

# DECISION-MAKING UNDER UNCERTAINTY IN AUTOMOTIVE METROLOGY

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**Abstract:** *This paper presents a structured risk assessment applied to industrial metrology processes in the automotive components sector. The study focuses on identifying and evaluating potential sources of uncertainty and disruption that may affect measurement accuracy, repeatability, and compliance. Using a qualitative model based on expert judgment and a standardized risk scoring system, ten common risks were assessed within the operational context of an accredited metrology laboratory. Most of the identified risks were categorized as tolerable and manageable under current procedures. However, the analysis highlights the added value of implementing context-specific mitigation strategies, even for low-probability or low-impact risks. These strategies include preventive maintenance, external audits, digital monitoring, and staff training, measures that enhance both measurement reliability and organizational resilience. The findings support a proactive, cost-effective approach to risk management that aligns with international quality standards and contributes to long-term operational continuity.*

**Key words:** *industrial metrology, risk assessment, measurement reliability, automotive sector, uncertainty management, accredited laboratory.*

## 1. Introduction

According to the provisions of the international standard ISO 31000, risk is defined as the impact of uncertainty on the achievement of objectives. Uncertainty is defined as a lack of the information needed to understand, anticipate or evaluate an event, its consequences or the likelihood of its occurrence [9].

In an organisational environment characterised by technological complexity and operational variability, such as industrial metrology within the automotive industry, all activities related to measurement, verification and dimensional control are inherently exposed to uncertainty-generating factors [12]. These factors mean that risk is an intrinsic

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element of metrological processes and must be systematically identified, assessed and managed to ensure compliance with quality standards and the reliability of measurement results.

Effectively managing these risks is essential for maintaining product quality, meeting regulatory requirements, and supporting continuous improvement efforts within the automotive manufacturing sector [10, 11].

Risk management involves a systematic approach to identifying, analysing, evaluating and developing generic and specific strategies for addressing identified risks. This proactive process (Figure 1) involves continuous monitoring of the internal and external context, as well as the ongoing adaptation of control measures [6]. The PDCA (Plan-Do-Check-Act) model, also known as the Deming cycle, is an effective methodological framework for risk management and the continuous improvement of organisational processes. Developed by W. Edwards Deming in the 1950s, the model promotes a cyclical four-step approach: planning objectives and related resources; implementing defined measures; verifying results obtained against anticipated results; and taking corrective action based on performance analysis to further optimise processes [20].

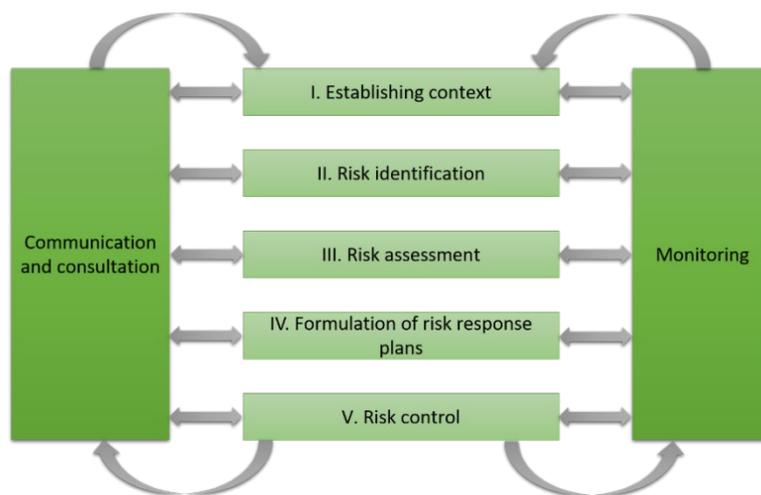


Fig. 1. *Risk management process*

In the area of risk management, applying this framework allows for a rapid response to emerging risks and contributes to their effective control. At the same time, the effectiveness of the model depends on the involvement of the organization as a whole and on continuous assessment, which can pose considerable challenges [8].

Given the particularities of each sector—in terms of needs, target audiences, perceptions, and operational criteria—an essential element of the risk management process is defining the context, an initial step that underpins the entire strategic approach. Complementarily, communication and consultation prove essential for maintaining the relevance of response strategies and increasing the likelihood of achieving objectives [1]. The internal context is shaped by socio-technical structures, organizational policies, internal capacities, relationships with internal stakeholders, institutional culture, the contractual framework,

and the operational standards and models adopted [9].

