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A Review of Non-Linear Vibrations in Heavy Trucks: Challenges, Control Strategies, and Advances in Suspension Technologies

Wutthipath Tinsuwan, Nattadon Pannucharoenwong*, Phadungsak Rattanadecho

Department of Mechanical Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Pathum Thani 12120, Thailand

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ABSTRACT

Non-linear vibrations in heavy trucks affect transportation efficiency, vehicle durability, and operational safety. They arise from interactions among suspension components, tire–road dynamics, and varying payloads, increasing fuel consumption, component wear, and cargo damage. This study reviews advances in the characterization, modeling, and control of non-linear vibration in heavy truck suspensions. Studies published between 2000 and 2024 were retrieved from Scopus, IEEE Xplore, ScienceDirect and SpringerLink and screened against predefined criteria ([N] studies included). Existing analytical and computational models capture fundamental dynamics, but their accuracy is limited by dynamic loading, geometric effects, and stochastic road inputs. Semi-active and active suspensions improve vibration suppression yet need better adaptability in unpredictable environments. Opposite-phase (counter-phase) force control, in which an actuator applies a force opposing the measured body motion as in active noise control, is examined and compared with passive, semi-active and active suspensions in terms of control principle, reported vibration reduction and limitations. Its potential for improving ride comfort and reducing structural loads is assessed against the reported evidence. Key research gaps include adaptive suspension design, real-time non-linear vibration prediction, and intelligent control. Addressing them is essential for sustainable, reliable, and cost-effective freight transportation.

Keywords: Truck Vibration, Non-linear Dynamics, Suspension Systems, Vehicle Vibration, Opposite-phase Control

***Corresponding author:** pnattado@engr.tu.ac.th
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1. Introduction

The transportation industry is a backbone of global supply chains, enabling the continuous movement of goods across domestic and international routes [1–8]. Among all transport modes, heavy trucks play a particularly critical role in long-distance freight logistics due to their flexibility, load capacity, and operational reach [5, 6, 9–11]. However, one major technical challenge that significantly affects their operational safety and efficiency is non-linear vibration.

Non-linear vibrations arise from complex interactions among suspension components, tire–road dynamics, cargo loading, and road unevenness [2, 12–14]. Unlike linear vibration systems—where input and response maintain proportional relationships—non-linear systems exhibit amplitude-dependent stiffness, damping asymmetry, hysteresis, and unpredictable dynamic responses [15–18]. In heavy trucks, these effects are amplified by large payload variations, long wheelbases, and axle configurations [6, 14, 19, 20]. Such vibrations compromise vehicle durability, driver comfort, and cargo safety, reducing overall freight reliability and performance [21]. From an operational perspective, non-linear vibrations affect three main areas Driver safety, where prolonged exposure increases fatigue and reduces alertness [22, 23], Vehicle durability, since suspension, tires, and drivetrain components experience accelerated wear [7, 24, 25], Transport efficiency, particularly for fragile or vibration-sensitive cargo, which can suffer damage during transit [26–29].

Managing these vibrations remains a key challenge in transportation logistics due to the dynamic nature of road conditions, cargo variability, and real-time operational constraints [10, 24, 25, 30-33], rucks must adapt to diverse terrains, ranging from smooth highways to rough, uneven roads, while accommodating fluctuating cargo loads [6, 34-36]. his variability makes it difficult to develop universal vibration control strategies, necessitating advancements in adaptive suspension systems, predictive maintenance, and real-time monitoring technologies [25, 37, 38].

This review explores non-linear vibrations in the context of freight transportation, examining their causes, modeling techniques, and potential mitigation strategies. It highlights mathematical modeling, computational simulations, and experimental methods used to analyze vibrations. [26, 27, 29, 39-45], explaining what causes them and why they occur in trucks. It also reviews current techniques used to study these vibrations, such as mathematical models, computer simulations, and experiments. Some advanced methods, like delayed feedback systems and motion magnification technologies, are also discussed as promising tools for understanding and addressing the problem. Finally, the review looks at strategies for controlling vibrations. [29, 45-48], including adaptive suspension systems and other technologies designed to reduce the effects of vibrations.

Despite ongoing advancements, significant challenges remain. Current control systems struggle with real-time adaptability, and non-linear vibrations require more sophisticated predictive models to enhance mitigation strategies. By bridging the gap between vibration dynamics and logistics efficiency, this review contributes to the ongoing effort to develop safer, more durable, and cost-effective freight transportation solutions [3, 5, 49]. This review provides several unique contributions that distinguish it from existing literature

1.1 Clear integration across modeling, experimentation and logistics impact

Existing reviews typically focus on either mechanical modeling [27] or control strategies [33]. This paper links non-linear vibration theory directly with freight

logistics outcomes, bridging engineering and practical transport perspectives.

1.2 Explicit classification of non-linear sources in heavy truck suspensions

The review systematically categorizes non-linearities (e.g., cubic stiffness, hysteretic damping and load-dependent dynamics), providing clearer definitions than prior generalized discussions.

1.3 Comparative evaluation of modeling techniques

Methods such as multibody modeling, numerical simulation, harmonic balance, and data-driven estimation are compared, highlighting applicability

1.4 Incorporation of recent experimental findings

Unlike many earlier works, this review includes findings from recent field and rig experiments (e.g., force displacement hysteresis, road-dependent non-linearity amplification).

1.5 Introduction of opposite-phase vibration cancellation for trucks

While widely used in acoustics, the application of counter-phase force cancellation to large commercial vehicles has received limited attention in the studies retrieved for this review (Section 2). This review formulates the concept for heavy-truck suspension systems (Section 6) and compares it with passive, semi-active and active suspensions (Table 3).

1.6 Identification of research gaps and future directions

The paper outlines key challenges—real-time adaptability, model uncertainty, computational limits and proposes directions for adaptive, intelligent, and predictive vibration mitigation technologies

The remainder of the paper is organised as follows. Section 2 describes the literature search and selection protocol. Section 3 classifies passive, semi-active and active truck suspensions and presents the baseline models. Section 4 reviews non-linear vibration mechanisms and the modelling and experimental approaches used to study them, with a comparative synthesis in Table 2. Section 5 presents an experimental case study. Section 6 introduces opposite-phase force control and compares it with the semi-active and active systems of Section 3 (Table 3). Section 7 discusses current challenges and future directions and critically analyses the evidence. Sections 8 and 9 present the discussion and the conclusions.

2. Materials and Methods

This review followed the search and selection protocol described below. It analysed research articles, technical reports and conference papers on non-linear vibrations in truck systems, covering experimental, computational and mathematical approaches.

2.1 Search strategy

Records were retrieved from Scopus, IEEE Xplore, ScienceDirect and SpringerLink for the period 2000–2024 (date of last search: [dd Month yyyy]). Titles, abstracts and author keywords were searched with Boolean strings adapted to the syntax of each database. The main string was: [("heavy truck" OR "heavy-duty vehicle" OR "semi-trailer") AND suspension AND (nonlinear OR "non-linear") AND (vibration OR "ride comfort")]. A second string targeted control strategies: [the main string AND ("semi-active" OR "active suspension" OR "counter-phase" OR "active noise control")]. [Replace these strings with those actually used.]

2.2 Eligibility criteria

Studies were included if they (i) were peer-reviewed journal or conference papers, technical reports, books or theses [confirm document types], (ii) addressed

non-linear vibration of truck or commercial-vehicle suspensions, or of quarter-, half- or full-vehicle models applicable to trucks, and (iii) reported a modelling, simulation, experimental or control result. Studies were excluded if they (i) concerned passenger cars only without transferability to trucks, (ii) did not address vibration or suspension behaviour, (iii) had no accessible full text, or (iv) were duplicates [or were not written in English]. Publications cited only to give transport and logistics background (Section 1) lie outside this protocol and are not counted as included studies.

2.3 Screening and selection

The search returned [n] records; [n] remained after duplicates were removed, [n] after title and abstract screening, and [n] full texts were assessed, of which [n] studies were included [a flow diagram may be added].

2.4 Data extraction and synthesis

For each included study, the vehicle or model type, the non-linearity considered, the method (analytical, simulation or experimental), the road excitation and payload, the main quantitative result and the reported limitation were extracted (Table 2). Because the studies use different metrics, road inputs and vehicle classes, results were synthesised narratively and in tables rather than by meta-analysis.

3. Overview of Truck Suspension System

3.1 Classification truck suspension

Suspension systems in trucks are essential for maintaining vehicle stability, driver comfort, and operational safety (Fig. 1). Transportation demands have evolved, and advancements in technology have led to the development of various types of suspension systems tailored to different driving conditions and vehicle needs. Broadly, truck suspension systems can be categorized into three types: passive, semi-active, and active systems. Each category represents a progression in complexity [27], adaptability, and performance, addressing the diverse challenges trucks face in real-world operations.

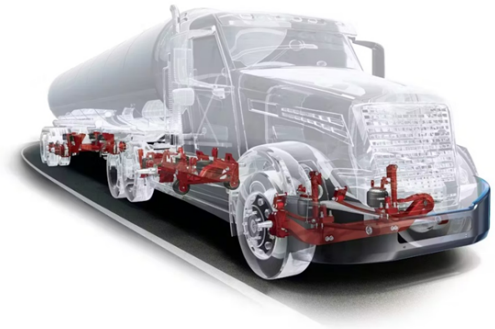


Fig. 1. The structure of a typical suspension system in a commercial truck.

The passive suspension system is the most traditional and widely used type. It relies solely on mechanical components such as springs, dampers, and anti-roll bars to absorb road shocks and maintain ride quality. The defining feature of passive systems is their fixed characteristics, which do not adapt to changing road or load conditions. Components like leaf or coil springs provide cushioning by storing and releasing energy, while shock absorbers convert kinetic energy into heat to dampen vibrations as Fig. 2 (a). This simplicity makes passive suspension cost-effective and highly reliable, particularly for trucks carrying heavy loads over long distances. However, the inability to dynamically adjust to varying road conditions limits their comfort and handling performance, making them less suitable for modern vehicles requiring real-time optimization [50, 51].

