International Journal of Future Engineering Innovations

Optimization of Vibration Isolation Systems for Vibratory Rollers: From Passive Cab Mounts to Quasi-Zero-Stiffness and Intelligent Control - A Critical Review

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Article Info

ISSN (online): 3049-1215
Impact Factor (RSIF): 8.25
Volume: 03
Issue: 05
Received: 24-06-2026
Accepted: 26-07-2026
Published: 28-08-2026
Page No: 36-42

Abstract
Vibratory rollers expose operators to a coupled vibration environment generated by terrain irregularity, drum excitation, frame motion, and low-frequency resonances of the cab and seat. This critical review examines the evolution of vibration-isolation optimization for vibratory rollers from passive rubber and hydraulic cab mounts to drum isolation, hydro-pneumatic and semi-active systems, negative-stiffness structures (NSS), quasi-zero-stiffness (QZS) seat suspensions, and intelligent control. A focused evidence base of 30 publications is synthesized, combining a long-term research line on single- and double-drum vibratory rollers with recent SCIE studies on nonlinear isolation and data-driven control. The reviewed work shows that passive mounts remain simple and reliable but are strongly limited by the conflict between load support and low-frequency isolation. Hydraulic and hydro-pneumatic mounts improve damping and resonance suppression, while semi-active control extends adaptability to changing operating conditions. NSS/QZS concepts further reduce effective dynamic stiffness and can substantially improve seat isolation, but their practical performance depends on payload, stroke, nonlinear stability, and the width of the low-stiffness region. Intelligent control and machine-learning methods offer a route toward condition-dependent tuning, although sensing requirements, model uncertainty, robustness, and vehicle-level validation remain unresolved. The main research gaps are coordinated drum-cab-seat optimization, multi-condition robust objectives, simultaneous vertical-pitch-roll whole-body-vibration criteria, and experimental validation under deformable terrain. A staged framework is proposed that links excitation identification, model validation, sensitivity screening, multi-objective optimization, robust verification, and vehicle testing.

DOI: https://doi.org/10.54660/IJFEI.2026.3.5.36-42

Keywords: Vibratory roller, vibration isolation, cab mount, negative stiffness, quasi-zero stiffness, intelligent control

1. Introduction

Vibratory rollers operate under a vibration environment that differs fundamentally from conventional road vehicles. The operator is exposed not only to road or soil irregularity but also to periodic excitation generated by the vibratory drum, structural coupling between the drum and frame, and low-frequency motion of the cab and seat. Early studies by Quynh and collaborators established the importance of cab isolation design, deformable-soil interaction, experimental ride-comfort assessment, and parameter optimization for this class of machine [1-5]. These studies also showed that the dominant excitation path changes between travelling and compaction, so an isolation system tuned at one operating point cannot automatically be assumed to perform well over the full duty cycle.

Research then expanded from conventional cab mounts to more realistic off-road models and alternative isolation devices. Comparative analysis of rubber, hydraulic, and pneumatic mounts [6], fuzzy-PID control [7], sensitivity of cab-mount parameters [8], hydro-pneumatic isolation [9], modal-based design [10], drum isolation optimization [11], and an earlier review of cab isolation systems [12] progressively clarified the trade-off between static load capacity, damping, resonance control, suspension stroke, and ride comfort. Additional work linked ride response to drum excitation frequency [13] and horizontal cab shaking [14], demonstrating that a purely vertical single-degree-of-freedom view is insufficient.

The next stage of development moved toward optimization and semi-active control. Optimal cab-isolation design [15], semi-active hydraulic cab mounts for double-drum rollers [16], and semi-active isolation for earth-moving machinery [17] provided a basis for adapting damping characteristics to operating conditions. Parallel work on integrated cab-seat suspension design [18], QZS seat suspension optimization [19], and machine-learning-based isolation control [20] indicates a broader transition from component tuning toward multi-layer and intelligent vibration management. Recent SCIE literature reinforces this transition. Negative-stiffness seat suspensions [21], magnetic-air QZS isolators [22], semi-active QZS systems [23], and X-shaped nonlinear QZS structures [24] address the classic contradiction between high static stiffness and low dynamic stiffness. Studies focused directly on vibratory rollers have reported substantial gains from optimized QZS and NSS seat isolation [25,26], while comparisons among alternative NSS architectures [27], advanced hydraulically damped rubber mounts [28], semi-active QZS seat systems [29], and machine-learning-based active seat control [30] extend the design space toward adaptive low-frequency isolation.

