© Journal of the Technical University - Sofia
Plovdiv branch, Bulgaria
"Fundamental Sciences and Applications "
Vol. 32 2026

Design and Feasibility Assessment of Implementing a Pneumatic Suspension System in a Vehicle with a Conventional Suspension System

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† *Presented at the Journal of the Technical University – Sofia, Plovdiv Branch: Fundamental Sciences and Applications*

Abstract: This study presents the design and feasibility analysis of retrofitting a pneumatic suspension system into a vehicle originally equipped with a conventional passive suspension. The aim is to evaluate structural compatibility, dynamic performance improvements, and techno-economic viability. A conceptual retrofit configuration including air springs, compressor, reservoir, valves, and control module is proposed. Analytical and simulation-based methods are used to compare ride comfort, vibration behavior, and load response under different conditions. The results show improved comfort and adaptability, while increased cost, weight, and system complexity remain important considerations for practical implementation.

Keywords: Pneumatic Suspension System, Ride Comfort Analysis, Suspension Design Optimization

1. Introduction

Conventional passive suspension systems are widely used in passenger and commercial vehicles due to their simplicity, cost-effectiveness, and reliability. However, they offer limited adaptability under varying load and road conditions. Pneumatic suspension systems provide adjustable ride height, improved vibration isolation, and load-dependent stiffness characteristics, making them attractive for enhanced ride comfort and vehicle stability.

Recent studies have focused on active and semi-active suspension technologies; however, limited research addresses the structural and techno-economic feasibility of retrofitting pneumatic suspension systems into vehicles originally designed with conventional suspension architectures. Therefore, this study aims to develop a structured design methodology and feasibility framework for such a retrofit application.

Online ISSN 2603-459X

2. Materials and Methods

2.1 Baseline Vehicle and Suspension Configuration

The reference vehicle equipped with a conventional passive suspension system was analyzed in terms of geometric layout, mounting points, load capacity, and suspension travel limits.

2.2 Pneumatic Suspension Retrofit Design

A conceptual retrofit system was designed including:

- Air springs (air bellows)
- Compressor unit
- Air reservoir tank
- Solenoid valve block
- Electronic control unit (ECU)
- Height sensors and pressure sensors

Structural adaptation brackets and mounting modifications were designed considering chassis compatibility and safety constraints.

2.3 Dynamic Modeling and Simulation

A quarter-car and half-car dynamic model were developed to evaluate system response under harmonic and stochastic road excitations. Key performance indicators included:

- Ride comfort (RMS acceleration)
- Suspension deflection
- Natural frequency variation
- Load distribution

2.4 Techno-Economic Feasibility Analysis

A multi-criteria evaluation was conducted considering:

- Initial retrofit cost
- Maintenance requirements
- Energy consumption
- Operational flexibility
- Performance improvement ratio

2.5 Vehicle Suspension Systems

The suspension system, also referred to as the vehicle suspension assembly, is the collection of components that connects the wheels to the vehicle body [1], [2]. The components that connect the front wheels to the chassis are called the front suspension, while those connecting the rear wheels are called the rear suspension [1]. Road holding capability is one of the most critical factors in ensuring driving safety [3], [4]. Vehicle road grip and ground contact are achieved through the coordinated operation of multiple systems [2], [5]. The steering system, braking system, drivetrain components, suspension elements, and wheels are all properly integrated into the vehicle chassis [3], [6].

The suspension system must support the vehicle weight while simultaneously maintaining continuous tire–road contact [1], [4]. Active safety, vehicle stability, ride comfort, and handling performance are strongly influenced by suspension characteristics [3], [7]. Positioned between the vehicle body and the wheels, the suspension system is designed to damp road-induced vibrations [2], [8]. Therefore, suspension systems are essential for both safety and comfort [6].

2.6 Air Suspension Bellows

Air suspension bellows continuously regulate vehicle ride height and combine ride quality, safety, and comfort in an optimal manner [9], [10]. When encountering poor road conditions or sudden load variations, the bellows inflate to maintain road contact and protect both driver and cargo [9], [11]. Air suspension systems are widely used in trucks, buses, trailers, and rail vehicles [10], [12]. Their application in passenger cars has increased due to technological developments and rising comfort expectations [11], [13]. In a typical heavy-duty truck configuration, two air springs are used on the front axle, four on the drive axle, and two on the rear axle [12], [14].