In contrast, the semi-active suspension system offers a more advanced solution by incorporating electronically adjustable dampers. These systems retain the mechanical foundation of passive suspensions but add electronic control units (ECUs) and sensors to monitor vehicle dynamics and road conditions. Based on

sensor inputs, the ECU adjusts the stiffness of variable dampers to optimize ride comfort and stability in real time. This adaptability allows semi-active suspensions to provide a balance between cost and performance, making them a popular choice for medium to heavy-duty trucks as Fig. 2(b). While they offer significant advantages in ride quality and adaptability, the added complexity introduces higher costs and maintenance requirements compared to passive systems. Despite these drawbacks, semi-active systems are particularly valued in applications where improved comfort and handling are essential, such as long-haul transportation and vehicles carrying mixed loads. [33, 50, 52-56].

The active suspension system represents the pinnacle of suspension technology, leveraging advanced sensors, actuators, and computer-controlled systems to actively control wheel motion and body stability as Fig. 2 (c). Unlike passive or semi-active systems, active suspensions can generate forces independent of road inputs, allowing them to counteract body roll, pitch, and dive during braking, cornering, or acceleration. These systems use hydraulic or electric actuators to adjust suspension settings continuously, ensuring optimal performance regardless of terrain or driving conditions. While active suspensions deliver unmatched comfort and control, their complexity and cost make them suitable primarily for premium trucks or specialized vehicles. Applications include luxury long-haul trucks, military vehicles, and off-road transport, where adaptability and superior ride quality are critical. Active suspension systems add hydraulic actuators to the passive components of the suspension system. The advantage of such a system is that even if the active hydraulic actuator or the control system fails, the passive components come into action. (27, 57-61), The equations of motion are written as Eqs. (3.1)-(3.2).

$$m_s\ddot{x}_s + c_s(\dot{x}_s + \dot{x}_u) + k_s(x_s - x_u) - \mathrm{u}_a = 0, \qquad (3.1)$$

$$m_u\ddot{x}_u - c_s(\dot{x}_s - \dot{x}_u) - k_s(x_s - x_u) + k_u(x_u - y)\mathrm{u}_a = 0. \qquad (3.2)$$

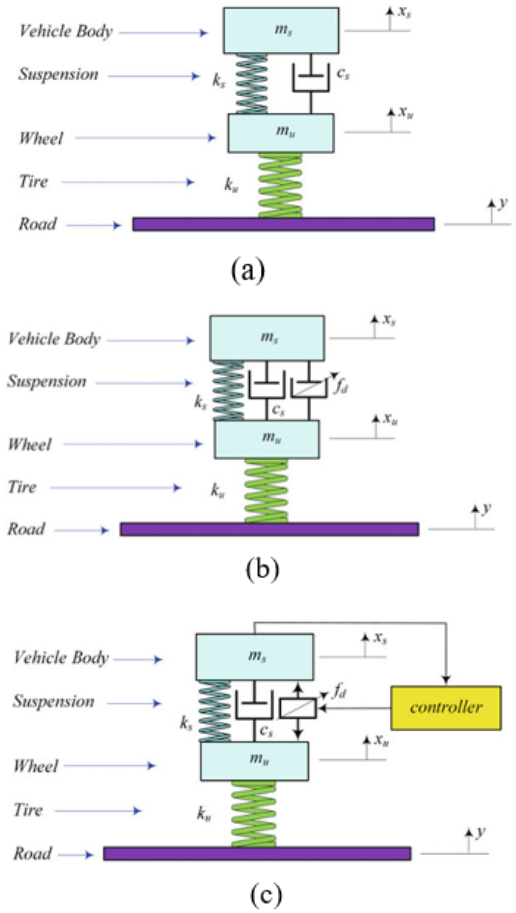


Fig. 2. Schematic diagrams of several types of vehicle suspension system [27] (a) Passive suspension system; (b) A semi-active suspension model; (c) A semi-active suspension model.

In conclusion, truck suspension systems demonstrate a clear progression in technological sophistication, from the simplicity and reliability of passive systems to the dynamic adaptability of semi-active systems and the precision control of active suspensions. Passive systems remain a practical choice for cost-sensitive and heavy-duty applications, while semi-active systems offer enhanced comfort and stability for more demanding operations. Active suspension systems, though expensive, provide

unparalleled performance for specialized needs. Manufacturers carefully select suspension types based on the specific operational and economic requirements of their vehicles, ensuring the best balance of performance, cost, and maintenance.

Table 1. Advantages, disadvantages, and applications of different suspension types in truck [33].

Suspension type	Advantage	Dis-advantage	Applica-tion
Passive	Simple, reliable, low cost	Fixed damping, less effective in varying condition	The most common, entry-level vehicle
Semi-active	Improve damping. Energy-efficient, realizable	Complex design Control-dependent	Mid to high-end vehicle, aerospace
Active	Best performance, real-time adjustment	High energy consumption Expensive, less reliable	High-end vehicles, racing cars, limited use

3.2 Analytical modelling of truck suspension (quarter-car and full-vehicle models)

This modeling enables engineers to predict how the suspension and the truck's body will react to varying driving conditions such as rough terrain, changes in speed, and variations in load. Several critical factors are considered in the analytical models, including wheel dynamics, body dynamics, and the suspension system itself as Fig. 3 [2, 13, 24, 46, 50].

Wheel dynamics refer to how the wheels interact with the road, influencing tire grip and vehicle handling. This analysis helps engineers understand the effect of road conditions on the truck's performance [62, 63]. on the other hand, examine how the truck's body moves and vibrates in response to forces from the wheels and suspension. This is essential for assessing the comfort and safety of the vehicle. The suspension system is modeled to analyze how the springs and dampers function to absorb and dissipate vibrations. [44], helping to maintain the truck's stability.

In the mathematical modeling of truck vibrations, a mass-spring-damper system is widely used to represent the complex interactions between various components of the vehicle. This model helps in simplifying the analysis of how external forces, such as road irregularities and terrain-induced vibrations, are transmitted through the tires and suspension system before ultimately affecting the truck's body. By breaking down these interactions into manageable equations, engineers can better understand the dynamic behavior of the vehicle, predict its response to different driving conditions, and optimize suspension design for improved ride comfort, stability, and overall performance. This approach is essential in developing more efficient and durable heavy trucks capable of handling diverse operating environments [24, 64, 65].

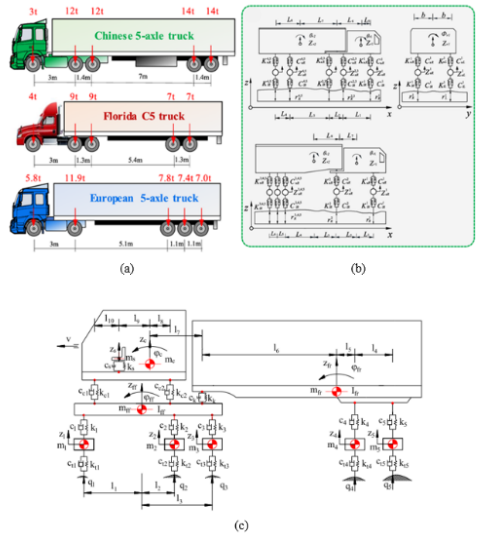


Fig. 3. Configurations of three typical trucks, truck semi-trailer (a) axle weight and spacings (b) analytical truck model (refined tire model unassembled) (c) articulated truck semi-trailer dynamic model [43, 66].

The dynamics of the truck system are governed by second-order differential equations derived from Newton's second law of motion. [43, 44, 62, 67, 68]. These equations capture the relationships between

the various forces acting on the system, such as the forces on the truck body and wheels, as well as the forces from the suspension's springs and dampers. These equations allow for the simulation of the truck's behavior under different road conditions, enabling engineers to predict important factors like body displacement, which directly affects ride comfort and wheel displacement. [35], which influences road holding and vehicle handling [69].

The governing equations include those for both the wheel and body displacements. The wheel displacement equation represents the vertical motion of the wheels as they encounter irregularities or bumps in the road surface, providing insight into how the wheels absorb and respond to the road's unevenness. The body displacement equation describes how the truck body reacts to the forces transmitted from the suspension system. [51], which is vital for assessing how vibrations from the road are transferred into the cabin and chassis, affecting the ride's comfort and stability.

By utilizing this analytical model, engineers can simulate various driving conditions, such as navigating uneven roads or carrying heavy loads, to predict how the truck will behave in real-world scenarios. This allows for a more accurate understanding of how different factors like road surface conditions, load variations, and speed affect the vehicle's overall performance. This analysis is essential for optimizing suspension designs to enhance ride quality, improve vehicle stability, and ensure that trucks can handle the stresses of daily operation effectively. Ultimately, this modeling helps in fine-tuning vehicle dynamics to ensure a balance between comfort, safety, and performance. [7, 65]

3.3 Multi-axle heavy-truck dynamic model

Sun and Nguyen [70] evaluated how heavy truck vibrations affect road damage for two-axle, three-axle and four-axle trucks. A multi-degree-of-freedom dynamic model was developed (Fig. 4). Key parameters include Mass: M, $M1$ (sprung mass of tractor and trailer), (unsprang mass of axles). Suspension: $k1{-}3$, $c1{-}3$ (stiffness and damping of suspension).Wheels: and (stiffness and damping of wheels). Displacements & Angles: (sprung mass displacement), (pitch angles), (axle displacements). Vehicle Dimensions: (distances within the vehicle) [70].
This model helps analyse truck-induced road damage more accurately

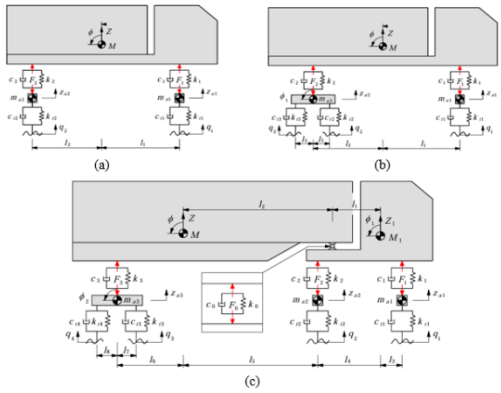


Fig. 4. Vibration model for the class of the heavy vehicle [71].2-axle heavy truck (a) 3-axle heavy truck (b) 4-axle heavy truck (c).