In contrast, the external context refers to all exogenous factors that may influence the organization's decisions and activities, structured into cultural-social, political-legislative, technological, economic, natural, and competitive dimensions at various levels—international, national, regional, and local [9].

Given the rapid evolution of manufacturing, automation, and quality control technologies [7], identifying potential risks that may affect metrology processes in the automotive components industry is an ongoing endeavour. Risk factors are constantly changing as new precision standards, regulatory requirements or variations in operating and environmental conditions emerge. Currently, the focus is on identifying sources of metrological error and clarifying key issues, such as the nature, potential severity and impact of the risk on the production chain or quality validation [13], [17].

Given the integrated and automated nature of modern measurement processes, metrological risk management must include continuous monitoring and feedback mechanisms derived from operators, digital calibration systems, self-diagnostic systems, and statistical data analysis systems. This enables rapid adjustment to any deviations or recurring errors.

Risks in automotive component metrology can have negative effects, such as incorrect measurements, product non-conformities, delivery delays and additional costs, as well as positive implications, such as identifying opportunities to optimise measurement processes and improve traceability and accuracy. These risks may or may not be quantifiable and can be classified as follows:

- pure risks, or hazard risks (e.g. failure of metrology equipment or unstable environmental conditions affecting measurement)
- control risks are related to the planning, documentation and monitoring of metrology processes in industrial projects.
- speculative risks are associated with the introduction of new measurement technologies, such as high-precision sensors, automated inspection systems or IoT technologies for real-time monitoring.

Speculative risks, unlike the other categories, can generate significant benefits if managed correctly and taken on strategically, and they contribute to innovation, competitiveness and efficiency. Therefore, identifying risks is an essential step in classifying and fully understanding all factors that can influence metrological performance, and implicitly the quality of automotive products, positively or negatively.

## **2. Methodology**

### **2.1. Risk identification**

Risk identification is a critical step in the risk management process, with the objective of systematically and proactively recognizing all events, conditions, or malfunctions that may influence the achievement of metrological performance objectives in a specific industrial environment, such as that of automotive components. This activity provides the foundation for the subsequent stages of risk assessment, analysis, and treatment, with

the role of defining the full spectrum of variables with a potential impact on measurement and verification processes.

The identification process involves a structured examination of all activities and resources associated with industrial metrology, including technical infrastructure, operational flows, working procedures, environmental conditions, and the applicable regulatory context [4], [13]. In addition, the degree of interdependence between measurement systems and other production processes, as well as external technological, economic, or regulatory influences, must be considered.

Methodologically, risk identification is achieved by combining several sources and tools: documentary analysis of historical data, internal audits, direct observations from the process, and consultations with technical experts in the field. This integrated approach allows for the extraction of relevant information and the construction of a coherent perspective on potential sources of risk, without introducing a classification or assessment of severity at this stage.

The results of the identification activity are summarized in a table of potential risks (Table 1), which serves as the starting point for assessing and addressing risks in the following sections.

*Identification of specific risks in automotive component metrology* Table 1

Symbol	Risk	Manifestation	Type of risk
R1	Temperature variations	Deviations in measurement accuracy due to temperature changes	Hazard
R2	Humidity fluctuations	Impact on sensitive measurement equipment and results	Hazard
R3	Measurement equipment calibration	Inaccurate measurements caused by improper or outdated calibration	Hazard
R4	Incorrect measurement method selection	Use of unsuitable measurement techniques leading to errors	Hazard
R5	Misinterpreting metrological data	Erroneous decisions caused by data analysis errors	Hazard
R6	Systematic and random errors	Diverse manifestations of measurement deviations primarily caused by human error	Control
R7	Equipment malfunction	Real-time interval between calibrations shorter than planned, affecting measurement reliability	Hazard
R8	Non-compliance with regulatory standards	Failure to meet ISO, ASTM, or other metrological standards	Control
R9	Investment in new technologies	Adoption risks of unproven equipment or methods	Speculative
R10	Expansion of measurement scope	Risks related to increasing volume or complexity of measurements	Speculative

Temperature variations (R1) are one of the most critical factors affecting the accuracy and repeatability of metrological measurements in the automotive industry. Both measuring equipment and measurand can undergo dimensional changes due to thermal

expansion or contraction [16]. Length measuring instruments, whether contact-based (such as micrometers, dial indicators, calipers, or mechanical comparators) or non-contact systems (such as interferometers, laser triangulation sensors, structured light scanners, or video-based optical measurement systems) can be sensitive to environmental and process variations, which may significantly affect calibration accuracy and measurement reliability. Additionally, the materials used to produce automotive parts have different thermal expansion coefficients, so temperature changes during the measurement process can cause significant deviations from nominal values [2]. Therefore, it is essential to strictly control thermal conditions in metrology laboratories and production environments to minimise errors and comply with the strict tolerances imposed by automotive standards. Furthermore, thermal analysis of the environment and the implementation of temperature corrections are mandatory practices in advanced metrology processes.

