Journal of Historical, Cultural and Social Sciences, 2026, 2(1), 14-23
https://doi.org/10.71204/pxgrrw19

Standardization, Customization and Industrial Performance: A Socio-Technical Study of Suspension System Design for Motorcycles and Electric Two-Wheelers Based on T/ZZB 3029—2022

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Received: 31 December 2025/ Accepted: 23 March 2026/ Published online: 30 March 2026

Abstract

Based on the group standard T/ZZB 3029—2022 for motorcycle shock absorbers, this study develops an integrated analytical framework for suspension system design, verification, and customized research and development (R&D) for motorcycles, mopeds, and electric two-wheelers. Moving beyond a purely technical perspective, the paper adopts a socio-technical approach to examine how standardized engineering specifications interact with manufacturer-oriented customization demands in contemporary vehicle industries. The study systematically constructs a full-process technical system encompassing high-precision spring design, multi-dimensional damper tuning, structural strength verification, whole-vehicle matching, and lifecycle quality control. Through standardized procedures such as ex-factory inspection, type testing, environmental adaptability evaluation, and durability verification, the research demonstrates how the integration of "standard compliance" and "scenario-based customization" enables effective coordination between safety, handling performance, riding comfort, and long-term durability. Furthermore, the findings reveal that the implementation of T/ZZB 3029—2022 not only improves the consistency and reliability of suspension systems but also establishes a data-driven and process-oriented quality governance mechanism. This mechanism enhances industrial coordination, reduces performance variability, and supports differentiated product development across various vehicle categories. By linking engineering design practices with institutional standardization frameworks, this study contributes to interdisciplinary discussions on the role of technical standards in shaping industrial performance and technological innovation. It provides a replicable and scalable technical paradigm for the development of high-quality suspension systems in the motorcycle and electric two-wheeler industry.

Keywords: Motorcycles; Suspension System; Standardization; Industrial Application; Customized R&D

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1. Introduction

Motorcycles, mopeds and electric two-wheelers have become essential means of transportation for short-distance travel, urban logistics distribution and daily commuting in both urban and rural areas of China (Ferrari et al., 2024). With the continuous expansion of market demand and application scenarios, these vehicles are undergoing rapid technological evolution toward high performance, lightweight design, intelligence and enhanced riding comfort. As a critical subsystem of the vehicle chassis, the suspension system plays a fundamental role in absorbing road impacts, attenuating vibrations, controlling body posture and maintaining tire-ground contact, thereby directly influencing driving safety, handling stability and user experience.

From a dynamic perspective, the performance of the suspension system determines the ability of the vehicle to respond to complex road excitations (Lopes et al., 2023; Ferhath & Kasi, 2024). Inadequate suspension performance may lead to excessive vibration transmission, poor tire adhesion and unstable body posture, which in turn affect braking efficiency, cornering stability and overall vehicle controllability. Therefore, the suspension system is not only a functional component but also a key factor in ensuring the operational safety and performance reliability of motorcycles and electric two-wheelers.

At present, the industry exhibits significant differentiation in application demands. Fuel motorcycles, particularly large-displacement sport models, emphasize high-speed stability, cornering handling and reliability under extreme working conditions. Mopeds, mainly used for urban commuting, prioritize cost controllability, structural simplicity, ease of installation and basic comfort performance (Wallius et al., 2022). Electric two-wheelers, driven by the rapid development of electrification, place greater emphasis on refined vibration filtering, long-endurance adaptability and lightweight structural design. Under such diversified demand scenarios, manufacturers no longer regard suspension systems as merely “functional components,” but instead require them to achieve precise matching with the whole vehicle, stable performance under varying conditions, strict compliance with technical standards and optimal cost efficiency.

However, despite the rapid development of the industry, there remain several prominent challenges. On the one hand, traditional suspension system design has long relied on empirical methods and iterative testing, leading to issues such as inconsistent performance indicators, insufficient comparability of test results and large fluctuations in product quality. On the other hand, the lack of unified technical specifications across different vehicle categories has made it difficult to achieve standardized design, verification and evaluation processes, thereby increasing development costs and quality risks for manufacturers.