To simulate vehicle vibrations, a combined method using multi-body system theory and D'Alembert's principle is applied. Multi-body system theory divides the truck into subsystems connected by force and moment equations. D'Alembert's principle establishes these equations to describe the truck's dynamic behavior (70-73). The vibration equation for a 2-axle heavy truck is formulated based on this approach (Fig. 4).

$$\begin{cases} M\ddot{Z} = F_1 + F_2, \\ I\ddot{\phi} = F_1 l_1 - F_2 l_2, \end{cases} \quad \begin{cases} m_{a1}\ddot{z}_{a1} =_{a1} F_{t1} - F_1, \\ m_{a2}\ddot{z}_{a2} = F_{t2} - F_2, \end{cases}$$

$$\begin{cases} M\ddot{Z} = F_1 + F_2, \\ I\ddot{\phi} = F_1 l_1 - F_2 l_2, \end{cases} \tag{3.3}$$

where the force responses of the suspension systems of the vehicle and wheels of and are determined as in Eq. (3.4):

$$\begin{cases} F_i = k_i[Z_{ai} - Z + (-1)^i l_i \phi] + c_i[\dot{z}_{ai} - \dot{Z} - (-1)^i l_i \dot{\phi}], \\ F_{ti} = k_{ti}(q_i - z_{ai}) + c_{ti}(\dot{q}_i - \dot{z}_{ai}), \mathrm{i} = 1,2. \end{cases} \quad (3.4)$$

The vibration equation of a 3-axle heavy truck:

$$\begin{cases} M\ddot{Z} = F_1 + F_2, \\ I\ddot{\phi} = F_1 l_1 - F_2 l_2, \\ m_{a1}\ddot{z}_{a1} = {}_{a1}\ F_{t1} - F_1, \\ m_{a2}\ddot{z}_{a2} = F_{t2} + F_{t3} - \mathrm{F}_2, \\ I_1\ddot{\phi}_1 = F_{t2} l_3 - F_{t3} l_4 \end{cases} \quad (3.5)$$

where the force responses of the suspension systems of the vehicle and wheels of and are determined as in Eq. (3.6)

$$\begin{cases} F_i = k_i[z_{ai} - Z + (-1)^i l_i \phi], \mathrm{i} = 1,2, \\ F_{t1} = k_{t1}(q_1 - z_{a1}) + c_{t1}(\dot{q}_1 - \dot{z}_{a1}), \\ F_{tj} = k_{tj}[q_j - z_{a2} + (-1)^{j+1} l_{j+1}\phi_1] + c_{tj}[\dot{q}_j - \dot{z}_{a2} + (-1)^{j+1} l_{j+1}\dot{\phi}_1], j = 2,3. \end{cases} \quad (3.6)$$

The vibration equation of a 4-axle heavy truck:

$$\begin{cases} M_1\ddot{Z}_1 = F_1 + F_2 - F_0, \\ I_1\ddot{\phi}_1 = F_1 l_3 + F_0 l_1 - F_2 l_4, \\ M\ddot{Z} = F_0 + F_3 \\ I\ddot{\phi} = F_0 l_2 - F_3 l_6, \end{cases} \quad (3.7)$$

$$\begin{cases} m_{a1}\ddot{z}_{a1} = F_{t1} - \mathrm{F}_1, \\ m_{a2}\ddot{z}_{a2} = F_{t2} - \mathrm{F}_2, \\ m_{a3}\ddot{z}_{a3} = F_{t3} + F_{t4} - \mathrm{F}_3, \\ I_2\ddot{\phi}_2 = F_{t3} l_7 - F_{t4} l_8 \end{cases}$$

where the force responses of the suspension systems of the vehicle and wheels of and are determined as in Eq. (3.8):

$$\begin{cases} F_i = k_i(z_{zi} - Z_i) + c_i(z_{ai} - \dot{Z}_i), \mathrm{i} = 1,2,3, \\ F_{tj} = k_{tj}(q_j - z_{aj}) + c_{tj}(\dot{q}_j - \dot{z}_{aj}), \mathrm{j} = 1,2,3,4, \\ F_0 = k_0(Z_1 - l_1\phi_1 - Z - l_2\phi) + c_o(\dot{Z}_1 - l_1\dot{\phi}_1 - \dot{Z} - l_2\dot{\phi}_1). \end{cases} \quad (3.8)$$

The differential Eqs. (3.3), (3.5), and (3.7) are given by the following matrix form:

$$M\ddot{Z} + C\dot{Z} + KZ = C_t\dot{Q} + K_tQ, \quad (3.9)$$

The mass matrix of the heavy truck, the damping matrix and stiffness matrix of the suspension system, as well as the damping matrix and stiffness matrix of the wheels, are key parameters in the vibration system. Here, represents the displacement vector, and denotes the vibration excitation vector from the road surface.[9, 70].

4. Nonlinear Vibration in Truck Suspension

In heavy trucks, the suspension system plays a vital role in isolating the vehicle body from road irregularities, ensuring a smooth ride, and maintaining tire contact with the road. [6, 14, 20, 56, 74, 75]. However, due to the complex interactions between the suspension components, road conditions, and vehicle loads, nonlinear vibration phenomena often arise. Nonlinear vibrations differ from linear vibrations in that the system's response is not directly proportional to the input forces, leading to more complex and unpredictable behaviors. These nonlinearities are crucial to understand for optimizing suspension design and enhancing vehicle performance. [18, 58, 76, 77].

4.1 Definition and characteristics of non-linear vibration

Nonlinear vibration occurs when the relationship between the applied forces and the resulting displacement, velocity, or acceleration is not linear. This means that as the magnitude of the force increases, the

system's response does not increase proportionally. In truck suspensions, nonlinearities can arise from several factors such as material properties, suspension geometry, and the nature of the road surface. [47, 71, 77]. Nonlinear systems are often characterized by amplitude-dependent stiffness, where the suspension's stiffness changes based on the displacement or load applied, and amplitude-dependent damping, where the damping force varies with the speed or amplitude of vibration as Fig. 5.

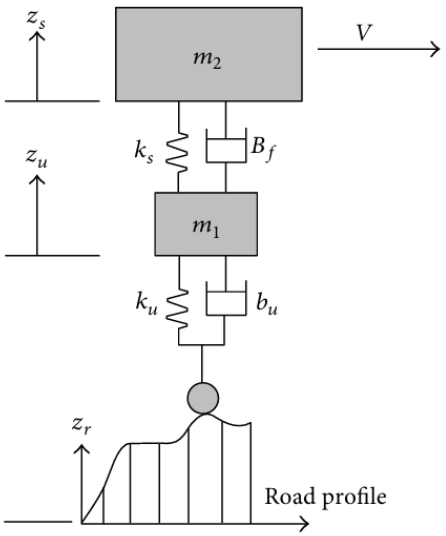


Fig. 5. Quarter truck suspension model on road profile of nonlinear [51].

Furthermore, nonlinear systems can exhibit complex resonance behaviours, where multiple resonant frequencies emerge and the response can significantly change with different vibration amplitudes. [16, 44, 73, 78-80] The behaviour of the system can be described with the following equations:

$$m_s\ddot{x}_s = c_s\left(\dot{x}_u - \dot{x}_s\right) + k_s(x_u - x_s), \tag{4.1}$$

$$m_u\ddot{x}_u = -c_s\left(\dot{x}_u - \dot{x}_s\right) - k_s(x_u - x_s) + k_t(u - x_u) + c_t\left(\dot{u} - \dot{x}_s\right). \tag{4.2}$$

Equations describing the nonlinear characteristics of spring and the damper are:

$$F_k = k_i \cdot \mathrm{sgn}(\Delta u)\left|\Delta u\right|^{n_i}, \tag{4.3}$$

$$F_c = c \cdot \mathrm{sgn}\left(\Delta\left(\frac{du}{dt}\right)\right)\left|\Delta\left(\Delta\left(\frac{du}{dt}\right)\right)\right|^{n_{cs}}. \tag{4.4}$$

4.1.1 Classification of nonlinear vibration

Nonlinear vibrations can be classified into various types based on the specific nonlinearity present in the system. Geometrical nonlinearity occurs when large displacements alter the geometry of the suspension system, changing the force-displacement relationship. For example, leaf springs in trucks show nonlinear stiffness at large deflections. Material nonlinearity arises from the nonlinear properties of the suspension materials, such as rubber bushings, which exhibit nonlinear stress-strain behavior under high deformation. Nonlinear damping occurs when the damping force is not proportional to velocity, with shock absorbers in truck suspensions often exhibiting velocity-dependent damping characteristics. (16). Self-excited nonlinear vibration results from internal feedback mechanisms, such as friction or aerodynamic forces, and is seen in phenomena like stick-slip behavior in truck brakes. Parametric nonlinearity involves periodic changes in system parameters, such as stiffness or damping, which can introduce nonlinear behavior. [81-83]. Internal resonance happens when energy is transferred between different vibrational modes of the suspension system, leading to complex oscillations, particularly in systems with multiple degrees of freedom. [17, 39, 84].

4.1.2 Damping mechanism of nonlinear vibration

Damping plays a critical role in controlling vibrations and dissipating energy in nonlinear systems. In truck suspensions, nonlinear damping is introduced by components like shock absorbers and elastomer bushings. The damping mechanism is more complex than in linear systems, as the damping force depends on both the amplitude and velocity of the motion. Progressive damping, where the damping force increases with the speed of suspension movement, helps to control larger impacts more effectively, reducing the amplitude of vibrations. Nonlinear energy dissipation varies with vibration amplitude, with higher amplitudes leading to greater energy dissipation, but potentially insufficient control over small vibrations at lower amplitudes, causing residual oscillations. [52, 63, 76, 86]. Additionally, hysteresis effects in some nonlinear damping systems, particularly involving rubber or elastomer materials, lead to energy loss that depends on the vibration cycle, exhibiting different damping forces during compression and rebound.