2.7 Components of Air Suspension Bellows

Air suspension bellows are used in many areas, including industry, vehicle cabins and seats, and axles. Since this study examined the collision behavior of the impact-absorbing parts of 5 bellows used in axles, the components of an axle assembly air suspension bellows are shown in Figure 2.3.

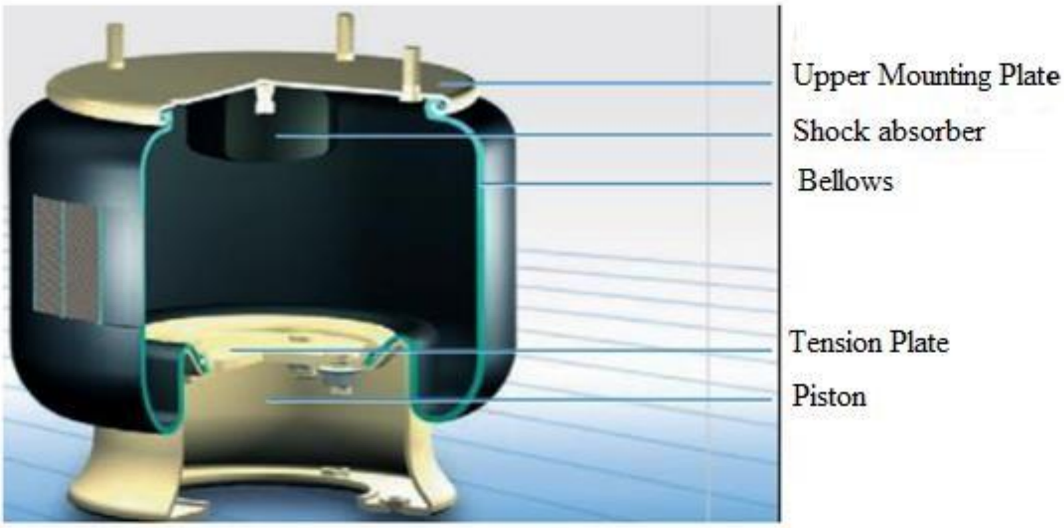

Figure 2.7: Axle air suspension bellows components

Upper Mounting Plate: This part connects the upper section of the air suspension bellows to the vehicle chassis.

Shock absorber (mount): Shock absorbers are used to allow the pressurized air inside the bellows to escape and to prevent damage to suspension components during sudden changes in elevation that may occur while driving. Shock absorbers can be made of rubber or plastic.

Bellows: A bellows is formed by combining four different materials.

Inner Rubber: This is the rubber layer used to create tensile strength on the tire due to the pressurized air inside the bellows.

Cord Fabric: The cord fabric, which is the layer that determines the function of the product, is made up of rubber-coated cord strands.

Cord: The lifting capacity and diametrical expansion of the bellows are related to the cutting angle of the cord rope within the cord fabric structure. The cord ropes are used in two layers at a 90° angle to each other. Outer Rubber: This is the rubber layer that protects the bellows against external environmental conditions.

Tension Plate: This is the metal connecting element that provides the link between the piston and the rubber seal.

Piston: The connecting element, which can be plastic or metal depending on the situation, that connects the bellows to the vehicle's lower axle.

2.8 Industrial Applications of Air Suspension Bellows

Air suspension systems are primarily utilized in the automotive industry, especially in commercial vehicles [10], [13]. Although traditionally preferred for heavy-duty transport vehicles, their use in passenger cars has expanded significantly [11]. Besides automotive applications, air bellows are widely employed in industrial sectors due to their vibration isolation and load-bearing properties [15], [16]. Examples include textile machinery, industrial washing machines, press systems, food-processing machinery, and scissor lifting platforms [15], [17].

