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Design and Virtual Validation of a Coil-Spring Cab Suspension System for a Heavy Commercial Vehicle

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Abstract: This paper details a structured methodology for designing and validating a coil-spring cab suspension system for a heavy commercial vehicle (HCV) to enhance driver ride comfort. The design process focuses on isolating the cabin from road-induced chassis vibrations. Key inputs include vehicle weight distribution and data obtained through road load data acquisition (RLDA). A single-degree-of-freedom base excitation model is utilized to set a target natural frequency of 2 Hz for the cab suspension. Detailed calculations determine the stiffness and geometrical parameters for the front and rear coil springs. The performance of the designed system is virtually validated using Multi-Body Dynamics (MBD) analysis in MSC ADAMS. Simulations for standard ride events, such as rough road and low-speed bumps, yield a Ride Quality Number (RQN) between 6.5 and 7.5, indicating satisfactory performance. A comparative analysis confirms the superiority of the four-point coil spring configuration over alternative design schemes. The study concludes that an integrated approach, combining theoretical calculations with advanced CAE tools, is effective for developing a cost-effective and performance-optimized cab suspension.

Keywords: Cab Suspension, Ride Quality, Vehicle Dynamics, Spring Design, Finite Element Analysis, Heavy Commercial Vehicle.

I. INTRODUCTION

In the competitive commercial vehicle sector, driver comfort has become a critical factor, directly influencing driver fatigue, operational efficiency, and overall vehicle utilization [1]. Operators of heavy commercial vehicles (HCVs) frequently endure long hours on diverse road terrains, leading to continuous exposure to vibrations transmitted through the tires, axles, and chassis frame. The prevalent cab-over-engine design in modern HCVs positions the cabin directly above the chassis, making it particularly vulnerable to these vibrations [2].

While significant research exists on primary axle suspensions [3, 4], comprehensive studies dedicated to the systematic design of coil-spring cab suspensions for HCVs are less common. The design process presents a complex challenge, requiring a balance between achieving a soft spring rate for effective vibration isolation and meeting stringent constraints related to packaging, cost, and structural durability [5, 6].

This work presents a complete design cycle for a four-point coil-spring cab suspension system for an HCV cabin. It methodically outlines the identification of critical design parameters, the calculation of static and dynamic loads via RLDA, the determination of optimal spring stiffness and natural frequency, and the detailed geometrical design of the springs. The proposed system is then evaluated through virtual validation using Multi-Body Dynamics (MBD) simulation to assess its ride quality, demonstrating a practical and analytical framework for cab suspension development.

II. CAB SUSPENSION SYSTEM DESIGN METHODOLOGY

A. Design Constraints and Objectives

The design is governed by several critical constraints, the most significant being the vertical space between the cabin floor and the engine. This imposes a strict limit on the suspension stroke and requires a minimum clearance of 90mm, as illustrated in Fig. 1. The load case was defined by the weight of the heaviest cabin variant, with a total laden weight of approximately 1050 kg. Packaging limitations restricted the spring's outer diameter to 120mm at the front and 110mm at the rear. Furthermore, cost considerations led to the selection of metallic coil springs over air springs. The primary performance objective was to achieve a cab suspension natural frequency of 2 Hz to ensure effective isolation from the chassis frame's dominant beaming frequency of 6 Hz.

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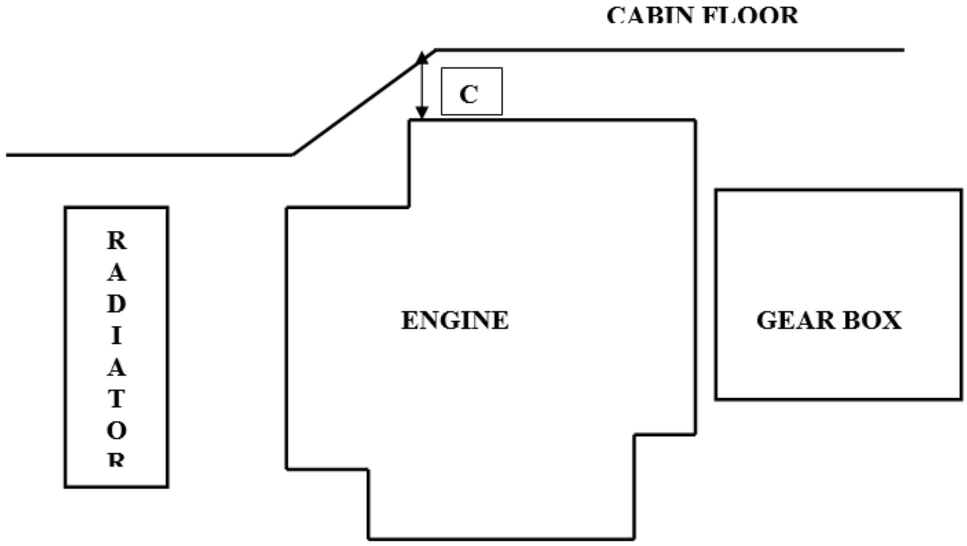