When comparing nonlinear and linear vibration systems, several key differences emerge. In linear systems, the force-displacement relationship is directly proportional, meaning the system's response increases proportionally with the applied force. In nonlinear systems, however, the response is not proportional to the force, and the system may exhibit different behaviors at various amplitudes. In terms of resonance [48], linear systems experience resonance at a specific frequency, with vibration amplitude increasing sharply at the natural frequency. In contrast, nonlinear systems exhibit more complex resonance behavior, with multiple resonant frequencies and possible shifts between different vibration modes, often leading to sudden changes in response. Linear systems dissipate energy at a constant rate, with damping proportional to velocity, while nonlinear systems' energy dissipation depends on amplitude and velocity, providing better control at higher amplitudes but less effectiveness at lower amplitudes [47]. Linear systems tend to be more predictable and stable, while nonlinear systems can exhibit bifurcations, where small changes in parameters lead to significant shifts in behavior, potentially causing instability. Finally, in nonlinear systems, the vibration response is dependent on the amplitude of excitation, with larger excitations leading to increased stiffness or damping, altering the system's behavior under different load conditions [26, 43].

4.2 Development and research status of nonlinear vibration in trucks

The study of nonlinear vibration in trucks has progressed significantly, employing computational, mathematical, and experimental approaches to address the complexities of truck dynamics under real-world conditions. These methods aim to improve understanding and optimize the design of truck suspension systems, enhancing their ability to handle vibrations effectively.

4.2.1 Development of computational nonlinear vibration models

Computational approaches to nonlinear vibration analysis have advanced with the development of high-performance computing and sophisticated numerical methods [34]. Finite element methods (FEM), multi-body dynamics (MBD), and nonlinear finite element analysis (NFEA) are commonly used to simulate the behavior of truck components under various loading conditions. [18, 45]. These simulations allow researchers to model material nonlinearity, large deformations, and contact phenomena, providing valuable insights into the vibrational responses of components like suspension systems, chassis, and tires. Recent developments include the coupling of FEM with optimization algorithms to

improve model accuracy and efficiency as Fig. 6. Additionally, advanced software tools such as ANSYS, Abaqus, and Sim-pack enable the simulation of complex nonlinear interactions, including friction, damping, and plastic deformation. These computational models are instrumental in predicting truck behavior, reducing reliance on physical prototypes, and supporting the design of effective vibration-damping solutions. [45,87, 88].

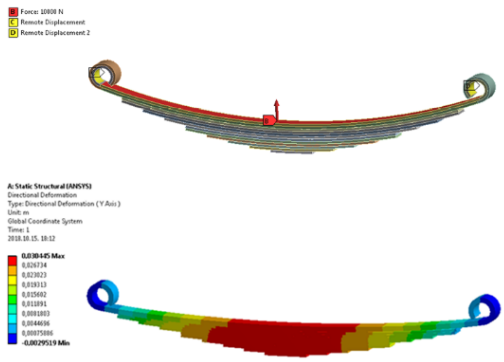


Fig. 6. Finite element model of the leaf spring.

4.2.2 Development of mathematical nonlinear vibration models

Mathematical modelling also plays a crucial role in analysing nonlinear vibrations. Researchers employ various analytical and semi-analytical techniques, such as perturbation theory, the method of multiple scales, and the harmonic balance method, to derive approximate solutions for nonlinear vibration problems. [89, 90]. These models often focus on simplified truck systems to capture essential nonlinear effects, such as geometric nonlinearity in beam structures or nonlinear stiffness in suspension components. Recent research has introduced new techniques, including fractional-order derivatives and chaos theory, to explore more complex behaviours in truck dynamics, offering fresh perspectives on understanding nonlinear vibrations in real-world scenarios. [43, 53, 54]. These mathematical models are valuable for validating computational simulations and guiding experimental research as Fig. 7, providing a theoretical framework for interpreting the nonlinear phenomena observed in trucks.

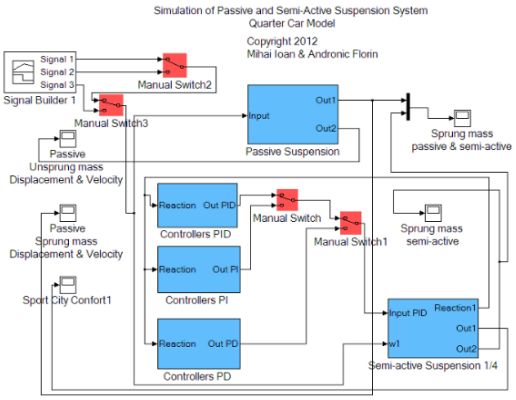


Fig. 7. The MATLAB suspension simulation scheme, quarter car model development of Computational and Mathematical Nonlinear Vibration Models (50).

4.2.3 Development of experimental nonlinear vibration techniques

Experimental research is essential for validating the results of computational and mathematical models. Various experimental setups have been developed to measure and analyze the nonlinear vibrational behavior of trucks under dynamic loading conditions [91]. Full-scale truck tests on specialized tracks simulate real-world road conditions, including rough terrains and variable loads, to observe the nonlinear response of suspensions, axles, and tires. Laboratory- scale experiments, such as shaker tests and dynamic testing of individual truck components like tires and suspension systems, offer detailed insights into the nonlinear behavior of specific parts [54]. Advancements in sensor technology, data acquisition systems, and signal processing have enhanced the precision and resolution of experimental studies as Fig. 8 [92, 93]. Modern techniques, such as modal analysis and non-contact laser vibrometer, are increasingly used to measure complex nonlinear vibrations. By experimentally validating computational models,

researchers can ensure that these models accurately reflect the real-world behavior of trucks, which is crucial for developing more efficient, durable, and safe heavy vehicle systems [94, 95].

In summary, the development of computational, mathematical, and experimental methods for studying nonlinear vibrations in trucks has enabled significant advances in understanding and managing truck dynamics [41, 62, 68]. These approaches not only improve the prediction and analysis of truck behavior but also contribute to the optimization of suspension systems, ultimately leading to better ride quality, safety, and performance in heavy vehicles [96].

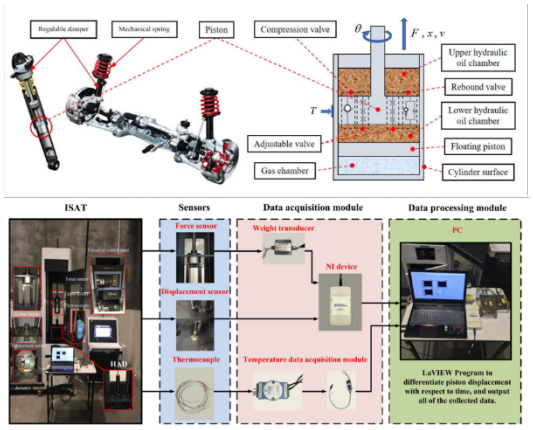


Fig. 8. Adaptive Artificial Neural Network Surrogate Model of Nonlinear Hydraulic Adjustable Damper, Commercial Semi-Active suspension stem and Schematic diagram of the damper (SAS system with the nonlinear HAD), Ther process of data collection [97].

4.2.4 Comparative summary of reviewed studies

Table 2 summarises representative studies discussed in Sections 3 to 5 by vehicle or model, non-linearity, method and outcome. Among the tabulated studies, quarter-car models are the most frequent model type (four of ten) and two studies are primarily experimental. Because the studies differ in vehicle class, road input, payload and metric (Section 2.4), the outcomes are not directly comparable and should be read as an overview of the state of the art rather than as pooled estimates.

Table 2. Summary of representative studies on non-linear truck and suspension vibration.

Ref. / study	Vehicle or model	Focus and method	Key outcome and limitation
[41] Chen et al. 2022	Composite MR damping system	Non-linear vibration of the damping system; Experiment	[complete from source]
[43] Van Cuong et al. 2019	Heavy truck	Dynamic load coefficient versus operating conditions; method [complete from source]	[complete from source]
[50] Mihai and Andronic 2014	Quarter-car, semi-active vs passive	Response on an uneven road; MATLAB simulation	[complete from source]
[51] Özcan et al. 2013	Quarter-vehicle, light commercial vehicle	Non-linear suspension characteristics ; optimisation; Model-based optimisation	[complete from source]
[60] Watanabe et al. 2024	Quarter-car	Chaos with jumping non-linearity; delayed-feedback active control; Model-based study	[complete from source]
[65] Le 2017	Semi-trailer truck	Two air suspension systems compared; method [complete from source]	[complete from source]
[70] Sun and Nguyen 2023	Two-, three- and four-axle heavy trucks	Road-surface damage caused by vibration; Multi-body model, D'Alembert's principle	[complete from source]

[73] Litak et al. 2008	Quarter-car	Chaotic vibration under road-profile excitation; Model-based study	[complete from source]
[97] Lin et al. 2020	Semi-active suspension, non-linear hydraulic damper	Surrogate model of the damper; Data-driven (neural network)	[complete from source]
[102] Soleimani and Ahmadi 2014	Truck bed and suspension	Vibration level versus package location; Measurement	[complete from source]

5. Case study: Experimental Nonlinear In Truck Suspension

Experimental investigations on non-linear behaviour in heavy-duty truck suspensions have gained increasing attention due to their substantial impact on ride comfort, road-holding, and durability under varying payloads. A representative study was conducted on a 6×4 heavy-duty commercial truck (≈18–20 tons GVW) equipped with a conventional multi-leaf spring suspension system [43, 98–101].

The test vehicle was instrumented with triaxial accelerometers (±50 g, 0.5–1000 Hz bandwidth) placed at the axle and chassis, and strain gauges mounted on the leaf spring pack to capture bending strain representative of suspension deformation. Data acquisition was performed using a high-speed DAQ system at 1–2 kHz sampling rate, allowing the capture of transient, high-frequency non-linear events such as bump impacts, rebound snap-through, and bushing hysteresis. The truck was tested under controlled and repeatable test conditions, including:

- Sinusoidal road input (0.5–4 Hz, varying amplitudes of 10–40 mm) for low-frequency body motion analysis
- ISO 8608 random road profiles for broadband excitation
- Step-input obstacles (50–100 mm) to induce high-amplitude non-linear stiffness response
- Different payloads (empty, 50% load, and full GVW) to assess load-dependent non-linearities

The experimental campaign was conducted using real measured data from on-vehicle tests, not synthetic or simulated datasets. Computational models were later developed only to validate and interpret the experimental results, using techniques such as piecewise linearization and harmonic balance analysis [33, 41, 60, 73].