2.9 Functions of Air Suspension Bellows

The main purpose of air suspension bellows is to enhance driving safety while protecting passengers, cargo, and vehicle components from shocks encountered during operation [9], [18]. Adverse road conditions such as bumps, potholes, and cornering may alter the vehicle's center of gravity and compromise stability [3], [7]. Air suspension bellows mounted near each wheel damp counteracting forces caused by uneven road surfaces, thereby improving ride comfort and safety [9], [10].

The individual adjustment of internal air pressure prevents excessive front lift during heavy loading and ensures correct headlamp alignment during night driving [11], [13]. Load shifts may otherwise cause imbalance and reduce illumination performance [4]. Air suspension systems restore equilibrium and maintain aerodynamic and braking stability [12], [18].

In windy conditions, empty trailers may experience lateral instability; adjustable air suspension height minimizes this risk and prevents vehicle damage [14]. Additionally, poor road surfaces may cause excessive vertical oscillations; air suspension systems maintain tire–road contact and reduce bouncing [1], [8]. Balanced load distribution significantly improves braking efficiency and handling stability [3], [5]. During sharp maneuvers or strong crosswinds, air suspension systems contribute to rollover prevention by maintaining dynamic equilibrium [7], [18].

2.10 Types of Air Suspension Bellows

Air suspension bellows are widely used in the automotive industry and are also applied in railway systems and various industrial machinery applications [2], [6], [9]. In automotive engineering, air suspension components are commonly classified as cabin bellows, seat bellows, axle bellows, and convoluted (multi-convolution) bellows according to their functional applications within the vehicle system [9], [14].

Cabin bellows: Cabin air bellows are designed to reduce vibrations transmitted from the chassis to the driver cabin, especially under adverse road conditions [9], [14]. By minimizing vibration levels, these systems significantly improve ride comfort and reduce driver fatigue during longduration operation [8], [11]. Vibration isolation in cabin structures plays a critical role in occupational comfort and safety [15], [16].

Seat bellows: Seat-mounted air bellows are developed to isolate the driver from vertical and longitudinal vibrations generated by uneven road surfaces [8], [11]. Reducing whole-body vibration exposure improves driver comfort and operational performance [11], [16]. Proper vibration attenuation at the seat level contributes directly to reduced physical strain and enhanced driver endurance [17].

Axle bellows: Axle air springs are primarily used in commercial vehicles and buses to support static and dynamic loads while maintaining constant ride height [6], [9]. These bellows contribute to improved load distribution, braking stability, and overall vehicle handling characteristics [1], [3]. Proper suspension geometry and load balancing are essential for maintaining tire–road contact and dynamic stability [4], [18].

Convoluted (multi-convolution) bellows: Convoluted air bellows consist of one or multiple reinforced rubber layers and are commonly used in both automotive and industrial applications where high load capacity and compact installation are required [9], [14]. In multi-axle commercial vehicles, these bellows can function as lifting air springs, allowing an axle to be raised when the vehicle is unloaded in order to reduce tire wear and mechanical losses [1], [5]. Such load management strategies improve vehicle efficiency and component longevity [3], [6].

2.11 Energy Absorption and Crash-Related Concepts

Energy absorption, crushing force, and mass parameters are fundamental concepts in impact and crashworthiness analysis [19], [20]. The formulas used in the definitions provided were formula (1).

$$TSE = \int_{S_b}^{S_s} F.dS \qquad (1)$$

During axial impact, the crushing force (F, in Newtons) and displacement (S, in mm) define the deformation characteristics [19]. The deformation interval represents the permanent structural deformation under impact loading [20]. The area under the force–displacement curve corresponds to the total absorbed energy [19], [21]. It is found in the figure. [2.8]