Humidity can directly and indirectly affect the reliability of metrological processes in the automotive industry, particularly when measuring sensitive components in terms of their dimensions and materials. Humidity fluctuations (R2) can affect the physical properties of materials, such as the swelling or shrinkage of wood, which can lead to measurement errors. For metal or composite components, condensation can lead to surface corrosion or the formation of deposits that alter the contact surface of measuring instruments. Electronic or optical equipment used in metrology is also vulnerable to humidity, which can result in malfunctions or errors in signal processing. To reduce the associated risks, precise humidity control in metrology chambers is imperative, as is the use of materials with stable properties under environmental variations [17], [21] and the implementation of protective procedures.

Calibrating measuring equipment is essential for ensuring compliance with automotive industry quality standards. If equipment is not properly calibrated (R3), it can produce erroneous results, which can lead to non-compliant components being accepted or compliant parts being rejected [18]. This affects both costs and the manufacturer's reputation. The calibration process must be carried out according to a well-defined plan using certified reference equipment, with traceability to national or international standards (e.g. ISO/IEC 17025). Calibration intervals must be observed and adapted according to use, operating conditions and the equipment's history. Additionally, continuously monitoring instrument's performance using statistical methods enables the early detection of calibration drifts, ensuring proactive intervention and minimising operational risk.

Selecting the appropriate measurement method is essential for ensuring the accuracy of data obtained for automotive components. Methods can range from traditional techniques, such as micrometers or callipers, to advanced methods, such as 3D scanning, optical metrology and industrial tomography. Each method has specific limitations in terms of resolution, scope of application, execution speed, and cost. Incorrect selection (R4) can lead to systematic errors, a lack of repeatability and misinterpretations of part conformity [19]. For instance, using an optical method on components with reflective or transparent surfaces without making the necessary adjustments can produce inaccurate results. Therefore, rigorous technical analysis must be conducted to consider the part's

geometry, material, tolerance requirements and measurement environment before applying the method.

Misinterpreting metrological data (R5) can have significant consequences in the any industry, influencing decisions regarding the acceptance, rejection or redesign of components. This can stem from a poor grasp of the statistical properties of measurements, such as error distribution and confidence intervals, or from misinterpreting results in the context of relevant standards (e.g. ISO GPS – Geometrical Product Specification). Additionally, errors can be introduced by the software used for data analysis if it is not configured properly, or if the operator misinterprets the generated reports [15]. Integrating technical knowledge with advanced statistical methods is essential to avoid such risks and support objective, valid decision-making.

Systematic and random errors (R6) are a fundamental source of uncertainty in measurement activities and directly affect the validity and reproducibility of the results obtained [15]. These errors manifest as deviations from the true value and have a complex etiology in which the human factor plays a significant role.

Systematic errors are recurring and reproducible deviations resulting from imperfections in the measurement method, equipment calibration or operator interpretation of data. These errors can lead to consistently inaccurate value estimations reducing the accuracy of measurements and influencing subsequent interpretations.

Random errors, on the other hand, are the result of uncontrollable and unpredictable variations influenced by external factors or intrinsic fluctuations in the measurement system. Random errors affect the accuracy of results and can induce non-systematic variations between successive measurements, even under apparently identical conditions.

In the context of scientific research and applied metrology, a thorough understanding of the mechanisms that generate these types of error is essential for correctly interpreting experimental data. Identifying and characterising them contributes to substantiating decisions regarding the reliability of results and the relevance of conclusions.

The risk associated with measuring equipment failure (R7) refers to a significant deviation in measurement results caused by premature decalibration, which in turn requires a reduction in the time interval between two successive calibration cycles compared to the initial plan [5]. This deviation can compromise the reliability and reproducibility of the measurements performed, introducing additional uncertainty into the validation of the results. In scientific research and quality control contexts, data integrity critically depends on the functional stability of the equipment; any interruption or degradation in its performance can affect the entire metrological evaluation chain.