Results showed pronounced non-linear stiffness and damping effects, including:

- Hysteresis loops in force–displacement curves due to frictional and geometric non-linearities in leaf springs
- Amplitude-dependent effective stiffness, especially under full load
- Coupled vertical–longitudinal vibrations, which linear quarter-car models typically ignore

These findings confirmed that linear suspension representations systematically underestimate dynamic loads and fail to predict high-frequency peak forces that contribute to structural fatigue. The insights serve as a technical foundation for the development of adaptive and semi-active suspension systems capable of adjusting to non-linear operating behaviour under diverse road and loading conditions [33, 50, 65, 66, 103, 104].

6. Opposite-phase Force Control: Concept, Formulation and Comparison with Active and Semi-Active Suspensions

The control of non-linear vibrations in truck suspension systems is crucial for enhancing ride stability, minimizing structural fatigue, and improving freight transportation efficiency. Excessive vibrations not only accelerate vehicle wear

and tear but also impact cargo integrity, fuel consumption, and driver safety—critical factors influencing operational costs and logistics performance. Opposite-phase force control has been proposed as a way of actively mitigating non-linear vibrations (Fig. 9). As in active noise control, an actuator applies a force in antiphase with the measured body motion so that the two cancel. Because this force is delivered by actuators, the technique is treated here as a control strategy built on the active and semi-active suspensions of Section 3, and it is compared with them in Section 6.5.

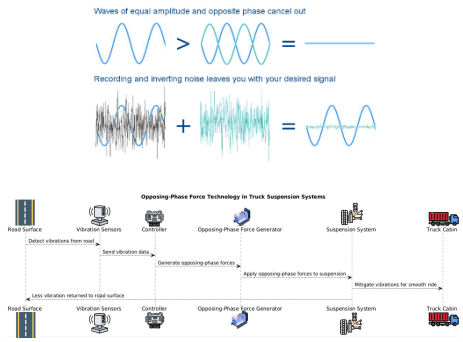


Fig. 9. Using noise-cancelling to create the opposite phase reduces vibrations by cancelling out unwanted ones with counteracting vibrations (a).; Diagram of Non-linear Vibration Reduction in Truck Suspension Systems Using Opposing-phase Forces (b).

6.1 Potential advantages of opposite-phase control

(a) Broad-spectrum vibration control
Opposite-phase control is intended to address a wide range of vibration frequencies and patterns. Unlike traditional passive suspensions, it can respond adaptively to changing road conditions and cargo loads [reference to be added].

(b) Real-time dynamic response
Sensor-based control can detect vibration and command opposing-phase forces with low latency; the achievable response time depends on sensor, controller and actuator dynamics [reference to be added]. Reduced body motion would in turn limit cargo movement, which matters for fragile or high-value goods.

(c) Reported efficiency and cost benefits
Vibration reductions of [40–60]% have been claimed for opposite-phase systems, compared with [20–30]% for passive suspensions [reference and test conditions to be specified]. If confirmed, such reductions would translate into better fuel economy, longer vehicle life and reduced maintenance.

6.2 Formulation for a non-linear quarter-car model

Heavy truck suspensions exhibit complex nonlinear dynamic behavior due to large sprung mass (m_s), unsprung mass (m_u), and road-induced excitations. To improve ride comfort and roadholding, modern approaches use opposite-phase active/semi-active control, such as MR dampers or active actuators, to counteract vibrations in real time. A non-linear quarter-car model with active control can be expressed as:
Sprung mass (body):

$$m_s\ddot{x}_s + c_s(\dot{x}_s - \dot{x}_u) + k_s(x_s - x_u) + k_3(x_s - x_u)^3 = F_{act}. \quad (6.1)$$

Unsprang mass (wheel/tire):

$$m_u\ddot{x}_u + c_s(\dot{x}_u - \dot{x}_s) + k_s(x_u - x_s) + c_t(\dot{x}_u - \dot{x}_r) + k_t(x_u - x_r) = -F_{act}, \quad (6.2)$$

where m_s, m_u are sprung and unsprung mass, k_s, k_3 are linear and cubic suspension stiffness, c_s is suspension damping (linear or nonlinear), k_t, c_t are tire stiffness and damping, x_s, x_u, x_r are body, wheel, and road displacements, F_{act} is active control force (opposite-phase).

An active actuator generates a force F_{act} **in opposite phase** to body acceleration ($\ddot{x}_s$) to **cancel or reduce vibrations**, similar to active noise control. A semi-active damper can only approximate this behaviour,

because it can produce a force only in the direction opposing the relative velocity across the suspension (a dissipative force); an ideal counter-phase force therefore requires an active actuator.

6.3 Effect on ride comfort and road-holding

Ride Comfort: Body acceleration $\ddot{x}_s$ RMS is minimized when F_{act} is accurately opposite-phase, reducing low-frequency oscillations. Nonlinearities (k_3, $c_s(\dot{x})$) affect the effective natural frequency, so active control must adapt to amplitude variations. Roadholding: Tire force: Opposite-phase control must avoid excessive unsprung mass motion to maintain tire contact. Improper tuning of m_u/m_s ratio can degrade roadholding even if ride comfort improves.

6.4 Design considerations for opposite-phase control

Optimize m_s/m_u ratio to ensure actuator force effectively reduces sprung mass vibration without destabilizing unsprung mass. Include nonlinear stiffness k_3 in controller design to maintain phase accuracy over large displacements. Tune damping c_s and active control gains considering actuator dynamics and road frequency spectrum. Use real-time adaptive control (semi-active MR damper or full active actuator) to account for varying payload and road conditions.

6.5 Comparison with passive, semi-active and active suspensions

Table 3 compares opposite-phase control with the suspension types of Section 3. The main distinction is force capability: passive and semi-active suspensions can only dissipate energy, whereas an active actuator can also inject energy, which is what counter-phase cancellation requires. A semi-active damper (for example an MR damper) can approximate opposite-phase control only when the desired force happens to oppose the relative velocity across the damper, so its benefit is limited to those parts of the motion cycle. Opposite-phase control therefore inherits the cost, energy demand and reliability concerns of active systems (Table 1) and adds a requirement for accurate real-time phase estimation in the presence of non-linear stiffness and damping (Section 6.4). Reported reductions differ in metric and test conditions and are therefore listed in Table 2 where available.

Table 3. Comparison of passive, semi-active, active and opposite-phase suspension control for heavy trucks.

System	Principle and force capability	Requirements	Limitations
Passive	Fixed spring and damper; dissipative force only	No external energy; no sensors	Fixed characteristics cannot adapt to road or load
Semi-active	Electronically adjustable damping; dissipative force only	Sensors, ECU and adjustable damper; low power	Cannot inject energy; performance depends on the control law; higher cost and maintenance than passive
Active	Hydraulic or electric actuator generates force independent of road input; can inject energy	Sensors, controller and actuator; high power	High cost and energy use; lower reliability, with passive components acting as fail-safe
Opposite-phase	Actuator force in antiphase with measured body motion (Eqs. 6.1–6.2); ideal form needs an active actuator	As active, plus fast and accurate phase estimation	Sensitive to actuator dynamics, non-linear stiffness and unsprung-mass motion (road-holding); reported reduction [x–y]% [ref.]

6.6 Simulation and outlook

High-fidelity vehicle-dynamics simulation platforms such as IPG CarMaker can be used to evaluate opposite-phase control under realistic road profiles and load

conditions. No simulation results for the configurations discussed in this review are reported here [insert the simulation set-up and results if available; otherwise delete this paragraph].

Outlook. The adoption of opposite-phase force technology may mark a shift toward intelligent suspension systems that improve freight efficiency and sustainability, provided that the reported benefits are confirmed experimentally on heavy trucks. Future research should focus on integrating machine learning, digital twins and energy-harvesting mechanisms, and on validating the approach with high-fidelity simulation tools and full-scale tests.

7. Current Challenges and Future Directions

The development of truck suspension systems is a field grappling with numerous challenges, particularly in managing nonlinear vibrations and ensuring durability under demanding operating conditions. These challenges are compounded by the need for enhanced performance and sustainability [105]. At the same time, the industry is exploring innovative directions to meet future demands, focusing on advanced technologies, materials, and analytical methods.

7.1 Current challenges of truck suspension systems

One of the primary hurdles lies in understanding and managing nonlinear vibrations, which result from the complex interactions between the suspension system, road conditions, and vehicle dynamics. [20, 27, 28, 39]. Nonlinearities such as internal friction in dampers and varying stiffness under different loads make it difficult to predict the suspension system's behavior accurately. [106]. This complexity limits the effectiveness of conventional design methods in addressing the full spectrum of real-world operating conditions such as Fig. 10. Additionally, increased payload demands in modern trucks strain suspension systems, making them more susceptible to damage under harsh conditions. [6, 19, 30], particularly on uneven roads. These payloads exacerbate structural stresses, potentially leading to failures in suspension components.

A critical concern is the need to balance performance and ride comfort. While robust suspension systems are essential for durability, they can sometimes compromise comfort by failing to absorb vibrations effectively. [2, 56, 65, 66, 75, 81]. Unwanted vibrations negatively affect driver and passenger experience, making it challenging to design systems that excel in both performance and comfort

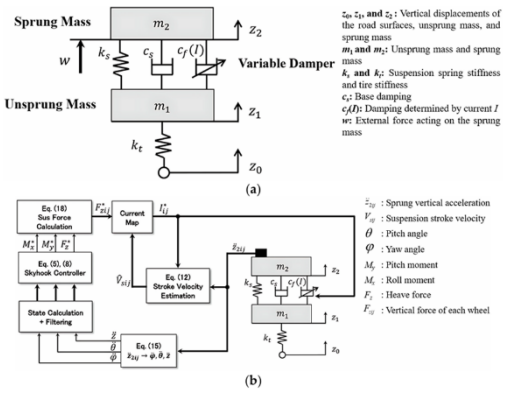


Fig. 10. The proposed enhanced energy-efficient skyhook control [33]: (a) quarter-car model of a semi-active suspension system; (b) block diagram of the control system. Semi-active suspension system.