Fig. 1 Schematic representation of floor and engine clearance

B. Force Determination

The forces acting on the front and rear suspension points were calculated by modeling the cabin as a simply supported beam. The total laden cab weight was 1050 kg (810 kg curb weight + 3 occupants at 80 kg each). The distances from the cabin's centre of gravity to the front and rear suspension points were 1184 mm and 966 mm, respectively, as shown in Fig. 2.

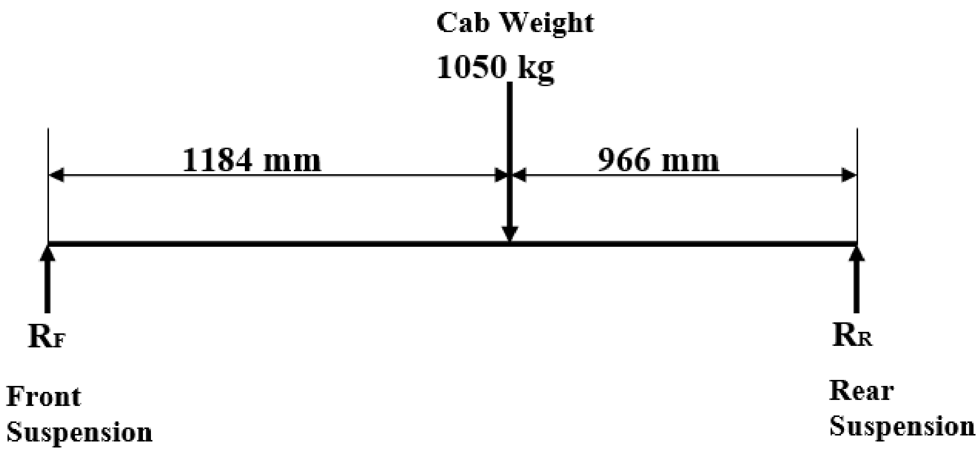

Fig. 2 Simplified cab and suspension load model

Taking moments about the front support (RF) to solve for the rear reaction force (RR):

$$R_R \times 2150 = 1050 \times 1184$$
$$R_R = 578 \text{ kg}$$

Consequently, the front reaction force is $R_F = 1050 - 578 = 472$ kg. With two springs per axle, the load is distributed, resulting in a load of 236 kg per front spring and 289 kg per rear spring. Dynamic load inputs were informed by Road Load Data Acquisition (RLDA), which recorded maximum accelerations of 3.7g, 1.9g, and 2.1g in the X, Y, and Z directions, respectively.

C. Natural Frequency and Stiffness Calculation

The cab suspension was modeled as a single-degree-of-freedom base excitation system, depicted in Fig. 3. The undamped natural frequency, ω_n, is given by:

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$$\omega_n = \sqrt{\frac{k}{m}} \qquad (1)$$

where k is the spring stiffness and m is the sprung mass.

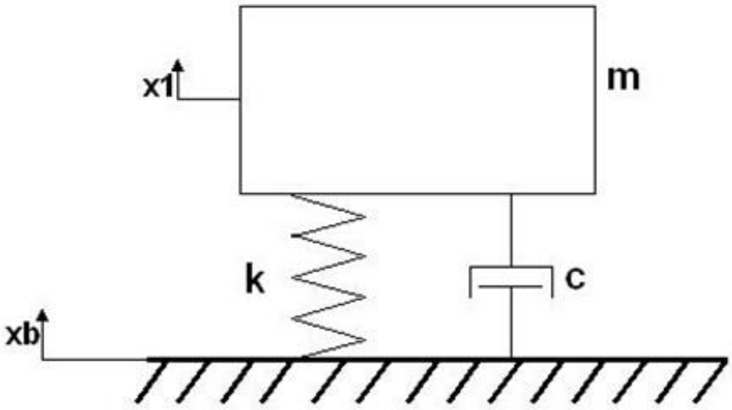

Fig. 3 Single degree of freedom base excitation model

The target frequency in Hertz is $f_n = \omega_n/2\pi$. To ensure effective isolation from the chassis frame's excitation frequency of 6 Hz, a frequency ratio of 3 was selected, resulting in a target cab suspension natural frequency of 2 Hz [7]. The relationship between transmissibility and the frequency ratio is illustrated in Fig. 4.