This paper critically reviews the optimization of vibration isolation systems for vibratory rollers using these 30 studies as a focused evidence base. The objective is not to rank a single best mount, but to identify how the design problem has evolved, which objectives and constraints are most meaningful, where current methods remain fragile, and how future research can coordinate drum, frame, cab, and seat isolation. Section 2 discusses excitation sources, isolation architectures, and performance criteria. Section 3 compares optimization and control methods. Section 4 synthesizes the main limitations and research directions. Section 5 summarizes the principal conclusions.

2. Vibration Sources, Isolation Architectures, and Performance Criteria

2.1. Excitation pathways and operating conditions

The excitation of a vibratory roller is multi-source and operating-condition dependent. During travelling, terrain roughness and wheel-soil interaction dominate the lower-frequency input, whereas during compaction the rotating eccentric mass of the drum adds a strong periodic component. Deformable terrain further changes the effective support stiffness and damping seen by the vehicle. The soil-ground study in [2] and later dynamic models in [6,13] show why rigid-road assumptions can distort the prediction of cab and seat motion when the machine is operating on soft or elasto-plastic ground.

These sources propagate through several isolation layers. Drum mounts first affect the force transmitted to the frame, cab mounts filter frame motion before it reaches the operator compartment, and the seat suspension provides the final isolation stage. The performance of each layer therefore depends on the upstream dynamics. Optimizing the cab while retaining an unfavorable drum isolation, or optimizing the seat under an assumed fixed cab input, can shift rather than eliminate resonance. This coupling is already implicit in drum-isolation optimization [11], cab design [10,15], and integrated cab-seat studies [18].

Operating variables also matter. Vehicle speed, drum excitation frequency, compaction state, soil stiffness, payload, and driver mass change the spectral content and the relative importance of vertical, pitch, and roll responses. The frequency study in [13] is especially important because the vibratory mechanism is both a functional source of compaction energy and a source of harmful vibration. Isolation optimization must therefore preserve compaction performance while reducing transmission to the frame and operator.

Table 1: Evolution of vibration isolation strategies for vibratory rollers and related off-road machinery.

Isolation strategy	Main design/control variables	Engineering implication
Passive rubber cab mounts	Stiffness, damping, preload, location	Simple and robust, but fixed load-support/isolation trade-off
Hydraulic / hydro-pneumatic cab mounts	Orifice, chamber volume, fluid/gas parameters	Tunable low-frequency damping, but nonlinear and condition-dependent
Drum isolation mounts	Rubber stiffness/damping, mount geometry	Reduces frame excitation, but must preserve compaction effectiveness
NSS / QZS seat suspension	Negative-stiffness geometry, preload, stiffness, stroke	Low dynamic stiffness, but sensitive to payload and stroke
Semi-active / intelligent isolation	Controllable damping/force, controller and sensors	Adaptive, but requires sensing, bandwidth, robustness, and fail-safe logic

Table 1 shows that the technology has evolved by adding degrees of design freedom. Rubber mounts mainly offer fixed stiffness and damping. Hydraulic and hydro-pneumatic mounts introduce fluid inertia, orifice losses, compressibility, and frequency-dependent damping. Semi-active systems add controllable damping or force. NSS/QZS mechanisms deliberately reshape the restoring force so that static load capacity can coexist with very low dynamic stiffness near an operating equilibrium.

This evolution improves low-frequency isolation potential but also increases sensitivity to modeling assumptions. Passive rubber mounts are easy to manufacture and validate, while hydraulic and QZS systems require accurate representation of nonlinear stiffness, damping, fluid behavior, friction, clearances, and load variation. Consequently, a more advanced device is not automatically superior unless the model, operating range, and constraints are equally advanced.