Failure to comply with international reference standards (R8), such as those issued by ISO, ASTM or other relevant bodies, poses a systemic risk that affects the legitimacy and recognition of the activities carried out. Deviation from these standards can invalidate experimental results, leading to rejection by third parties (including regulatory authorities and industrial partners) and preventing the integration of data into internationally standardised databases [15]. In an institutional framework geared towards scientific excellence, compliance with metrological standards is fundamental to credibility and transferability of knowledge.

Adopting new-generation metrological equipment or technologies (R9) that have not been validated through extensive use or rigorous comparative studies introduces a considerable degree of uncertainty regarding their measurement performance and their ability to integrate effectively into existing systems. This uncertainty is further amplified by the lack of accumulated operational experience needed to assess their reliability under real-world conditions [3]. Therefore, transitioning prematurely to insufficiently tested technological solutions may affect the stability of experimental processes and the quality of the resulting scientific data.

As the scope of measurement activities increases (R10), either through an expansion in the volume of data collected or the introduction of new parameters or environmental conditions, additional complexity is generated that may exceed the operational or technical capacity of existing systems. This risk can lead to problems with the adaptability of procedures, the scalability of equipment and maintaining consistency in the evaluation of results. Furthermore, an expansion that lacks parallel investments in human skills and support infrastructure may create a mismatch between the operational demands of new applications [14, 15] and the system's capacity to address them.

The risk identification activity carried out in the context of industrial metrology for automotive components has revealed a wide range of factors that can have a significant impact on the quality, accuracy, repeatability and reliability of the measurement processes.

## 2.2. Risk assessment

Ultimately, the objective of risk assessment is to determine the severity and likelihood of each identified risk materializing. This involves a two-dimensional analysis, as risks can be quantified using a risk factor assessment model that combines the probability  $P$  of occurrence with the potential impact  $I$ . The resulting risk factor  $F_r$  is calculated as:

$$F_r = P \cdot I \quad (1)$$

In the present study, the evaluation of these parameters was carried out by experts holding doctoral degrees DA in metrology, with extensive practical experience in automotive component metrology, who work in an accredited measurement laboratory. Their qualified judgment ensures both scientific rigor and operational relevance. The scoring was performed on an integer scale from 1 to 10, reflecting realistic conditions specific to industrial metrology systems (Table 2).

As shown in Table 2, several risk sources present notable levels of combined probability and impact, warranting careful monitoring despite the laboratory's current optimal and accredited operational status. The highest risk factor ( $F_r = 6$ ) is associated with five distinct risks: temperature variations (R1), loss of calibration of measurement equipment (R3), misinterpretation of metrological data (R5), systematic and random errors (R6), and equipment malfunction (R7). These results highlight that even under controlled conditions, the effects of moderate-probability technical disruptions may significantly influence measurement reliability.

*Risk assessment specific in automotive component metrology* Table 2

Risk symbol	Probability	Impact	Risk factor
R1	2	3	6
R2	1	2	2
R3	2	3	6
R4	1	5	5
R5	1	6	6
R6	2	3	6
R7	1	6	6
R8	1	5	5
R9	2	2	4
R10	1	3	3

Risks such as incorrect measurement method selection (R4) and non-compliance with regulatory standards (R8), both scoring  $F_r = 5$ , also represent critical points of attention due to their high potential impact, despite lower expected frequency. These findings emphasize the importance of maintaining strict procedural oversight and up-to-date knowledge of applicable standards.

On the lower end of the spectrum, risks such as humidity fluctuations (R2), investment in unvalidated technologies (R9), and expansion of the measurement scope (R10) registered the lowest scores ( $F_r = 3$ ), suggesting a minor level of threat under current laboratory practices. Nevertheless, their inclusion reinforces a comprehensive and anticipatory approach to quality assurance.