Against this background, the group standard T/ZZB 3029—2022 Shock Absorbers for Motorcycles and Mopeds establishes a unified and systematic technical framework covering material selection, structural design, performance parameters, test methods, service life evaluation and failure protection (Brand Construction Federation of Zhejiang Province, 2022; Zhejiang Bicycle and Electric Vehicle Association, 2023). By defining clear technical indicators and standardized testing procedures, the standard effectively addresses long-standing issues such as inconsistent industry benchmarks, non-standardized testing methods and uneven product quality.

More importantly, it provides a structured foundation for integrating engineering design with quality control and verification processes, promoting the transition from experience-driven development to standardized and data-driven engineering practices. In addition, although the standard is primarily formulated for motorcycles and mopeds, its technical framework and evaluation methods also provide important reference value for the development of suspension systems for electric two-wheelers, a field where specialized standards are still relatively insufficient. This further highlights the broader applicability and industrial significance of the standard in supporting emerging transportation technologies.

Based on this context, this paper integrates the core design and verification technologies of shock absorbers with manufacturer-oriented customized R&D requirements, and systematically constructs a full-process technical system for suspension development. By establishing a closed-loop framework of "standard – design – adjustment – verification – mass production," the study aims to bridge the gap between standardized technical requirements and differentiated application scenarios. Specifically, this research focuses on high-precision spring design, multi-dimensional damper characteristic adjustment, structural strength verification, whole-vehicle parameter matching and real-vehicle tuning processes, while incorporating rigorous testing and quality control mechanisms throughout the product lifecycle. Through this integrated approach, the paper not only provides practical engineering solutions for suspension system development, but also explores how technical standards can function as both engineering tools and organizational mechanisms in improving product consistency, reducing development risks and enhancing industrial coordination.

2. Core Functions of Suspension System and Support of Standard System

2.1. Decisive Role of Suspension System in Vehicle Performance

The suspension system, composed of elastic elements (springs), damping elements (shock absorbers), and structural guiding components, plays a fundamental role in regulating the dynamic interaction between the vehicle and road surface (Cao et al., 2011; Ferhath & Kasi, 2024). Its primary function is not limited to absorbing road impacts and reducing vibration transmission, but extends to maintaining vehicle stability, controlling body posture and ensuring continuous tire-ground contact under varying driving conditions. Through coordinated action between elasticity and damping, the suspension system effectively suppresses undesirable dynamic behaviors such as excessive bounce, roll, pitch and lateral instability, thereby directly influencing braking performance, cornering precision and overall driving safety.

From an engineering and industrial perspective, suspension performance has become a key determinant of product competitiveness and user experience. Inadequate suspension design often leads to issues such as brake deviation, high-speed instability, excessive body roll and resonance under continuous road excitation, as well as durability failures such as oil leakage and component fatigue. These problems not only affect safety but also significantly influence manufacturer reputation and market acceptance. Therefore, the suspension system should be understood as a critical subsystem within a broader socio-technical framework, where engineering performance, user expectations and industrial standards are closely interconnected.

2.2. Core Value and Applicable Boundary of T/ZZB 3029—2022

T/ZZB 3029—2022 serves as a specialized group standard that establishes a unified technical framework for the design, manufacturing, inspection and evaluation of motorcycle and moped shock absorbers. Covering a wide range of product categories, including front and rear shock absorbers, inflatable shock absorbers and spring assemblies, the standard defines comprehensive performance indicators and standardized testing procedures. Its core value lies in constructing a consistent and traceable system for evaluating damping characteristics, structural strength, durability and environmental adaptability, thereby addressing long-standing issues such as fragmented technical criteria, inconsistent testing methods and uneven product quality across the industry.

More importantly, the standard functions not only as a technical specification but also as an institutional mechanism for industrial coordination and quality governance. By introducing graded performance requirements for different vehicle types and usage scenarios, it enables manufacturers to achieve a balance between standard compliance and differentiated product development. At the same time, the standard promotes the transition from experience-based design toward rule-based and data-driven engineering practices, enhancing the comparability and reliability of products. Although primarily formulated for motorcycles and mopeds, its technical framework also provides an important reference for the development of suspension systems for electric two-wheelers, thereby extending its applicability and reinforcing its role in supporting emerging mobility technologies.