2.2. Passive and hydraulic isolation architectures

Passive cab isolation remains the reference configuration because of its simplicity, fail-safe behavior, and low implementation cost. The comparison of three cab-mount types in [6] demonstrated that changing the mount architecture can materially alter low-frequency response. However, fixed passive parameters must simultaneously carry the cab mass, limit displacement, avoid bottoming, and attenuate vibration. Increasing stiffness improves static support but generally raises the isolation threshold, whereas increasing damping suppresses resonance at the cost of higher transmissibility above resonance.

Hydraulic and hydro-pneumatic mounts provide additional freedom through chamber compliance, fluid inertia, flow restriction, and nonlinear loss mechanisms. The hydro-pneumatic system in [9] and the recent hydraulically damped rubber mount in [28] show that fluid-based mounts can produce stronger frequency-dependent damping than conventional rubber elements. This is attractive for construction machinery, where low-frequency cab resonance is a primary concern. The design challenge is that mount behavior depends on excitation amplitude, frequency, temperature, fluid properties, and manufacturing tolerances.

Drum isolation should be considered as part of the same transmission chain. The optimization in [11] used a genetic algorithm to search drum-isolator parameters with the objective of reducing vehicle vibration. A strategically important point is that drum mounts cannot be optimized only for operator comfort: excessive isolation can modify the dynamic force delivered to the ground and therefore affect compaction effectiveness. Future designs should treat compaction performance and operator exposure as coupled objectives rather than independent requirements.

Horizontal and rotational dynamics are also relevant. The auxiliary horizontal damping concept in [14] was proposed specifically to suppress cab shaking, illustrating that mount orientation and installation position can be as important as nominal vertical stiffness. For full-vehicle designs, the spatial distribution of mounts controls cab pitch and roll modes. This supports using a three-dimensional model when the objective includes multi-axis whole-body vibration rather than only vertical seat acceleration.

2.3. Objectives, constraints, and validation metrics

Ride-comfort optimization requires objective functions that reflect human exposure rather than only mechanical displacement. The long-term vibratory-roller research line commonly uses weighted root-mean-square acceleration, frequency-domain power spectral density, and cab pitch or roll responses [2,3,6,10,13]. These measures are consistent with the logic of ISO 2631-1 whole-body-vibration assessment, in which frequency weighting is important because the human body is not equally sensitive at all frequencies.

A single objective is rarely sufficient. Minimizing vertical seat acceleration alone may increase suspension travel, cab angular motion, mount force, or control effort. For NSS/QZS seats, displacement stroke and static equilibrium are especially important because the low-stiffness region is finite. For hydraulic systems, pressure-related loads, mount deflection, and controllable force limits should also be constrained. A credible optimization problem should therefore include comfort, stability, stroke, load support, and implementation limits.

Validation should proceed at several levels. The dynamic model must first reproduce measured time histories or frequency characteristics under representative excitation. The isolation component should then be validated separately when nonlinear stiffness or hydraulic dynamics dominate. Finally, the optimized system should be re-tested at the vehicle level under conditions not used for parameter tuning. The experimental work in [3,5,10,25,26] is valuable because it prevents optimization gains from being interpreted solely from an unverified numerical model.

Robustness is equally important. Soil properties, operator mass, speed, drum frequency, mount temperature, and manufacturing variation are uncertain in service. A design optimized for a nominal parameter set may lose its advantage when these quantities change. Future studies should report not only a best-case percentage reduction but also performance ranges across operating conditions and uncertainty sets.

3. Optimization and Control Methods

3.1. Parametric and multi-objective optimization

Parametric analysis remains useful at the beginning of the design process because it reveals physical trends and eliminates weak variables. The early cab and drum studies [1,4,8,11] show the value of examining stiffness and damping before applying a global optimizer. This step is particularly important for nonlinear isolation because the same geometric parameter can simultaneously change static load support, local dynamic stiffness, resonance frequency, and allowable displacement.