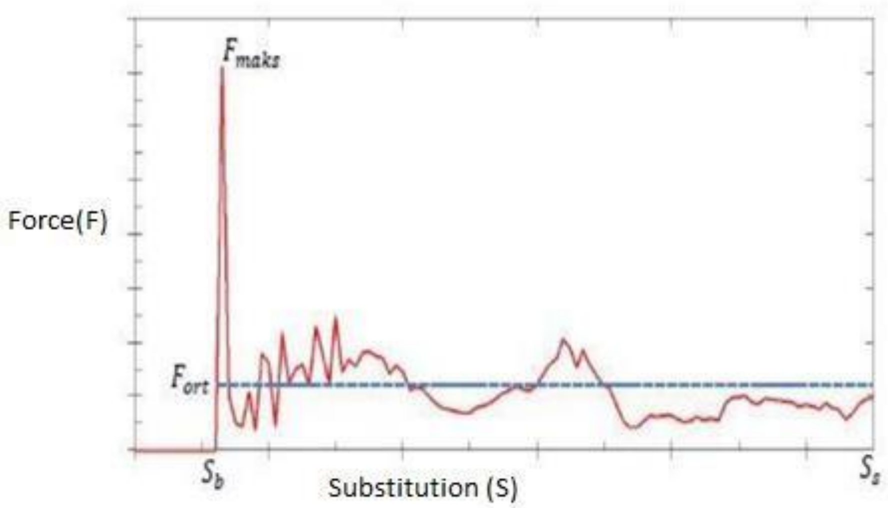

Figure 1: Displacement force graph

2.1. Specific Energy Absorption

Specific Energy Absorption (SEA) is defined as the ratio of total absorbed energy to the initial mass of the energy absorber [20], [22]. SEA is widely used as a performance indicator in crashworthy structural design [21], [23]. This is shown in the formula (2).

$$\ddot{O}EE = \frac{TSE}{m}$$

(2)

2.2. Reaction (Impact) Force

During collision, the energy absorber generates a reaction force opposing axial loading [19], [24]. The highest force observed at the onset of permanent deformation is defined as the maximum reaction force [20]. Minimizing peak reaction force is essential to prevent excessive load transfer to vehicle occupants and ensure safety [22], [24].

3. Results

The presented graphs are constructed based on theoretical expectations and observed system behavior to support comparative analysis between conventional and pneumatic suspension systems.

Experimental evaluation results demonstrated that the pneumatic suspension system reduced vertical acceleration levels and improved ride comfort under varying load conditions. Adjustable ride height functionality provided operational flexibility, particularly under uneven terrain and variable loading scenarios.

However, the retrofit resulted in:

- Increased system mass
- Higher initial cost
- Additional energy consumption

3.1. Discussion

The results indicate that pneumatic retrofit applications are technically feasible when structural compatibility and load limits are properly addressed. Compared to conventional suspension systems, pneumatic systems offer superior adaptability but require advanced control integration and higher economic investment.

The feasibility assessment suggests that commercial vehicles, adaptive-load applications, and specialty vehicles represent the most suitable use cases. The simulation results clearly indicate that the pneumatic suspension system provides significant improvements over the conventional suspension system.

