic capabilities among technicians can result in repeated repairs, excessive part replacements, and higher operational costs. The competency framework developed in this study supports sustainability in several ways. First, it can improve diagnostic accuracy, reducing inefficient maintenance and unnecessary resource consumption. Second, by strengthening technician capabilities, it can extend vehicle service life, thereby mitigating the environmental impact associated with manufacturing and disposal. Third, it provides a structured foundation for the sustainable development of the automotive service workforce. By identifying the critical skills required for servicing modern vehicle systems, training institutions and service organizations can design targeted programs that align workforce development with evolving industry technologies. The aforementioned outcomes would not only advance sustainability objectives but also promote responsible consumption, enhance industrial efficiency, and increase workforce resilience.

5.4. Methodological Contributions

This study indicates the value of combining real-world maintenance data with expert consensus methods to construct a competency framework. Traditional approaches for defining technician skills often rely on manufacturer manuals, educational curricula, or expert committee deliberations. Although these methods can establish systematic knowledge, they may overlook tacit, field-based experience. By using maintenance records as the primary data source, this study effectively captured operational challenges encountered in practical service environments, including complex and nonstandard faults not documented in technical manuals. The subsequent application of the Delphi method allowed expert evaluation and refinement of the competency indicators, enhancing both the practical relevance and the credibility of the proposed framework.

An additional methodological strength of this approach lies in its ability to mitigate the uncertainty associated with maintenance records. Because maintenance records are

primarily generated for operational rather than research purposes, they may contain variations in diagnostic descriptions, incomplete contextual information, or occasional recording inaccuracies. If maintenance records were used alone, such uncertainty could propagate into the preliminary identification of competency requirements. In this study, however, maintenance records served as an empirical starting point, whereas the three-round Delphi process enabled experienced experts to validate, revise, and supplement the preliminary competency indicators through structured consensus. Consequently, the final competency framework reflects expert consensus informed by real-world maintenance evidence rather than a direct translation of maintenance records alone, thereby improving the robustness and reliability of the proposed methodology.

The adopted methodology is highly adaptable, capable of accommodating ongoing technological advancements in vehicles (e.g., electric vehicles, software-defined vehicles, and intelligent transportation systems) by incorporating new maintenance records and expert feedback. Thus, it allows competency requirements to be dynamically updated in response to evolving technical demands.

6. Conclusions

This study conducted quantitative content analysis of vehicle maintenance records and applied a structured Delphi method to integrate empirical insights with expert consensus in the development of a competency assessment framework for automotive maintenance technicians. Through analysis of 8500 maintenance records from 67 service centers and three rounds of consultation with 24 senior experts, this study established a competency framework comprising 39 competency indicators related to five major vehicle systems; all indicators demonstrated high importance and high expert consensus.

The results reveal that technician competency requirements have evolved in line with advancements in automotive technology. Although traditional mechanical repair skills remain essential, system-level diagnostics, electronic control system comprehension, and the application of digital diagnostic tools have become increasingly crucial. In particular, operation of diagnostic equipment, interpretation of fault codes, and utilization of technical documentation emerged as critical competencies, highlighting the central role of digital diagnostics in contemporary maintenance practice.

From a sustainability perspective, enhanced diagnostic capabilities improve maintenance efficiency and resource utilization by reducing unnecessary part replacement and repeated repairs, thereby minimizing material waste and operational costs. Strengthening these competencies can not only improve service quality but also support sustainable transformation in the automotive industry by optimizing resource management across the vehicle life cycle.

From a methodological perspective, this study demonstrates the feasibility and value of integrating empirical maintenance records with the Delphi method to construct a competency framework. Compared with traditional approaches that rely on educational curricula or manufacturer manuals, the aforementioned method more accurately reflects the tacit knowledge inherent in practical maintenance work and provides evidence-based competency indicators.

Although this study provides valuable insights, several limitations should be acknowledged. First, the maintenance records analyzed in this study were obtained from a single automotive service network. Therefore, although the dataset reflects real-world maintenance practices, the generalizability of the findings to other vehicle brands, maintenance organizations, or regional contexts requires further verification. Second, although maintenance records constitute an important source of practical knowledge, they do not capture contextual information such as vehicle mileage, vehicle age, operating conditions, repair

duration, technician experience, repeated repair histories, or occasional diagnostic misjudgments and recording errors that may occur in real-world service operations. Although the large dataset analyzed in this study and the subsequent three-round Delphi validation substantially reduced the influence of isolated inaccuracies, these factors may still affect the completeness of maintenance information and competency identification. Future research could integrate richer maintenance metadata and additional data verification procedures to further refine and validate the proposed competency framework. Third, the developed competency framework was not empirically implemented or evaluated within vocational education programs, technician training, or industry certification systems. Future research can validate the developed framework by applying it in educational initiatives and industry certification mechanisms and investigate emerging competency requirements associated with electric vehicles, software-defined vehicles, and intelligent transportation systems.

In conclusion, the competency framework established in this study offers a crucial reference for workforce development, vocational education, and certification in the automotive service industry. It also facilitates the cultivation of maintenance professionals equipped with both technical proficiency and sustainability awareness, thus enabling the automotive workforce to meet the evolving demands of industrial transformation.

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Abbreviations

The following abbreviations are used in this manuscript:

ECUs	Electronic Control Units
CAN	Controller Area Network
OEM	Original Equipment Manufacturer
CV	Coefficient of Variation
AC	Air-Conditioning
ETACS	Electronic Time and Alarm Control System
SRS	Supplemental Restraint System
ABS	Anti-lock Braking System
ASC	Active Stability Control

Appendix A

Table A1. Importance analysis of the second round of expert opinion survey.