Genetic algorithms and multi-objective genetic algorithms became attractive once the problem included several conflicting responses. They can search nonlinear design spaces without analytical gradients and can accommodate geometric parameters, mount characteristics, and controller gains. The limitation is that an optimizer can only be as reliable as the model and objective formulation. A numerically sharp optimum obtained from uncertain soil or mount parameters may be less useful than a slightly inferior but robust design.

For vibratory rollers, the preferred formulation is increasingly multi-condition and multi-objective. Instead of minimizing one weighted RMS value at one speed, the design should seek a Pareto set over travelling and compaction conditions, different soil classes, and multiple comfort indices. Such a formulation would make the trade-off visible between vertical seat response, cab pitch and roll, suspension stroke, and compaction-related constraints.

3.2. Hydraulic and semi-active isolation

Semi-active isolation addresses one of the main weaknesses of fixed passive mounts: the optimum damping level changes with excitation frequency and operating condition. Fuzzy-PID control for soil-compactor cab mounts [7], semi-active hydraulic cab mounts [16], and the broader earth-moving machinery study [17] demonstrate the feasibility of adjusting damping or control force without requiring the continuous high power associated with fully active suspension.

The control objective should nevertheless be defined together with the physical mount. High controller gains cannot compensate for inadequate stroke, poor hydraulic bandwidth, or unfavorable passive stiffness. Semi-active systems are also subject to force-direction constraints and actuator dynamics. For this reason, co-design of mount parameters and controller parameters is more defensible than optimizing the controller after fixing the mechanical design.

Hydraulic mounts are especially suitable for this co-design because the passive flow path already provides frequency-dependent damping. The advanced mount in [28] demonstrates nonlinear softening and amplitude-frequency dependence arising from fluid and rubber behavior. In a vibratory roller, a controllable hydraulic path could therefore be used to shift damping emphasis between travel and compaction while retaining a passive fail-safe characteristic. A notable transition from passive parameter optimization to intelligent vibration control was reported in [7], where a PID–fuzzy strategy was introduced to improve the vibration isolation performance of the vibratory-roller cab. As illustrated in Fig. 1, the controlled system achieved lower vibration responses than the passive configuration, as evidenced by both RMS and PSD results.

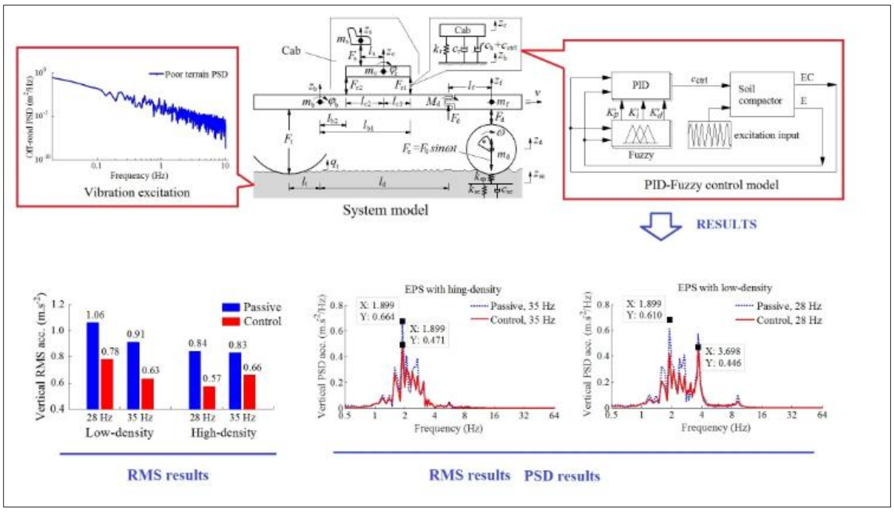

Fig 1: Dynamic model and performance evaluation of the PID–fuzzy controlled cab vibration isolation system for a vibratory roller [7].