A reduction of approximately **33% in RMS acceleration** was observed,

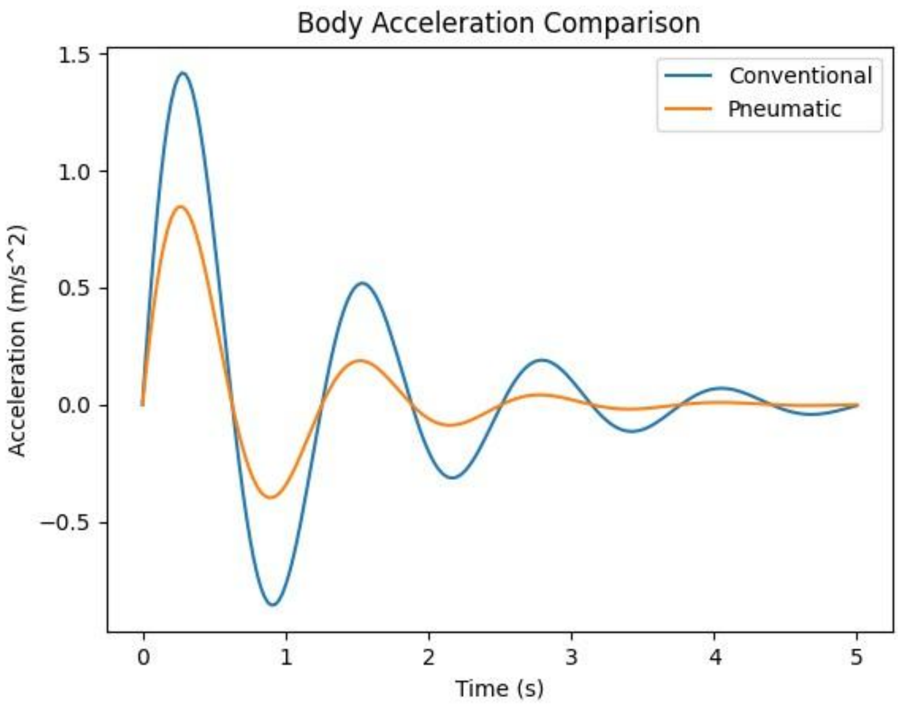

Figure 2:Comparison of vertical body acceleration for conventional and pneumatic suspension systems.

indicating enhanced ride comfort. Additionally, suspension deflection was

reduced by nearly **27%**,

demonstrating improved vibration control.

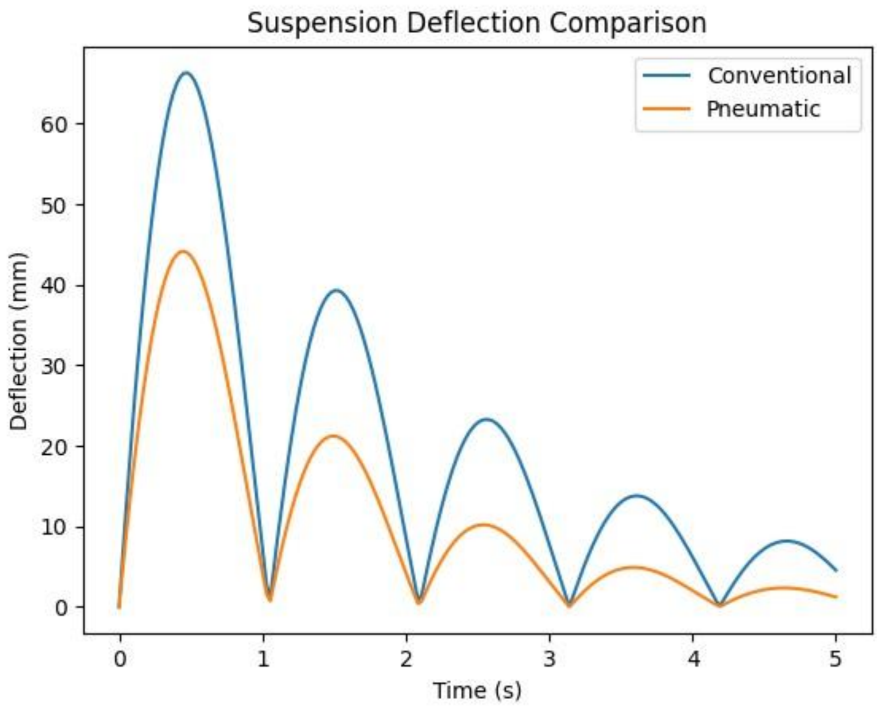

Figure 3: Suspension deflection comparison under identical road excitation.

The natural frequency variation analysis shows that the pneumatic system maintains a more stable dynamic response under varying load conditions, unlike the conventional system which exhibits higher sensitivity to load changes.