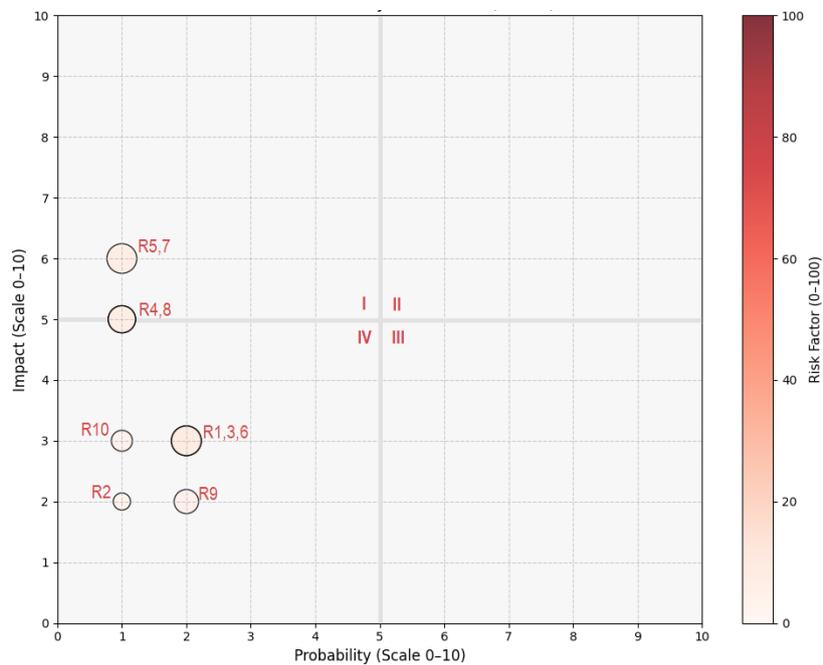
Taken together, these results support a strategy focused not on remediation, but on risk preparedness, ensuring that even unlikely yet high-impact events are systematically considered in continuous improvement processes.

### 3. Risk management strategies

Specific risk mitigation strategies should be chosen based on the general strategies belonging to the '4 Ts' group. These include strategies for: tolerance, treatment, transfer and termination.

#### 3.1. General strategy for risk management

The general strategy for combating each risk is chosen depending on its probability and impact and is selected from among the so-called '4 Ts' of risk management: tolerate, treat, transfer and terminate (avoid). One specific tool used in this process is the risk matrix (Figure 2), which provides a two-dimensional representation of risks based on their probability of occurrence and potential impact. The matrix facilitates the identification of the appropriate response strategy for each situation by placing risks in the correct quadrant, thus ensuring effective and proportionate risk management.

Figure 2. *Risk matrix*

Quadrant I contains risks for which the recommended strategy is transfer. These are risks that are severe enough to justify the partial or total outsourcing of their impact. This can be achieved through mechanisms such as partnerships, subcontracting or insurance, which allow the organisation to externalise potential consequences. In this quadrant are the risks of misinterpreting metrological data (R5) and of equipment malfunction (R7). These risks can have a significant impact on measurement reliability or continuity, making them suitable candidates for mitigation through external calibration services or maintenance contracts. However, in specific contexts — particularly when the cost of treatment exceeds the potential impact based on probability — these risks may fall under the tolerance strategy instead.

Quadrant II is associated with the termination (avoidance) strategy and involves risks with a high probability and impact; continuing the activity in these cases would be unacceptable. In the present assessment, no risks were placed in this quadrant, most likely due to the laboratory's accreditation and robust internal systems, which effectively prevent the emergence of such high-exposure scenarios.

Quadrant III, dedicated to treatment, generally includes risks with high probability and moderate impact, or low probability and high impact. These require proactive mitigation through internal measures, such as process improvements or additional controls. However, no risks fell directly into this quadrant, which confirms that the risk profile is relatively stable and well managed, with no high-probability events identified.

Quadrant IV is reserved for risks with a low probability of occurrence and a low potential impact, for which the tolerance strategy is typically employed. Here, risk is accepted as part of normal operational variability, particularly when the benefits of mitigation would

be outweighed by management efforts. The following are found within this quadrant: temperature variations (R1), humidity fluctuations (R2), measurement equipment calibration (R3), systematic and random errors (R6), investment in new technologies (R9), and expansion of the measurement scope (R10).

These risks are either inherent in environmental conditions or represent optional operational developments, and their impact is usually minimal. Monitoring is maintained, but no intensive intervention is warranted unless contextual factors change.

Two risks are situated at the boundary between Quadrant I (Transfer) and Quadrant IV (Tolerance), requiring a case-by-case decision: incorrect measurement method selection (R4) and non-compliance with regulatory standards (R8). Depending on the context, including factors such as resource availability, regulatory impact and cost-efficiency — these risks can be either mitigated (by transferring them to expert external reviewers or software tools) or tolerated (if the exposure is minor or rare). The decision should consider both impact and treatment cost.