3.3. Negative-stiffness and quasi-zero-stiffness isolation

NSS and QZS concepts directly target the low-frequency limitation of conventional suspensions. By combining a positive load-carrying element with a negative-stiffness mechanism, the net dynamic stiffness can be reduced near equilibrium without losing static load capacity. The seat suspension in [21] demonstrates the general principle, while magnetic-air [22] and six-oblique-spring [23] QZS systems show alternative mechanisms for creating a high-static-low-dynamic-stiffness characteristic.

The main engineering advantage is a lower effective isolation frequency. The main difficulty is that the QZS region is not unlimited. Payload mismatch, large displacement, parameter error, and nonlinear jump phenomena can move the system outside the desired operating range. The semi-active strategy in [23] explicitly addresses this problem by enlarging the effective QZS range, while the X-shaped structure in [24] seeks high load capacity with a nonlinear low-stiffness response.

Application to vibratory rollers is now supported by direct evidence. The optimized QZS seat in [25] was evaluated with a vibratory-roller model that included drum/wheel interaction with off-road terrain and was experimentally checked. The reported RMS seat acceleration reductions reached 61.7% during travelling and 67.5% during working, illustrating the potential of QZS when the mechanism is tuned to the actual excitation environment.

The optimal NSS study in [26] likewise combined a seat NSS with hydraulic cab mounts and a three-dimensional roller model. Its experimental results showed large reductions in peak PSD responses, including the seat and cab angular motions. This is important because it demonstrates that a seat-level nonlinear mechanism can influence a broader set of operator-exposure metrics when it is integrated with the cab isolation system.

Different NSS architectures should not be treated as equivalent. The comparison in [27] showed that steel-spring, roller-spring, and air-spring negative-stiffness structures have different restoring-force characteristics and isolation performance. The selection problem therefore includes geometry, load sensitivity, friction, manufacturing complexity, durability, and the ability to maintain a stable low-stiffness region over the required seat travel.

For practical vibratory-roller design, QZS optimization should be coupled with constraints on static sag, end-stop clearance, driver-mass variation, and transient shocks. An optimum derived only from steady harmonic or stationary random excitation can be unsafe if the seat experiences large transient displacement during obstacle crossing or abrupt changes in soil support.

3.4. Intelligent and data-driven control

Intelligent control extends semi-active isolation by allowing the control law to adapt to nonlinear and changing conditions. Machine-learning control has already been explored for vehicle isolation systems [20], and the recent review in [30] shows rapid growth of data-driven and learning-based active seat control. The opportunity for vibratory rollers is particularly strong because their operating states are distinguishable: travelling, entering compaction, steady compaction, reversing, and transient obstacle crossing can be treated as different control contexts.

Table 2: Comparison of optimization and control approaches for vibratory-roller vibration isolation.

Method	Typical use	Main strengths	Main limitations
Parametric / sensitivity analysis	Screening stiffness, damping, geometry, operating variables	Physically interpretable and efficient before optimization	May miss strong interactions and global optima
GA / multi-objective optimization	Coupled comfort, stroke, angular-motion, and design trade-offs	Handles nonlinear design spaces and produces Pareto solutions	Computational cost and dependence on model credibility
Fuzzy-PID / semi-active control	Condition-dependent hydraulic or damping control	Improves adaptability with moderate actuation power	Requires sensors, tuning, bandwidth, and force constraints
NSS / QZS optimization	Low-frequency seat isolation with high static load capacity	Can markedly reduce effective dynamic stiffness and isolation frequency	Sensitive to payload, preload, stroke, nonlinear stability, and tolerance
Machine learning / data-driven control	Mode recognition, gain scheduling, adaptive seat control	Can exploit operating-state information and complex nonlinear behavior	Needs representative data, safety constraints, robustness, and fallback control

The semi-active QZS seat study in [29] is a useful bridge between nonlinear mechanism design and intelligent control. It compared passive and semi-active seat configurations with QZS across one-, two-, and three-dimensional vibratory-roller models. This type of cross-model evaluation is valuable because a controller that appears effective in a low-order model may lose performance when cab pitch, roll, and coupled frame dynamics are introduced.