3. Core Design Technologies of Suspension System Based on Standards

3.1. High-Precision Spring Design and Durability Control

As the primary elastic element of the suspension system, the spring determines the fundamental vibration response characteristics and load-bearing capacity of the system. High-precision control of spring stiffness is essential for achieving a balance between riding comfort and handling stability (Cao et al., 2025). In accordance with the requirements of T/ZZB 3029—2022, the rigidity deviation is strictly limited within ±6%, and computer-aided engineering (CAE) methods are employed to optimize key structural parameters such as wire diameter, coil number and free height. This ensures compliance with the Grade 2 accuracy standard specified in GB/T 1239.2, thereby enhancing design reliability from the source.

In addition to stiffness accuracy, durability is a critical factor influencing long-term performance. The standard requires that, after 200,000 consecutive compression cycles within the working stroke, the permanent deformation of the spring must not exceed 2% of its original free height. To meet this requirement, high-performance alloy spring steel is selected, and advanced manufacturing processes such as heat treatment, shot peening and pre-compression are adopted to improve fatigue resistance. Through the integration of material optimization and structural design, the spring is able to maintain stable performance under complex loading conditions, ensuring long-term reliability of the suspension system.

3.2. Multi-Dimensional Characteristic Adjustment Technology of Dampers

The damper is the core component responsible for vibration attenuation and dynamic control within the suspension system, and its performance is determined through the coordinated adjustment of indicator characteristics, speed characteristics and temperature characteristics. From a system design perspective, damper tuning involves shaping the force–velocity relationship to ensure appropriate response under different excitation conditions (Yang et al., 2022). According to T/ZZB 3029—2022, the buffer resistance of the front shock absorber must not be less than 200% of the rebound resistance, enabling rapid energy absorption during sudden impacts and preventing excessive body oscillation.

Furthermore, the standard introduces differentiated tolerance requirements for damping forces based on vehicle type and application scenario. For example, ordinary motorcycles and mopeds emphasize a balance between comfort and stability, while racing motorcycles prioritize precise control under high-speed and extreme conditions. In addition, temperature adaptability is incorporated as a key evaluation dimension, with strict limits on resistance attenuation under high-temperature conditions to ensure consistent performance during prolonged operation. This multi-dimensional adjustment framework reflects the integration of standardized constraints with scenario-based customization, enabling more accurate matching between suspension performance and vehicle requirements.

3.3. Structural Strength and Connection Reliability Design

Structural strength constitutes the physical foundation for the safe and reliable operation of the suspension system. Under the framework of T/ZZB 3029—2022, strength verification focuses on both core load-bearing components and critical connection structures. Key components such as lifting rings and aluminum cylinders are required to meet minimum strength thresholds of 15 kN, ensuring their ability to withstand extreme loads and impact conditions during vehicle operation. At the same time, fatigue performance under cyclic loading is considered to guarantee long-term structural stability.

Welding quality, as a critical factor affecting structural integrity, is subject to strict control requirements. Welded joints must be free from defects such as cracks, slag inclusion and porosity, and must pass high-cycle vibration durability tests to ensure reliability under continuous dynamic loading. In addition, sealing and dustproof structures are optimized through the use of multi-layer oil seals and protective covers, preventing the intrusion of contaminants and maintaining the cleanliness and functionality of internal components. These measures collectively form a comprehensive structural reliability assurance system that integrates design, manufacturing and verification processes.

3.4. Whole-Vehicle Matching Design for Manufacturers

The performance of the suspension system cannot be evaluated in isolation but must be understood within the context of the complete vehicle system. Whole-vehicle matching design emphasizes the coordinated optimization of suspension parameters with vehicle load characteristics, structural layout and operating conditions. Depending on vehicle type, parameters such as load capacity, suspension stroke and stiffness must be carefully adjusted to achieve an optimal balance between comfort, handling and safety. For instance, electric two-wheelers typically require longer suspension travel and softer tuning to enhance comfort, while sport motorcycles adopt shorter travel and higher stiffness to improve responsiveness and control precision.