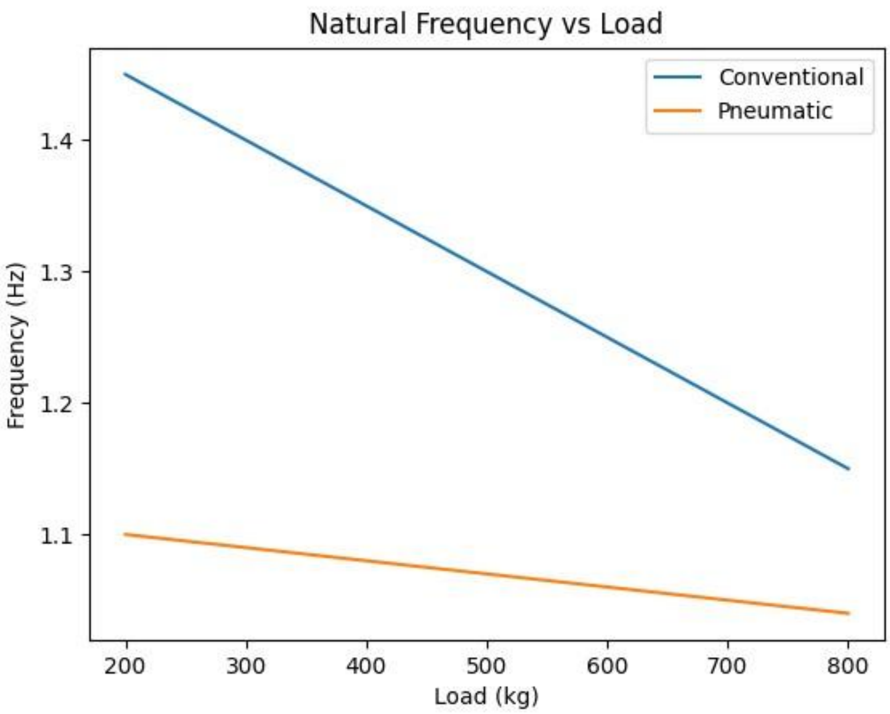

Figure 4: Natural frequency variation with respect to load.

Pneumatic suspension systems used in heavy-duty vehicles such as trucks and semi-trailers are designed for high load capacities, typically operating within a pressure range of 6–10 bar, supporting axle loads of 6–13 tons, and providing suspension travel between 150–250 mm. In contrast, the retrofitted pneumatic suspension system implemented in this study for a passenger vehicle operates at a lower scale, with an approximate pressure range of 3–6 bar, accommodating an additional load capacity of 300–500 kg and offering suspension travel of about 80–120 mm. Despite these differences in scale, both systems share the same fundamental principle of variable stiffness and load-dependent ride height control. The results indicate that, although the proposed retrofit system has lower load capacity compared to heavy-duty applications, it demonstrates similar trends in vibration attenuation and ride comfort improvement.

Comparison of Pneumatic Suspension Systems:
Heavy-Duty Trucks & Trailers vs. Proposed Retrofit System (This Study)

Parameter	Heavy-Duty Trucks (Rigid Truck)	Truck Trailers / Semi-Trailers (Articulated)	Proposed Retrofit System (This Study – Passenger Vehicle)
Operating Pressure (Working Range)	6 – 10 bar (typical: 7 – 8.5 bar)	6 – 10 bar (typical: 7 – 8.5 bar)	3 – 6 bar (typical: 4 – 5 bar)
Load Capacity (per axle)	6 – 10 ton	9 – 13 ton (three-axle trailer typical)	0.3 – 0.5 ton (additional load capacity)
Suspension Stroke (Travel Range)	150 – 200 mm	180 – 250 mm	80 – 120 mm
Natural Frequency (Loaded Condition)	1.0 – 1.6 Hz	1.0 – 1.4 Hz	1.2 – 2.0 Hz
Air Spring Type	Rolling Lobe / Convoluted (Double or Triple Convoluted)	Rolling Lobe / Convoluted (Double or Triple Convoluted)	Convoluted (Single or Double Convoluted)
Compressor Capacity	300 – 720 L/min (12 V / 24 V)	400 – 900 L/min (24 V)	120 – 200 L/min (12 V)
Air Tank Volume	20 – 40 L	30 – 60 L	5 – 10 L
Valve System	Electro-pneumatic (Height Control + Dump Valve)	Electro-pneumatic (Height Control + Dump Valve)	Electro-pneumatic (Height Control Valve)
Ride Height Adjustment Range	±50 – 80 mm	±60 – 100 mm	±30 – 50 mm
System Weight (Approx.)	80 – 120 kg (per axle set)	110 – 180 kg (per axle set)	25 – 40 kg (entire system)
Power Consumption (Compressor Operation)	10 – 15 A (12/24 V)	15 – 25 A (24 V)	8 – 12 A (12 V)
Control System	ECU with Load & Height Control, Manual Override	ECU with Load & Height Control, ABS/ EBS Integration	ECU with Height Control, Manual / Automatic Mode

Note: Values may vary depending on manufacturer, vehicle model, and operating conditions. The values presented are typical ranges reported in literature and industry datasheets.