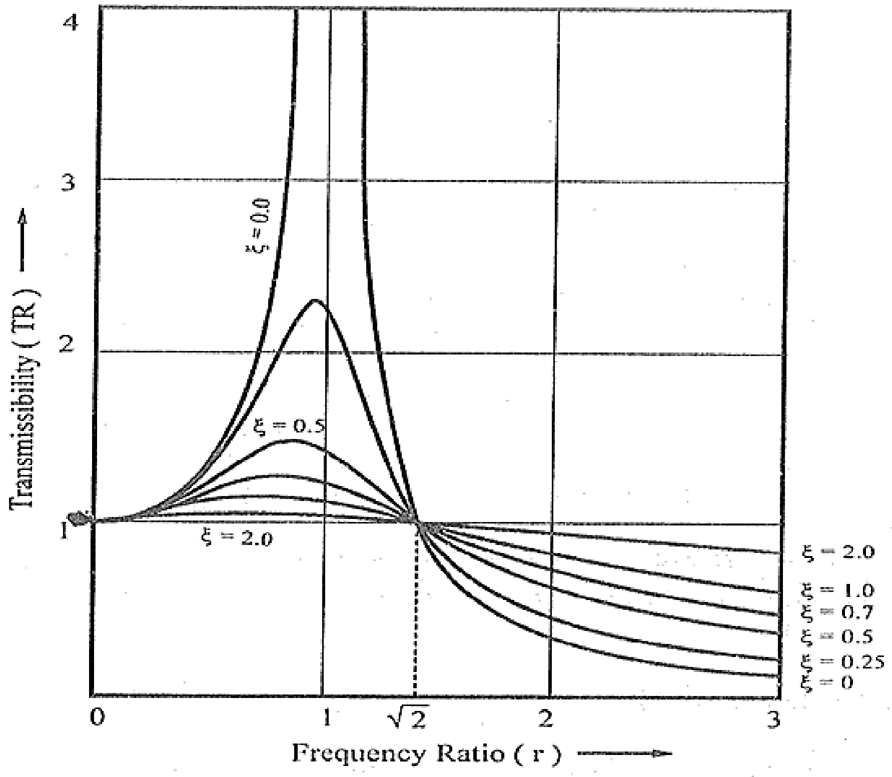

Fig. 4 Transmissibility as a function of frequency ratio and damping

Applying equation (1) with the target $f_n = 2$ Hz, the required stiffness for the springs was calculated.
For a front spring ($m = 236$ kg):

$$2 = \frac{1}{2\pi}\sqrt{\frac{k}{236}} \Rightarrow k = (4\pi)^2 \times 236 \approx 37229 \text{ N/m(or 3.72 kg/mm)}$$

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For a rear spring ($m = 289$ kg):

$$k = (4\pi)^2 \times 289 \approx 45590 \text{ N/m(or 4.55 kg/mm)}$$

D. Spring Design and Geometrical Parameter Selection

The geometrical parameters of the springs were determined using standard design formulae [8]. Key calculations included shear stress, the Wahl correction factor for stress concentration, the number of active coils, and solid and free lengths. A factor of safety of 1.5 was applied to the laden weight. These calculations were systematized in a spreadsheet to generate a matrix of viable spring options that conformed to the load, stiffness, and packaging constraints. The final selected parameters are summarized in Table I.

TABLE I SELECTED SPRING DESIGN PARAMETERS

Parameter	Front Spring	Rear Spring
Wire Diameter (d)	10.5 mm	11.25 mm
Mean Coil Diameter (Dm)	74.5 mm	93.75 mm
Outer Diameter (Do)	85 mm	105 mm
Stiffness (k)	3.72 kg/mm	4.55 kg/mm
Free Length (L)	222.41 mm	179.83 mm
Solid Length	136.5 mm	146.25 mm
Shear Stress (max)	70.18 kg/mm²	85.48 kg/mm²

The deflection of the springs under unladen and laden static loads was analyzed in CATIA V5, showing good correlation with physical measurements.

III. VIRTUAL VALIDATION AND PERFORMANCE ANALYSIS

A. Multi-Body Dynamics Simulation

The performance of the designed suspension system was evaluated using MSC ADAMS software. A full-vehicle wireframe model, shown in Fig. 5, was constructed, incorporating the cabin, chassis frame, powertrain, primary leaf springs, tires, and the detailed cab suspension model.