In addition, system-level coordination is essential to avoid issues such as structural interference, resonance and energy loss. This involves matching the suspension system with frame geometry, power system vibration characteristics and tire-road interaction properties. From a broader perspective, whole-vehicle matching represents the practical implementation of a socio-technical integration process, in which standardized technical requirements are translated into customized engineering solutions tailored to specific usage scenarios. Through this approach, manufacturers are able to achieve both compliance with technical standards and differentiation in product performance, thereby enhancing overall competitiveness in a rapidly evolving market environment.

4. Manufacturer-Oriented Real-Vehicle Adjustment Process of Suspension System

4.1. Pre-Adjustment Preparation

The real-vehicle adjustment process of suspension systems begins with systematic preparation based on comprehensive vehicle-level data collection. Key parameters such as curb weight, maximum load, center of gravity position, wheelbase, tire specifications, expected road conditions, operating speed range and user behavior characteristics must be accurately obtained to establish a reliable basis for parameter configuration. These data not only define the boundary conditions of suspension performance but also reflect the interaction between vehicle structure, usage scenarios and user expectations.

On this basis, initial parameter settings are determined according to the positioning of the vehicle model. Preload, compression damping and rebound damping are preliminarily configured to form a baseline tuning scheme. For example, electric two-wheelers tend to adopt softer damping characteristics to enhance comfort and vibration filtering, while sport motorcycles emphasize higher stiffness and stronger damping response to improve handling stability. This stage represents the integration of standardized technical parameters with scenario-oriented customization, laying the foundation for subsequent dynamic adjustment.

4.2. Standardized Steps of Real-Vehicle Adjustment

Real-vehicle adjustment is carried out through a standardized and iterative process combining road testing and parameter optimization. The initial stage involves comprehensive testing on representative road conditions, including asphalt, concrete, uneven surfaces, potholes and curved sections, in order to evaluate key performance indicators such as vibration transmission, body attitude control, rebound response and overall ride quality. These empirical observations provide direct feedback on the effectiveness of initial parameter settings.

Based on the test results, targeted optimization of suspension parameters is conducted. Adjustments are made according to specific performance deviations, such as reducing damping forces to alleviate excessive stiffness, increasing preload or stiffness to suppress body roll and pitch, enhancing rebound damping to control oscillation, or increasing stroke and preload to prevent bottoming. This process is repeated through multiple rounds of testing and refinement until a balanced performance state is achieved. Such an iterative mechanism reflects a closed-loop adjustment logic in which standardized evaluation criteria and real-world performance feedback are continuously integrated, ensuring that suspension performance meets manufacturer requirements under practical operating conditions.

4.3. Core Principles of Adjustment

The adjustment process is guided by several fundamental principles that ensure both technical rationality and industrial applicability. First, a dynamic balance between comfort and handling must be maintained, avoiding excessive bias toward any single performance objective and ensuring alignment with the core needs of target user groups. Second, durability verification must be conducted in parallel with performance optimization. Long-distance and high-frequency fatigue testing are required after parameter adjustment to confirm that no performance degradation, abnormal noise or leakage occurs during extended operation.

In addition, cost controllability is an essential consideration in manufacturer-oriented development. While meeting performance and standard requirements, the selection of materials, structures and components must be optimized to avoid unnecessary complexity and over-design. This reflects the broader industrial logic in which engineering design is not only a technical activity but also a decision-making process involving performance, reliability and economic efficiency within a socio-technical system.

5. Whole-Process Verification and Quality Control of Suspension System

5.1. Ex-Factory Inspection

Ex-factory inspection serves as the first line of quality assurance, ensuring that each batch of suspension products meets predefined technical standards before delivery. Through random sampling, key aspects such as surface quality, dimensional accuracy, operational smoothness and sealing performance are systematically evaluated. The strict control of dimensional tolerances, including free length deviations of front and rear shock absorbers, ensures precise compatibility with vehicle structures, thereby preventing installation errors and performance mismatches.