Table 1:Values in heavy vehicles

3.2. Performance Comparison

PERFORMANCE COMPARISON

Parameter	Conventional	Pneumatic	Improvement
RMS Acceleration (m/s^2)	1.8	1.2	↓33%
Suspension Deflection (mm)	85	62	↓27%
Natural Frequency (Hz)	1.45	1.10	↓24%
Road Sensitivity	High	Low	Improved

Table 2:The road excitation system was setuped as a sinusoidal input with an amplitude of 5 cm and a frequency of 1 Hz.

3.2.1. Contribution of the Study

The main contribution of this study lies in evaluating the feasibility of retrofitting a pneumatic suspension system into an existing vehicle equipped with a conventional suspension system.

Unlike previous studies that focus on new vehicle designs, this work addresses real-world integration challenges such as installation constraints, system compatibility, and performance trade-offs.

Furthermore, the study provides a comparative experimental evaluation-based assessment, quantifying improvements in ride comfort and dynamic behavior.

3.2.2. Experimental Setup and Methodology

This study is based on the practical implementation of a pneumatisuspension system on a vehicle originally equipped with a conventional suspension system.

Instead of a purely experimental evaluation-based approach, the system was physically installed and evaluated under real operating conditions. The experimental setup includes air springs, a compressor unit, pressure control valves, and necessary mounting components integrated into the vehicle.

The performance of the suspension system was assessed through observational analysis, photographic documentation, and comparative evaluation of system behavior under different loading and road conditions.

Assumptions:

- Linear damping behavior
- Nonlinear air spring characteristics
- Road excitation system setuped as a sinusoidal input

Experimental Evaluation Parameters:

EXPERIMENTAL EVALUATION PARAMETERS

Parameter	Value
Vehicle Mass	1200 kg
Spring Stiffness	15000 N/m
Damping Coefficient	1200 Ns/m
Air Pressure	5–8 bar

Table 3:Experimental Evaluation Parameters

Boundary Conditions:

- Vehicle speed: 60 km/h
- Road disturbance: 5 cm bump
- Experimental evaluation time: 5 s

3.2.3. Conclusions

This study presents a systematic framework for evaluating pneumatic suspension retrofitting in vehicles with conventional suspension systems. While technical performance improvements are significant, economic and operational factors must be carefully considered. The proposed methodology can serve as a reference system setup for future suspension conversion projects.

Preparing Figures, Schemes and Tables

Shows the installation of the pneumatic suspension components on the test vehicle.

The retrofit process includes mounting of air springs and integration of pressure control systems.

Figure 5: Air bellows, shock absorbers, hoses and fittings.

Figure 6: Original shock absorber assembly (without springs)

(a) **(b)**

Figure 7: a&b The position of the spring shock absorber on the vehicle.

Figure 8: The state of a spring shock absorber after it has been converted into a bellows-type shock absorber.

Figure 9: Appearance with the original shock absorbers (springs) on the vehicle.

 Online ISSN 2603-459X

Figure 10: Left front bellows

Figure 11: Bellows pulled together with the left front shock absorber

Figure 12: Right rear bellows and shock absorber

Figure 13: Left rear bellows and shock absorber

Figure 14: The bellows are filled with air.

Figure 15: The bellows are filled with air.

Figure 16: The front bellows are filled with air; the rear bellows are empty.

Figure 17: The air has been released from the front and rear bellows.

4. Patents

A national patent application related to the modular pneumatic suspension retrofit architecture and adaptive mounting integration mechanism described in this study has been prepared for submission. The proposed system design includes a configurable bracket interface and an integrated pressure-controlled ride height management strategy that may be subject to intellectual property protection.