7.2 Future directions

Advancements in suspension technology are steering toward innovative solutions to address these challenges:

7.2.1 Intelligent vibration damping technologies (Active Suspension Systems)

Active and adaptive suspension systems are poised to transform truck dynamics [72, 94, 97]. These systems leverage sensors and electronic controls to monitor and respond to road-induced

vibrations in real-time. By dynamically adjusting stiffness and damping, they promise smoother rides and reduced wear on vehicle components, enhancing both performance and longevity. [67, 107, 108]. Whereas these systems modulate stiffness or damping, opposite-phase control commands an actuator force in antiphase with the measured body motion; Section 6 compares the two families.

7.2.2 Use of advanced materials

The adoption of advanced materials, such as carbon fiber composites and lightweight alloys, is becoming a critical focus. These materials offer a high strength-to-weight ratio, enabling trucks to handle heavier payloads while minimizing the transmission of vibrations. [35, 74, 99]. Their integration can improve energy efficiency and reduce overall vehicle weight, aligning with sustainability goals.

7.2.3 Digital twin technology

Digital twin models represent a game-changing approach to suspension system design and testing. These virtual replicas allow engineers to simulate and analyse suspension behaviour under various scenarios, predicting potential issues and optimizing designs before physical implementation. [45, 109]. This approach accelerates development cycles, reduces costs, and improves the precision of suspension systems.

7.2.4 Smart materials and energy harvesting

Smart materials with adaptive damping and stiffness properties offer an opportunity for dynamic vibration control, enhancing both suspension durability and cargo protection. Energy-harvesting technologies that convert vibrational energy into usable power could improve fuel efficiency and align with eco-friendly logistics practices [reference to be added].

7.3 Critical analysis and perspectives

The evidence summarised in Tables 2-3 supports three observations. First, non-linear effects—hysteresis, amplitude-dependent stiffness and damping, and load dependence—are established in both models and measurements (Sections 4 and 5), yet most of the tabulated modelling studies rely on quarter-car representations and experimental validation on full heavy-truck configurations appears comparatively scarce. Second, every control approach trades one benefit against another: passive systems are simple and reliable but cannot adapt; semi-active systems adapt at moderate cost but can only dissipate energy; active systems, including opposite-phase control, can inject energy but at the price of higher cost, energy demand and lower reliability (Table 3). Third, ride comfort and road-holding pull in different directions, so a control law that lowers body acceleration must also keep unsprung-mass motion and tyre force within limits (Section 6.3).

Moreover, achieving a balance between mechanical performance and ride comfort should be a top priority for future development. Ride comfort is particularly vital in the transportation industry, where long hours of driving demand systems that reduce driver fatigue while maintaining vehicle stability.

Finally, greater emphasis should be placed on in-depth experimental studies that replicate real-world conditions. While computational and mathematical models are invaluable, experimental validation remains crucial to understanding the nuanced impacts of nonlinear vibrations and ensuring the practical applicability of new designs. Such an approach would facilitate the development of cost-effective and efficient suspension systems that meet the demands of the modern trucking industry.

The reported benefits of opposite-phase control should be treated with caution: the Fig.s cited for it are not yet tied to specific test conditions, its ideal form requires active

actuation, and semi-active implementations can only approximate it. Establishing where it offers a real advantage over skyhook-type semi-active control and conventional active control is therefore the main open question for heavy-truck applications.

8. Discussion

This section interprets the findings of Sections 4 to 7 and their implications for freight logistics; the comparative evidence itself is analysed in Section 7.3.

8.1 Interpretation and implications for logistics

Despite advancements in computational and mathematical modelling, accurately predicting non-linear vibration behaviour remains a challenge due to the inherent complexity of truck dynamics. Finite element methods, harmonic balance techniques, and machine learning-based models have improved the ability to simulate real-world operating conditions. However, discrepancies between theoretical models and experimental results highlight the need for more adaptive and data-driven approaches. The unpredictability of road conditions, coupled with varying load distributions, necessitates more robust predictive frameworks that can integrate real-time data and enhance vibration mitigation strategies.

A key challenge in logistics and transportation efficiency is balancing vehicle durability and ride stability while ensuring minimal disruptions to freight operations. Heavy trucks frequently operate under extreme conditions, including high payloads, uneven road surfaces, and continuous long-haul transport. These factors intensify non-linear vibrations, leading to accelerated wear of suspension components, increased fuel consumption, and higher maintenance costs. Furthermore, excessive vibrations affect cargo integrity, particularly for fragile or high-value goods, resulting in potential financial losses and supply chain inefficiencies.

8.2 Opposite-phase control in context

Opposite-phase control (Section 6) sits at the active end of the range compared in Table 3. Reductions in vibration intensity of 40–60% have been claimed for it, compared with 20–30% for passive suspensions, but the sources and test conditions of these figures are still to be specified [reference required]; until they are, the figures should be regarded as indicative only.

8.3 Limitations of this review

This review has limitations. The search was restricted to four databases and to publications from 2000 to 2024 (Section 2), so relevant work in other sources or later years may be missing. The included studies differ in vehicle class, road input, payload and performance metric, which is why Tables 2 and 3 are comparative summaries rather than pooled estimates. Evidence for opposite-phase control in heavy trucks is limited and appears to be largely of the concept-and-simulation type [confirm], so its benefits should be verified by full-scale tests.

9. Conclusion

This review examined non-linear vibration in heavy-truck suspensions across modelling, experiment and control. Amplitude-dependent stiffness and damping, hysteresis and load dependence mean that linear models can under-predict dynamic loads, as reported in the case study of Section 5, and that model predictions still need experimental validation. The comparative summary in Table 2 shows that quarter-car models are the most frequent model type among the tabulated studies and that full-scale experimental evidence is limited.

Passive, semi-active and active suspensions form a progression in adaptability, cost and energy demand (Table 1). Opposite-phase force control was

examined as an actuator-based strategy belonging to the active end of this range: its ideal form requires an active actuator, semi-active dampers can only approximate it, and the quantitative benefits reported for it are not yet tied to specific test conditions (Table 3). Whether it outperforms skyhook-type semi-active and conventional active control on heavy trucks remains to be demonstrated. The main research gaps are adaptive suspension design for varying payload and road conditions, real-time prediction of non-linear vibration, and intelligent (data-driven and predictive) control validated in full-scale heavy-truck tests. Addressing them, together with digital-twin, smart-material and energy-harvesting technologies, would support more reliable and cost-effective freight transport.

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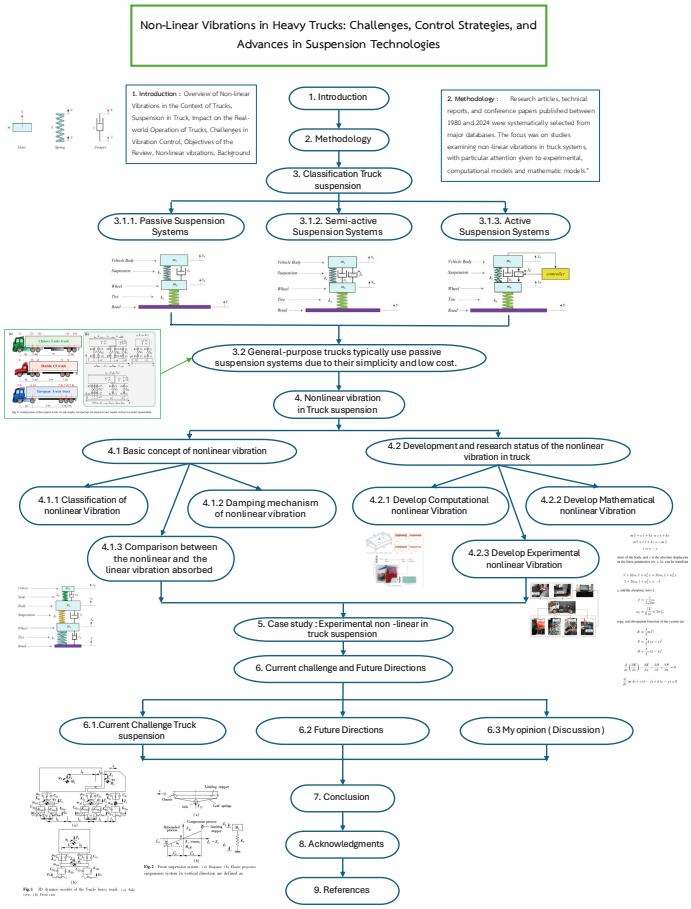


Fig. 11. Systematic Summary of Non-linear Truck Vibration for Simulation Purposes [27, 33, 43, 51, 66, 71].

References

[1] Zhang N, Wu Y, Rong J, Shao J, Chen J, Zhou C. Analysis of truckers' intentions in choosing freeways or parallel national and provincial roads. Research in Transportation Economics. 2023;101.

[2] Abdelkareem MAA, Makrahy MM, Abd-El-Tawwab AM, El-Razaz ASA, Kamal Ahmed Ali M, Moheyeldein MM. An analytical study of the performance indices of articulated truck semi-trailer during three different cases to improve the driver comfort. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics. 2017;232(1):84-102.

[3] Dadsena KK, Sarmah SP, Naikan VNA, Mathiyazhagan K, Rodrigues VS. Performance measurement of road freight transportation: A case of trucking industry. Transport Policy. 2023;137:125-40

[4] Hunt JD, Nascimento A, Tong W, Zakeri B, Jurasz J, Patro ER, et al. Perpetual motion electric truck, transporting cargo with zero fuel costs. Journal of Energy Storage. 2023;72.

[5] Ebrahimi H, Vosoughi S, Hosseini AF, Hatami A. Comprehensive survey of the truck transportation process: The impact of team driving on health and safety conditions. Heliyon. 2024;10(18):e37880.