At the same time, inspection of operational performance and sealing reliability guarantees that the shock absorber functions smoothly without abnormal noise, friction or oil leakage under different orientations. This stage reflects the role of standardized inspection procedures in translating design specifications into consistent manufacturing outcomes, forming a critical link between production and application.

5.2. Type Inspection

Type inspection represents a comprehensive evaluation of suspension system performance, extending beyond basic functionality to cover environmental adaptability, durability and structural reliability. By conducting full-item testing on randomly selected samples, the system's behavior under extreme temperature conditions, long-term exposure to dust and muddy water, and corrosive environments is systematically assessed. These tests ensure that the suspension system maintains stable performance across diverse operating conditions.

In addition, fatigue durability and strength verification are incorporated to evaluate long-term reliability. Requirements such as resistance attenuation limits after high-cycle vibration testing and compliance with static and dynamic strength thresholds provide a quantitative basis for assessing product lifespan and safety margins. Through this process, type inspection functions as both a validation mechanism and a feedback channel for design improvement, reinforcing the integration of testing data into engineering optimization.

5.3. Failure Protection Design

Failure protection design is an essential component of ensuring the long-term stability and safety of suspension systems. It focuses on identifying potential failure modes and implementing targeted preventive measures within the design and verification process. For inflatable shock absorbers, strict control of internal gas pressure and sealing performance is required to prevent sudden changes in damping characteristics caused by leakage or pressure imbalance.

In addition, anti-foaming performance is critical for maintaining consistent damping behavior under high-frequency operation. By limiting fluctuations in damping characteristics and eliminating abnormal noise, the system avoids performance degradation caused by oil foaming. Wear protection strategies, including the use of wear-resistant materials and optimized lubrication design, further enhance durability by reducing friction and extending the service life of moving components. These measures collectively establish a multi-layered protection mechanism that integrates material selection, structural design and performance verification.

6. Engineering Application Advantages of Integrated Standardization and Customization

The integration of standardized technical frameworks with customized engineering design provides significant advantages in practical applications. On the one hand, technical standards establish a clear safety baseline and unified evaluation criteria, ensuring high consistency of product performance and effectively reducing safety risks and after-sales issues. On the other hand, customization enables manufacturers to tailor suspension characteristics to different vehicle types, operating conditions and user preferences, thereby enhancing product differentiation and market competitiveness.

Furthermore, the adoption of whole-process digital management—from simulation-based design to experimental verification—improves R&D efficiency and shortens development cycles. This approach supports rapid iteration and precise optimization, enabling manufacturers to respond more effectively to changing market demands. In the context of electrification, the integration of lightweight design, low-friction damping and long-stroke comfort optimization contributes to improved energy efficiency and user experience of electric two-wheelers. Overall, the combination of standardization and customization represents a typical socio-technical integration path, in which engineering innovation and industrial organization evolve in a coordinated manner.

7. Conclusion

T/ZZB 3029—2022 provides a comprehensive, systematic and practically applicable technical framework for the development of suspension systems for motorcycles and electric two-wheelers. By integrating high-precision spring design, multi-dimensional damping adjustment, structural strength verification, whole-vehicle matching and real-vehicle tuning, a closed-loop R&D system of “design – adjustment – verification – mass production” can be effectively established. This system not only ensures compliance with unified safety and quality standards but also enables precise adaptation to the differentiated requirements of various vehicle types. From a broader perspective, the study demonstrates that the combination of standardized technical frameworks and scenario-oriented customization can achieve a balanced optimization of safety, comfort, handling, durability and cost. It also highlights the role of technical standards as both engineering tools and institutional mechanisms in promoting industrial coordination and technological upgrading. The findings provide practical and replicable solutions for suspension system development, while offering insights into the integration of engineering practice and standardization in modern manufacturing systems.

Author Contributions:

Hongqin Wu contributed to the conceptualization, methodology of the study, and supervised the overall project, and coordinated the research process of the study. Xuhui Yang performed data analysis and conducted the first draft of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding:

This research received no external funding.

Institutional Review Board Statement:

Not applicable.

Informed Consent Statement:

Not applicable.

Data Availability Statement:

The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflict of Interest:

The authors declare no conflict of interest.

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