In conclusion, strategy selection must remain context-dependent, particularly when assessing borderline risks. When the cost of treatment exceeds the estimated impact, especially for low-probability events, tolerance is the more efficient strategy. The absence of high-probability risks across the board reinforces the idea that the laboratory's accreditation and internal protocols are effectively minimising exposure and ensuring consistent operational control.

The updated Table 3 summarises the general risk management strategies assigned to each identified risk within the metrology processes for automotive components. The dominance of the 'Tolerate' strategy indicates that most risks are considered manageable within the laboratory's operational and environmental context, particularly when the cost of mitigation outweighs the potential impact.

Table 3

*Risk assessment specific in automotive component metrology*

<b>Risk symbol</b>	<b>Risk general strategy</b>
R1	Tolerate
R2	Tolerate
R3	Tolerate
R4	Transfer / Tolerate
R5	Transfer
R6	Tolerate
R7	Transfer
R8	Transfer / Tolerate
R9	Tolerate
R10	Tolerate

Examples of such risks include temperature variations (R1), humidity fluctuations (R2), equipment calibration (R3) and investment in new technologies (R9), which are characteristic of routine variability and are therefore justifiably tolerated. This strategic choice is grounded in a cost-benefit rationale and supported by effective monitoring and quality assurance protocols.

The 'Transfer' strategy is reserved for risks whose potential impact on the reliability or continuity of measurements is significant enough to justify outsourcing, such as misinterpreting metrological data (R5) or equipment malfunction (R7). These risks are better managed through external partnerships, such as maintenance contracts or expert consultancy, which can ensure prompt, specialised intervention.

Of particular interest are risks such as R4 (incorrect method selection) and R8 (non-compliance with standards), which are positioned between 'Transfer' and 'Tolerate', indicating that a context-dependent evaluation is necessary. Where risk exposure is minimal and probability is low, tolerance may suffice; however, where regulatory or quality implications are high, transfer mechanisms should be implemented.

The absence of any risks requiring termination or strict treatment strategies (quadrants II and III) confirms that the laboratory's accreditation, quality control systems and procedural discipline are effective in keeping high-exposure events under control.

### **3.2. Specific strategy for risk management**

While several of the identified risks are generally managed through a toleration approach, the current literature encourages adopting preventive measures when they are cost-effective and operationally feasible. Even in well-functioning, accredited laboratories, addressing tolerable risks through targeted strategies can enhance system resilience and long-term stability.

For example, in the case of temperature variations (R1), while the risk factor is moderate, additional control measures such as temperature monitoring sensors and localised climate control systems may be necessary in areas housing sensitive instrumentation. Regarding humidity fluctuations (R2), toleration remains a reasonable strategy in many cases. However, dehumidifiers or automated humidity regulation systems could provide added value in environments subject to seasonal changes. Periodic internal audits of environmental conditions may also help prevent cumulative deviations over time.

In the case of loss of calibration in measurement equipment (R3), implementing a strict calibration schedule, using digital traceability systems and routinely verifying using reference artefacts can further ensure measurement consistency. In the case of incorrect method selection (R4), the risk can be tolerated or transferred, for example by involving external reviewers or digital decision support tools. Where toleration is applied, the use of internal peer-review processes and method validation protocols is advisable.

The risk of misinterpreting metrological data (R5) can be mitigated by carrying out external audits, providing training in applied statistics and integrating automated data analysis tools that can detect anomalies. Although systematic and random errors (R6) are inherent to measurement processes, good practice involves statistical process control (SPC), uncertainty estimation and participation in proficiency testing schemes.

## **4. Conclusions**

This study examined a broad spectrum of risks associated with industrial metrology in the automotive components sector, using a structured methodology of identification,

evaluation, and strategy assignment. The analysis confirmed that, within an accredited laboratory operating under robust procedures, none of the identified risks reached a critical level requiring activity suspension. Most were effectively managed through strategies of tolerance and transfer, indicating a mature balance between internal control and targeted outsourcing.

Overall, while many of the risks identified are considered tolerable, the selective application of context-appropriate mitigation strategies contributes to maintaining high levels of metrological reliability and operational continuity. Rather than addressing deficiencies, these measures reinforce an already stable system through proactive and cost-effective practices.

This integrative approach not only ensures compliance with quality standards but also strengthens the laboratory's capacity to respond to emerging challenges, supporting long-term resilience and continuous improvement in measurement processes.

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