[6] Shirizadeh B, Ailleret A, Cartry C, Douguet S, Gehring T, Maden S, et al. Climate neutrality in European heavy-duty road transport: How to decarbonise trucks and buses in less than 30 years? Energy Conversion and Management. 2024;309.

[7] Su Z, Liu Y, Fang M, Liu Z, Su M. Couples traveling together and long-haul truckers' transport performance: A theory-based empirical test. Travel Behaviour and Society. 2024;37.

[8] Yang Y, Jia B, Yang Z, Yan X-Y, Zheng S-T, Liu J, et al. Revealing the impacts of COVID-19 pandemic on intercity truck transport: New insights from big data analytics. Transportation Research Part C: Emerging Technologies. 2024;169.

[9] Siripirote T, Sumalee A, Ho HW. Statistical estimation of freight activity analytics from Global Positioning System data of trucks. Transportation Research Part E: Logistics and Transportation Review. 2020;140.

[10] Myers C, Li W, Markham G. The cost of CO2 transport by truck and rail in the United States. International Journal of Greenhouse Gas Control. 2024;134.

[11] Schmidt F, Jacob B, Domprobst F. Investigation of Truck Weights and Dimensions Using WIM Data. Transportation Research Procedia. 2016;14:811-9.

[12] AS, , b SM, , c BB, , et al. Application of noise-cancelling and smoothing techniques in road pavement vibration monitoring data. International Journal of Transportation Science and Technology. 2024.

[13] Choi SB, Choi JH, Lee YS, Han MS. Vibration Control of an ER Seat Suspension for a Commercial Vehicle. Journal of Dynamic Systems, Measurement, and Control. 2003;125(1):60-8.

[14] Balke G, Adenaw L. Heavy commercial vehicles' mobility: Dataset of trucks' anonymized recorded driving and operation (DT-CARGO). Data Brief. 2023;48:109246.

[15] A CS, , b S-qR, , c J-wC, , et al. Integral precession calibration method of PIGA on linear vibration table. Chinese Journal of Aeronautics. 2024.

[16] M.M. Banerjee a, b JM. A review on linear and nonlinear techniques. Procedia Engineering. 2016.

[17] Jiang J, Ke L. Linear and nonlinear vibrations of nonlinearly elastically constrained functionally graded porous microbeams with rough surface. Engineering Structures. 2024;312.

[18] Banerjee MM, Mazumdar J. A Review of Methods for Linear and Nonlinear Vibration Analysis of Plates and Shells. Procedia Engineering. 2016;144:493-503.

[19] Chen E, Zhou Z, Li R, Chang Z, Shi J. The multi-fleet delivery problem combined with trucks, tricycles, and drones for last-mile logistics efficiency requirements under multiple budget constraints. Transportation

Research Part E: Logistics and Transportation Review. 2024;187.

[20] Le Van Quynh ZJ, Liu Xiaobo, Wang Yuan. Nonlinear Dynamic Analysis of Interaction Between Vehicle and Road Surfaces for 5-Axle Heavy Truck. Journal of Southeast University. 2011.

[21] Le Van Quynh VTH, Nguyen Thanh Cong. Influence of Tire Parameters of a Semi-trailer Truck on Road Surface. International Research Journal of Engineering and Technology (IRJET) 2019.

[22] Farbod Alijani, Amabili M. Non-linear vibrations of shells A literature review from 2003 to 2013. International Journal of Non-Linear Mechanics. 2014.

[23] Bovsunovsky A, Surace C. Non-linearities in the vibrations of elastic structures with a closing crack: A state of the art review. Mechanical Systems and Signal Processing. 2015;62-63:129-48.

[24] Jones CA, Reynolds P, Pavic A. Vibration serviceability of stadia structures subjected to dynamic crowd loads: A literature review. Journal of Sound and Vibration. 2011;330(8):1531-66.

[25] Shandhana Rashmi B, Marisamynathan S. Factors affecting truck driver behavior on a road safety context: A critical systematic review of the evidence. Journal of Traffic and Transportation Engineering (English Edition). 2023;10(5):835-65.

[26] Uzny S, Kutrowski Ł, Skrzypczak T. Non-linear free vibrations of the column loaded with a mass element and a local heat source. Journal of Sound and Vibration. 2021;507.

[27] Marzbani RNJH. Vehicle Vibrations_ Linear and Nonlinear Analysis: Springer; 2023.

[28] Wang S, Hua L, Yang C, Zhang Yo, Tan X. Nonlinear vibrations of a piecewise-linear quarter-car truck model by incremental harmonic balance method. Nonlinear Dynamics. 2018;92(4):1719-32.

[29] Zhang Z, Oberst S, Lai JCS. A non-linear friction work formulation for the analysis of self-excited vibrations. Journal of Sound and Vibration. 2019;443:328-40.

[30] Rao SS. Mechanical_vibrations_5th-edition 2010.

[31] Mardani HTA. Off-road Vehicle Dynamics_ Analysis, Modelling and Decision and Control2017.

[32] Masri J, Amer M, Salman S, Ismail M, Elsisi M. A survey of modern vehicle noise, vibration, and harshness: A state-of-the-art. Ain Shams Engineering Journal. 2024;15(10).

[33] Wang Z, Liu C, Zheng X, Zhao L, Qiu Y. Advancements in Semi-Active Automotive Suspension Systems with Magnetorheological Dampers: A Review. Applied Sciences. 2024;14(17).

[34] Fabra-Rodriguez M, Abellán-López D, Simón-Portillo FJ, Campello-Vicente H, Campillo-Davo N, Peral-Orts R. Numerical model for vibro-acoustics analysis of tyre-road noise generation caused by speed bumps. Applied Acoustics. 2024;216.

[35] He C, Jiang W, Wang T, Yuan D, Sha A. The evolution of tire-road wear particles and road surface texture under rolling friction. Construction and Building Materials. 2024;447.

[36] Huang P, Yao Y, Xiu W, Wu J, Geng D, Yang Z, et al. Vibration modelling and testing of off-road vehicle incorporating coupled roll and pitch vibrations. Biosystems Engineering. 2024;240:111-22.

[37] T.E. Putra H, M. Ikbal. Automotive suspension component behaviors driven on flat and rough. Heliyon. 2021.

[38] Qu J, Shi W, Wang J, Chen Z. Modeling and Analysis of Clutch Nonlinear Behavior in an Automotive Driveline for Suppressing Torsional Vibration. Machines. 2022;10(9).

[39] Yang F, Zhao L, Yu Y, Zhou C, Forte P. Matching, Stability, and Vibration Analysis of Nonlinear Suspension System for Truck Cabs. Shock and Vibration. 2019;2019(1).

[40] Zhang Z, Niu M, Yuan K, Zhang Y. Research on linear/nonlinear viscous damping and hysteretic damping in nonlinear vibration isolation systems. Applied Mathematics and Mechanics. 2020;41(7):983-98.

[41] Chen B, She N, Lin D, Yan X, Peng X. Experimental study on the nonlinear vibration of a new composite magnetorheological damping system. Mechanical Systems and Signal Processing. 2022;181.

[42] Jazar RN, Marzbani H. Vehicle vibrations: linear and nonlinear analysis, optimization, and design: Springer International Publishing AG; 2024.

[43] Van Cuong B, Van Quynh L, Long LX. Influence of Heavy Truck Operating Condition on Dynamic Load Coefficient. Advances in Engineering Research and Application. Lecture Notes in Networks and Systems2019. p. 372-9.

[44] Jazar RN. Advanced-vehicle-dynamics_compress.2019.

[45] Schramm D, Hiller M, Bardini R. Vehicle Dynamics _ Modeling and Simulation 2018 2018.

[46] Abdelkareem MAA, Xu L, Ali MKA, Elagouz A, Mi J, Guo S, et al. Vibration energy harvesting in automotive suspension system: A detailed review. Applied Energy. 2018;229:672-99.

[47] Lu Z, Wang Z, Zhou Y, Lu X. Nonlinear dissipative devices in structural vibration control: A review. Journal of Sound and Vibration. 2018;423:18-49.

[48] Yang J, Rajasekar S, Sanjuán MAF. Vibrational resonance: A review. Physics Reports. 2024;1067:1-62.

[49] Akter T, Hernandez S. Truck industry classification from anonymous mobile sensor data using machine learning. International Journal of Transportation Science and Technology. 2022;11(3):522-35.

[50] Mihai I, Andronic F. Behavior of a semi-active suspension system versus a passive suspension system on an uneven road surface. Mechanics. 2014;20(1).

[51] Özcan D, Sönmez Ü, Güvenç L. Optimisation of the Nonlinear Suspension Characteristics of a Light Commercial Vehicle. International Journal of Vehicular Technology. 2013;2013:1-16.

[52] Zareh SH, Khayyat AAA. Fuzzy Inverse Model of Magnetorheological Dampers for Semi-Active Vibration Control of an Eleven-Degrees of Freedom Suspension System. Journal of System Design and Dynamics. 2011;5(7):1485-97.

[53] Nguyen SD, Nguyen QH, Choi S-B. Hybrid clustering based fuzzy structure for vibration control – Part 1: A novel algorithm for building neuro-fuzzy system. Mechanical Systems and Signal Processing. 2015;50-51:510-25.

[54] Nguyen SD, Nguyen QH, Choi S-B. A hybrid clustering based fuzzy structure for vibration control – Part 2: An application to semi-active vehicle seat-suspension system. Mechanical Systems and Signal Processing. 2015;56-57:288-301.

[55] Sim K, Lee H, Yoon JW, Choi C, Hwang S-H. Effectiveness evaluation of hydro-pneumatic and semi-active cab suspension for the improvement of ride comfort of agricultural tractors. Journal of Terramechanics. 2017;69:23-32.

[56] Nguyen VL, Le VQ. Ride comfort performance of heavy truck with three control cases of semi-active isolation systems. Vibroengineering Procedia. 2019;22:93-8.

[57] Jazar R. Vehicle Dynamics: Theory and Application2008. p. 1-1015.

[58] Guo X, Wang J, Sun W. Nonlinear adaptive fault-tolerant control for full-car active suspension with velocity measurement errors and full-state constraints. Journal of the Franklin Institute. 2024;361(10).