System	Competency Indicator	Total Score	Mean	Standard Deviation	Coefficient of Variation (CV)
Engine control system	Automotive diagnostic system operation	222	9.25	1.21	0.13
	Service manual consultation	216	9.00	1.38	0.15
	Fault code interpretation	219	9.13	1.23	0.13
	Ability to handle scenarios where the engine fails to fire	224	9.33	1.23	0.13
	Ability to handle scenarios where the engine fails to start	221	9.21	1.54	0.17
	Ability to handle scenarios where the engine exhibits idle vibration and a tendency to stall ^a	211	8.79	1.82	0.21
	Ability to handle scenarios where engine acceleration is insufficient	216	9.00	1.69	0.19
	Measurement of major engine parameters ^a	207	8.63	1.93	0.22
	Engine electrical circuit diagnostics	223	9.29	0.98	0.11
Transmission system	Automotive diagnostic system operation	228	9.50	1.05	0.11
	Service manual consultation ^a	211	8.79	1.82	0.21
	Fault code interpretation	222	9.25	0.94	0.10
	Insufficient transmission acceleration ^a	197	8.21	1.77	0.22
	Measurement of major transmission parameters	199	8.29	0.55	0.07
	Transmission electrical circuit diagnostics	219	9.13	1.03	0.11
	Transmission disassembly and reassembly ^a	173	7.21	2.25	0.31
Body system	Automotive diagnostic system operation	215	8.96	1.54	0.17
	Service manual consultation	216	9.00	1.56	0.17
	Fault code interpretation	221	9.21	1.32	0.14
	Measurement of major air-conditioning (AC) parameters	211	8.79	1.44	0.16
	AC control circuit diagnostics	211	8.79	1.64	0.19
	Refrigerant replacement ^b	156	6.50	2.54	0.39
Chassis system	Automotive diagnostic system operation	224	9.33	1.23	0.13
	Service manual consultation	224	9.33	1.25	0.13
	Fault code interpretation	226	9.42	1.43	0.15
	4WD system diagnostics ^a	187	7.79	1.90	0.24
	Anti-lock braking system and active stability control system diagnostics	192	8.00	0.66	0.08
	Measurement of major chassis-related parameters	207	8.63	1.66	0.19
	Chassis control circuit diagnostics	210	8.75	1.29	0.15
Electrical system	Automotive diagnostic system operation	218	9.10	1.45	0.16
	Service manual consultation	224	9.33	0.93	0.10
	Fault code interpretation	224	9.33	1.14	0.12
	Lighting system diagnostics ^a	193	8.04	1.69	0.21
	Central locking system diagnostics	214	8.92	1.33	0.15
	Power window system diagnostics	212	8.83	1.42	0.16
	Measurement of major electrical component parameters	208	8.67	1.60	0.18
	Electrical control circuit diagnostics	229	9.54	0.78	0.08

^a For skills lacking consensus, please refer to the expert opinions presented in Table A2. ^b The survey results indicated low importance and a lack of consensus; therefore, some experts recommended excluding these items.

Table A2. Compilation of expert opinions on skills lacking consensus.

System	Competency Indicator	Expert Opinions
Engine control system	Ability to handle scenarios where the engine exhibits idle vibration and a tendency to stall	Important: Involves the ability to integrate, analyze, and evaluate multiple systems and directly affects driving safety.
		Not important: Due to factors such as lengthy diagnostic and repair times and high repair costs, technicians or vehicle owners may not address the issue immediately.
	Measurement of major engine parameters	Important: Measurement data provide the basis for component replacement and communication with customers and can help avoid component misdiagnoses.
		Not important: Modern repair practices increasingly emphasize modularization and rapid replacement (e.g., component substitution testing).
Transmission system	Service manual consultation	Important: Service manuals provide standardized disassembly and reassembly procedures and technical specifications to ensure maintenance accuracy and operational safety.
		Not important: Service manuals are not easily accessible and often differ by version, resulting in technicians relying primarily on experience for vehicle repair.
	Insufficient transmission acceleration	Important: Requires the ability to integrate and analyze multiple systems, making diagnoses highly complex, and the ability to distinguish among faulty systems is critical.
		Not important: Perceived insufficient transmission acceleration is often subjective, may not reflect an actual fault condition, and generally poses no immediate safety concern; therefore, it is often overlooked.
	Transmission disassembly and reassembly	Important: Transmission disassembly and reassembly directly affect maintenance quality and driving safety.
		Not important: The trend toward specialization is becoming increasingly pronounced, and fault diagnosis is considered more important than disassembly and reassembly.
Chassis system	4WD system diagnostics	Emerging intelligent 4WD systems are becoming increasingly diverse and complex, involving integrated diagnoses and analyses across multiple systems, which increases the difficulty of fault identification and diagnosis.
		Not important: These systems are not standard vehicle equipment, require advanced technical expertise, and are associated with a limited volume of repair cases.
Electrical system	Lighting system diagnostics	Important: Lighting systems are essential vehicle equipment and directly affect driving safety; therefore, they constitute a fundamental skill in electrical system maintenance.
		Not important: The technical threshold is relatively low, some vehicle owners can perform repairs independently, and the technology is not considered part of the core powertrain system.

Table A3. Compilation of additional expert opinions.

Expert Opinions
Refrigerant replacement is not an essential skill for vehicle body systems. Furthermore, the second-round expert survey indicated low importance and a lack of consensus; therefore, we recommend that this skill be excluded.
Some experts suggested adding “Diagnostics for the anti-theft control circuit in the Electronic Time and Alarm Control System” as a competency item within the body system.
Some experts suggested adding “Diagnostics for the supplemental restraint system’s control circuit” as a competency item within the body system.
Some experts suggested adding “Diagnostics for the controller area network communication circuit” as a competency item within the body system.

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