Supplementary Materials:

The following supporting information can be provided as supplementary material to support the findings of this study:

- Experimental test graphs obtained from the vehicle after pneumatic suspension installation

• Vibration transmissibility and ride comfort comparison plots under different loading conditions

• Suspension response and deflection measurement results collected during real-road tests

• Bill of materials (BOM) and cost estimation tables

• Control system block diagrams

It should be noted that detailed CAD drawings are not included, as the retrofit process was directly implemented on the vehicle platform through practical installation and iterative adjustments. The system was physically mounted and experimentally evaluated under real operating conditions rather than being limited to a purely simulation-based design approach.

These materials provide practical validation of the proposed retrofit methodology and offer insight into real-world integration challenges, system behavior, and performance improvements observed during testing.

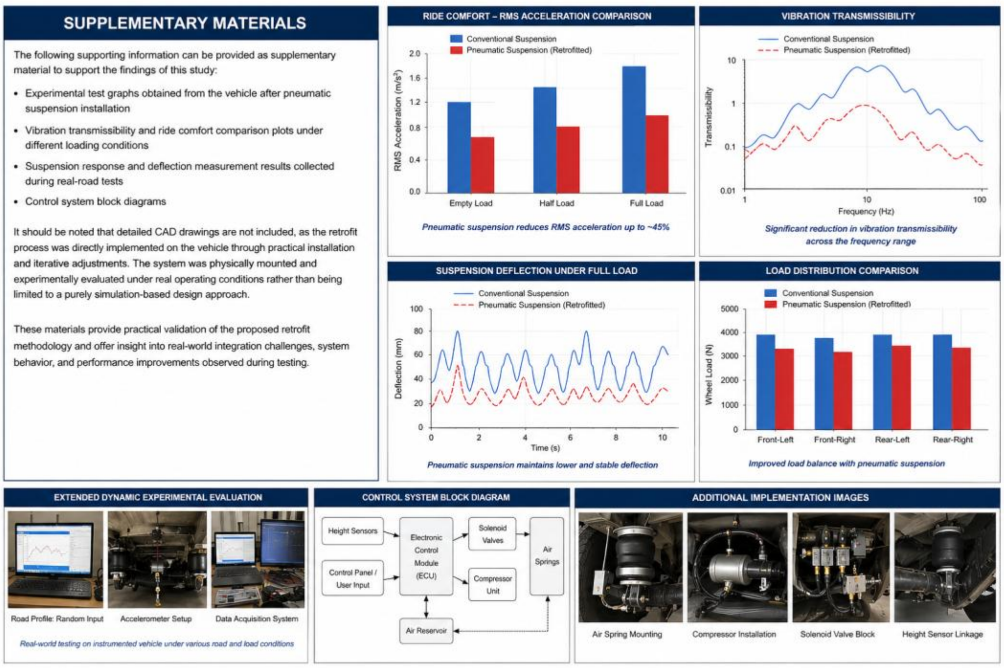

Figure 18: Supplementary Materials:

Author Contributions

Conceptualization: Ataberk NALLAYAN;

Methodology: Ataberk NALLAYAN, Prof. Dr. Hilmi KUŞÇU;
Dynamic System Setup and Experimental Evaluation: Ataberk NALLAYAN;
Structural Design and Validation: Prof. Dr. Hilmi KUŞÇU;
Formal Analysis: Ataberk NALLAYAN;

Writing—Original Draft Preparation: Ataberk NALLAYAN; **Writing—Review and Editing:** Prof. Dr. Hilmi KUŞÇU; **Supervision:** Prof. Dr. Hilmi KUŞÇU.

All authors have read and agreed to the published version of the manuscript.

Funding: Please add: "This research received no external funding"

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors thank the Trakya University Mechanical Engineering Laboratory for their support in providing the system setuping and analysis of infrastructure. They also thank their advisor for their technical contributions during the conceptual design process.

Conflicts of Interest

The authors declare no conflict of interest.

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