Data-driven control should be used strategically rather than as a substitute for physics. Training data must cover the operating states and uncertainty range in which the controller will be deployed. Physics-based constraints, safety limits, fallback passive behavior, and out-of-distribution detection are therefore important. A promising direction is hybrid control in which a validated vehicle model defines feasible actions while a learning algorithm adjusts gains or mode selection online.

4. Comparative Synthesis, Research Gaps, and Future Directions

4.1. What can be concluded from the reviewed methods?

No single isolation architecture is best under all conditions. Passive rubber mounts remain attractive when reliability, cost, and maintainability dominate. Hydraulic and hydro-pneumatic mounts provide stronger low-frequency damping and greater tuning freedom but require more accurate modeling and sealing quality. Semi-active systems improve adaptability but add sensors, control logic, and actuator bandwidth requirements. NSS/QZS systems offer the largest potential reduction in effective dynamic stiffness but are sensitive to load, stroke, and nonlinear stability.

The strongest evidence comes from studies that combine realistic excitation, multiple ride-comfort indices, optimization, and experimental validation. In this regard, the progression from modal and vehicle tests [3,10] to experimentally checked QZS/NSS roller systems [25,26] is strategically important. It indicates that the field has moved beyond demonstrating a nonlinear restoring-force curve and toward verifying operator-level benefits under machine-specific conditions. To investigate the vibration transmission characteristics of the complete machine, a finite-element model of the single-drum vibratory roller was established, incorporating the main structural components and the cab isolation system, as shown in Fig. 2.

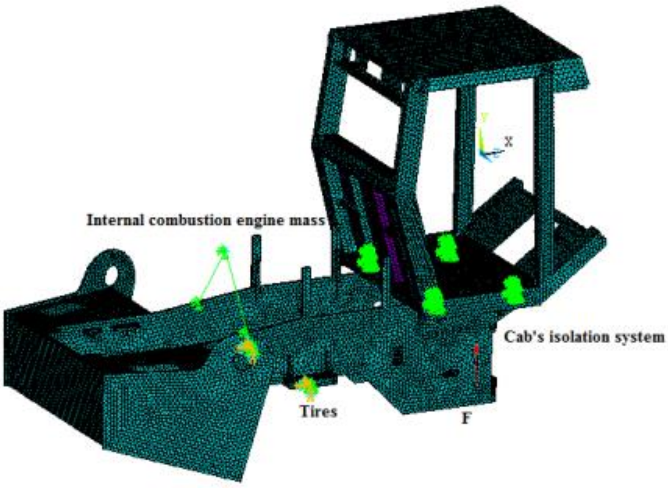

Fig 2: Finite-element model of a single-drum vibratory roller with the cab isolation system [10].

At the same time, reported percentage improvements should be interpreted carefully. A large reduction at one operating point does not prove superiority over the full duty cycle. Comparisons should use identical terrain inputs, vehicle parameters, driver mass, speed, drum frequency, and evaluation bandwidth. Absolute RMS and PSD values, suspension travel, and control demand should be reported together with percentage reduction.

4.2. Validation, robustness, and reproducibility

A recurring limitation is incomplete validation of the complete vibration path. A seat model may be verified while the cab input is prescribed rather than measured, or a cab model may be validated on a rigid test surface but then optimized for deformable terrain. Future work should validate the chain from drum/ground excitation to frame, cab floor, seat base, and operator interface using synchronized measurements.

Uncertainty should be incorporated explicitly. Soil stiffness and damping vary during compaction, the driver mass changes between operators, rubber and hydraulic properties are temperature dependent, and QZS mechanisms are sensitive to preload and geometric tolerance. Robust optimization should therefore evaluate distributions or bounded ranges rather than a single nominal parameter set. The preferred design is one that maintains acceptable comfort over these variations, not merely the one with the minimum nominal RMS acceleration.