[59] Jia T, Pan Y, Liang H, Lam H-K. Event-Based Adaptive Fixed-Time Fuzzy Control for Active Vehicle Suspension Systems With Time-Varying Displacement Constraint. IEEE Transactions on Fuzzy Systems. 2022;30(8):2813-21.

[60] Watanabe M, Prasad A, Sakai K. Delayed feedback active suspension control for chaos in

quarter car model with jumping nonlinearity. Chaos, Solitons & Fractals. 2024;186.

[61] Manna S, Mani G, Ghildiyal S, Stonier AA, Peter G, Ganji V, et al. Ant Colony Optimization Tuned Closed-Loop Optimal Control Intended for Vehicle Active Suspension System. IEEE Access. 2022;10:53735-45.

[62] González A, Obrien EJ, Cantero D, Li Y, Dowling J, Žnidarič A. Critical speed for the dynamics of truck events on bridges with a smooth road surface. Journal of Sound and Vibration. 2010;329(11):2127-46.

[63] Farshi B, Assadi A. Development of a chaotic nonlinear tuned mass damper for optimal vibration response. Communications in Nonlinear Science and Numerical Simulation. 2011;16(11):4514-23.

[64] Xing W, Tuo W, Li X, Wang T, Yang C. Micro-vibration suppression and compensation techniques for in-orbit satellite: A review. Chinese Journal of Aeronautics. 2024;37(9):1-19.

[65] Le VQ. Comparing the performance of suspension system of semi-trailer truck with two air suspension systems. Vibroengineering Procedia. 2017;14:220-6.

[66] Van Quynh L, Van Cuong B, Long LX, Van Quan D. Effects of Suspension Design Parameters of a Semi-trailer Truck on Vehicle Ride Comfort and Road Surface Friendliness. Advances in Engineering Research and Application. Lecture Notes in Networks and Systems2020. p. 281-9.

[67] A TL, , a RC, , b LDa, , et al. Dynamic Impact of Automated Truck Platooning on Highway Bridges. Engineering Structures. 2022.

[68] Zheng Y, Zhang X, Luo Y, Yan B, Ma C. Design and experiment of a high-static–low-dynamic stiffness isolator using a negative stiffness magnetic spring. Journal of Sound and Vibration. 2016;360:31-52.

[69] Zhang R, Zhao L, Qiu X, Zhang H, Wang X. A comprehensive comparison of the vehicle vibration energy harvesting abilities of the regenerative shock absorbers predicted by the quarter, half and full vehicle suspension system models. Applied Energy. 2020;272.

[70] Sun M, Nguyen V. Vibration influence of different types of heavy-duty trucks on road surface damage Extrica. 2023.

[71] Song H, Dong M, Gu L. Research on Efficient Suspension Vibration Reduction Configuration for Effectively Reducing Energy Consumption. Sustainability. 2024;16(10).

[72] Bhanot N. Artificial Neural Networks based Modeling and Analysis of Semi-Active Damper System. 2017.

[73] Litak G, Borowiec M, Friswell MI, Szabelski K. Chaotic vibration of a quarter-car model excited by the road surface profile. Communications in Nonlinear Science and Numerical Simulation. 2008;13(7):1373-83.

[74] Zarei Z, Sadeghi J, Sarkar A. Evaluation of heavy-vehicle-induced vibrations running on asphalt pavements. Construction and Building Materials. 2022;358.

[75] Le Xuan Long TTH, Le Van Quynn, Bui Van Cuong. Performance analysis of the hydro-pneumatic suspension system of heavy truck. International Journal of Mechanical Engineering and Technology (IJMET) 2018.

[76] Wang P, Chen J. Nonlinear rotational inertial double-tuned mass damper for reducing human-induced floor vibration with frequency detuning. Mechanical Systems and Signal Processing. 2022;172.

[77] Georgiou G, Foutsitzi GA, Stavroulakis GE. Nonlinear discrete-time multirate adaptive control of non-linear vibrations of smart beams. Journal of Sound and Vibration. 2018;423:484-519.

[78] Litak MBaG. Transition to Chaos and Escape Phenomenon in Two-Degrees-of-Freedom Oscillator with a Kinematic Excitation. Nonlinear Dynamics 2012.

[79] Zhong S, Chen Y-s. Bifurcation of piecewise-linear nonlinear vibration system of vehicle suspension. Applied Mathematics and Mechanics. 2009;30(6):677-84.

[80] Hajdu F, Szalai P, Mika P, Kuti R. Parameter Identification of A Fire Truck Suspension for Vibration Analysis. Pollack Periodica. 2018.

[81] Deubel C, Ernst S, Prokop G. Objective evaluation methods of vehicle ride comfort—A literature review. Journal of Sound and Vibration. 2023;548.

[82] Shihua Zhou GS, Mengnan Sun, Zhaohui Ren. Nonlinear Dynamic Analysis of a Quarter Vehicle System with External Periodic Excitation. International Journal of Non-Linar Mechanics. 2016.

[83] Liao P. Non-linear vibration and bifurcation analysis of Euler-Bernoulli beam under parametric excitation. Journal of Engineering and Applied Science. 2024;71(1).

[84] Li S, Yang S, Guo W. Investigation on chaotic motion in hysteretic non-linear suspension system with multi-frequency excitations. Mechanics Research Communications. 2004;31(2):229-36.

[85] B ZKa, , a J-JS, , a SB, , et al. An adapted two-step approach to simulate nonlinear vibrations of patterned tires rolling on a smooth surface. Appiled Mathematical Modeling. 2024.

[86] A AEM, , b AJ, , av KA. Optimization of linear multiple-tuned mass damper to control nonlinear. Structures. 2024.

[87] Chengling Lu a c, ZYa, XSb, QDa. Vibration compensation control strategy of composite cage rotor bearingless induction motor based on fuzzy coefficient adaptive-linear-neuron method. ISA Transactions. 2024.

[88] Matania O, Dattner I, Bortman J, Kenett RS, Parmet Y. A systematic literature review of deep learning for vibration-based fault diagnosis of critical rotating machinery: Limitations and challenges. Journal of Sound and Vibration. 2024;590.

[89] Aierken T, Li S, Tingqian MA. Multi-objective optimization study of LNG tank truck baffles under the most hazardous transport condition based on a combined approximate model. Ocean Engineering. 2024;314.

[90] Cheng X, Lin J. Is electric truck a viable alternative to diesel truck in long-haul operation. Transportation Research Part D: Transport and Environment. 2024;129.

[91] Gorantiwar A, Nalawade R, Nouri A, Taheri S. Experimental Analysis of a Novel Double Damper System with Semi-Active Control. Electronics. 2020;9(9).

[92] G.Litk MB, M.Ali,L.M. Saha,M.I. Friswell. Pulsive Feedback Control of a Quarter Car Model Forced by a Road Profile. Chaos, Solitons & Fractals. 2007.

[93] Jihai Gu HW, Chengwen Wang, Ming Pang, and Xiangyang Jin editor The Parameter Optimization and Performance Analysis of the Suspension System in the Cab of a Heavy Truck. IFIP International Federation for Information Processing; 2014.

[94] Ali D, Frimpong S. Artificial intelligence models for predicting the performance of hydro-pneumatic suspension struts in large capacity dump trucks. International Journal of Industrial Ergonomics. 2018;67:283-95.

[95] Mohammadi N. Airborne and Structure-Borne Noise Control in the MB Truck Cabin Interior by the Noise Reduction in the Transmission Path. Archives of Acoustics. 2023.

[96] Zhang B, Zhao Z, Li Y, Zhang X, Li X, Hao D, et al. Design and analysis of a piezoelectric energy harvesting shock absorber for light truck applications. Applied Energy. 2025;377.

[97] Lin J, Li H, Huang Y, Huang Z, Luo Z. Adaptive Artificial Neural Network Surrogate Model of Nonlinear Hydraulic Adjustable Damper for Automotive Semi-Active Suspension System. IEEE Access. 2020;8:118673-86.

[98] Van Quynh L. Influence of semi-trailer truck operating conditions on road surface friendliness. Vibroengineering Procedia. 2017;16:67-72.

[99] Van Van L, Thanh Tung N. Influence of road quality and suspension stiffness on passenger vehicles oscillation in Viet Nam. Materials Today: Proceedings. 2023.

[100] Widyotriatmo A, Nazaruddin YY, Putranto MRF, Ardhi R. Forward and backward motions path following controls of a truck-trailer with references on the head-truck and on the trailer. ISA Trans. 2020;105:349-66.

[101] Gnapa J, Setteya T, Baloghová L, editors. Examination of the development of the number and use of trucks up to 3.5 tons total weight. 14th International Scientific Conference on Sustainable, modern and safe transport; 2021.

[102] Soleimani B, Ahmadi E. Measurement and analysis of truck vibration levels as a function of packages locations in truck bed and suspension. Computers and Electronics in Agriculture. 2014;109:141-7.

[103] b GFa, , a SL, , a SY. Coupling vibration analysis of hub motor driving electric vehicle and. Applied Mathematical Modelling. 2025.

[104] Zhou H, Wu X, Wang P. Control of the air suspension system of semi-trailer trucks to enhance the road friendliness. Vibroengineering Procedia. 2020;35:13-9.

[105] Silveira M, Wahi P, Fernandes JCM. Effects of asymmetrical damping on a 2 DOF quarter-car model under harmonic excitation. Communications in Nonlinear Science and Numerical Simulation. 2017;43:14-24.

[106] Hamedi B, Shrikanthan S, Taheri S. The Reduced-Order Modeling Approach for a Double-Damper Concept: A Comparison with a Single Damper for Comfort Analysis. Vibration. 2024;7(3):644-61.

[107] Dindarloo SR. Dynamic impact of ageing dump truck suspension systems on whole-b. Doctoral Dissertations. 2016.

[108] AOUAD SFaN. Dump Truck Vibrations in High Impact Shovel Loading. 2014.

[109] Ali D, Frimpong S. Virtual Prototype Simulation for Vibration Analysis with Optimum Dumping Characterization under High Impact Shovel Loading Conditions. International Journal of Mining Science. 2019;5(3).