Reproducibility requires complete reporting of vehicle parameters, soil model, excitation definitions, mount force laws, controller limits, optimization settings, and experimental signal processing. For nonlinear QZS/NSS systems, the equilibrium definition and preload should be reported because small changes can shift the low-stiffness region. For semi-active systems, sampling rate, sensor filtering, force saturation, and delay should also be documented.

4.3. Toward coordinated drum-cab-seat optimization

The largest research opportunity is coordinated optimization of the complete isolation chain. Existing studies have generated valuable results for drum mounts [11], cab mounts [6,9,15,16], and seat NSS/QZS systems [19,25-27,29], but these components are usually optimized sequentially. A sequential procedure can produce conflicting resonances because modifying one layer changes the input spectrum seen by the next.

A vehicle-level formulation should treat drum-isolator parameters, cab-mount parameters, seat stiffness/damping or QZS geometry, and controller gains as a coupled design vector. Objectives can include weighted seat acceleration, cab pitch and roll acceleration, seat travel, mount travel, frame vibration, and a compaction-performance indicator. Multi-objective optimization can then reveal which improvements are obtained by redistribution of vibration and which represent a true reduction in operator exposure.

Such co-design also creates a natural role for intelligent control. A passive or QZS mechanical design can establish safe baseline performance, while a semi-active controller adapts damping or QZS operating conditions to speed, soil state, and drum mode. This hierarchical architecture is more realistic for construction machinery than relying on fully active control alone because it preserves fail-safe isolation if sensing or control is unavailable.

4.4. Recommended research framework

A rigorous future study should begin by identifying the dominant excitation paths in both travelling and compaction. A validated three-dimensional vehicle model should then be established using measured frame, cab, and seat responses. Sensitivity analysis should screen mechanical and control variables before optimization. The optimization stage should use multiple operating conditions and multiple objectives rather than a single weighted index.

For NSS/QZS concepts, the feasible design space should include equilibrium stability, driver-mass range, maximum stroke, end-stop clearance, manufacturable geometry, and durability. For hydraulic or semi-active mounts, constraints should include pressure, flow, temperature, actuator bandwidth, and force saturation. The selected Pareto designs should be re-evaluated with the original high-fidelity model and with perturbed parameters.

Finally, validation should progress from component testing to cab/seat bench testing and then to the complete vibratory roller on representative rigid and deformable surfaces. Publication-quality evidence should report both time- and frequency-domain metrics and should compare the optimized configuration with the baseline under identical excitation. This workflow would convert the field from isolated component improvements toward robust vehicle-level vibration management.

5. Conclusions

Optimization of vibration isolation for vibratory rollers has evolved from fixed passive cab mounts toward hydraulic and hydro-pneumatic systems, semi-active control, nonlinear NSS/QZS seat suspensions, and intelligent data-driven control. The literature consistently shows that low-frequency operator exposure cannot be addressed by stiffness reduction alone because static load capacity, resonance damping, suspension travel, cab angular motion, and operating-condition variability are coupled. Hydraulic mounts improve damping flexibility, while NSS/QZS mechanisms provide a powerful route to high-static-low-dynamic stiffness when their nonlinear operating region is correctly designed.

The next advance should be vehicle-level co-design of drum, cab, and seat isolation under multiple operating conditions and uncertainty. Robust multi-objective optimization, experimentally validated nonlinear models, and semi-active or learning-based adaptation should be combined with practical constraints on stroke, durability, sensing, control force, and compaction performance. Such an approach offers a clearer path from promising component-level results to reliable reduction of whole-body vibration in real vibratory-roller operation.

Acknowledgment

The author gratefully acknowledges the Faculty of Mechanical and Automotive Engineering, Viet Tri University of Industry, for its support during the preparation of this study.

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How to Cite This Article

Quan NH, Thanh CD. Optimization of vibration isolation systems for vibratory rollers: from passive cab mounts to quasi-zero-stiffness and intelligent control - a critical review. Int J Future Eng Innov. 2026;3(5):36-42. doi:10.54660/IJFEI.2026.3.5.36-42.