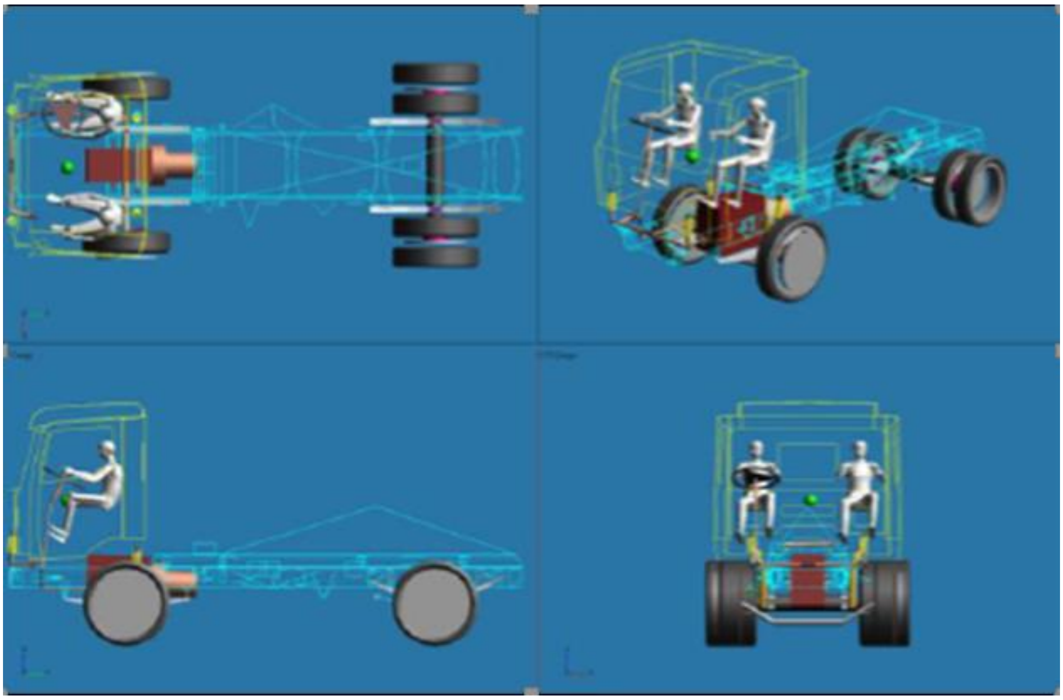

Fig. 5 ADAMS wireframe model of the full vehicle

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B. Simulation Events and Results

The validation involved two standard simulation events:

1. **Rough Road Event:** The vehicle was simulated on a rough road surface at constant speeds of 60 km/h and 80 km/h. Vibrations at the driver's seat were measured and synthesized into a Ride Quality Number (RQN), a metric where 0 represents the best possible ride and 10 the worst.
2. **Low-Speed Impact Event:** The vehicle was driven over standardized bumps to excite both parallel and offset wheel impacts. The resultant acceleration at the cabin's rear wall header was monitored to assess shock loads and durability.

The rough road simulation, results of which are shown in Fig. 6, produced an RQN of 6.5 at 60 km/h, which increased to 7.5 at 80 km/h. These values are considered acceptable for the HCV segment.
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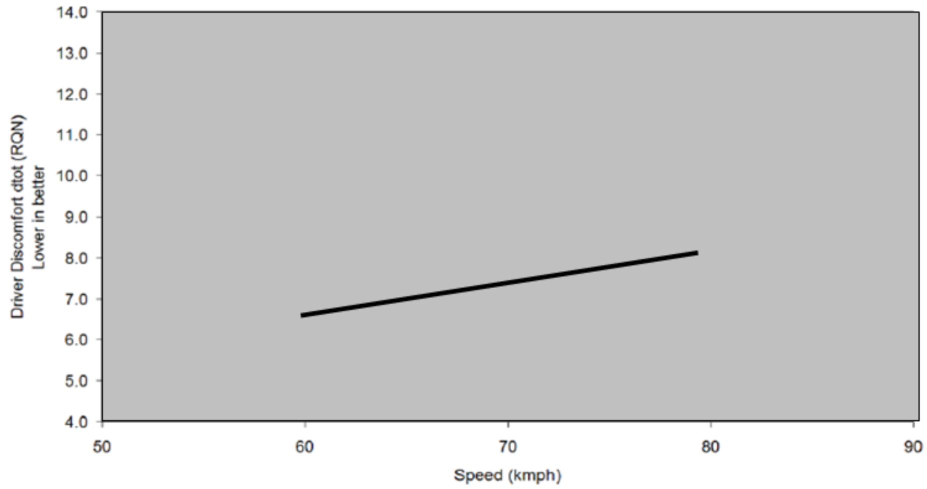

Fig. 6 RQN of the vehicle over a rough road at various speeds

The low-speed impact analysis, summarized in Fig. 7, provided peak absolute acceleration values at the rear wall header, which were cross-referenced with RLDA data for durability assessment.

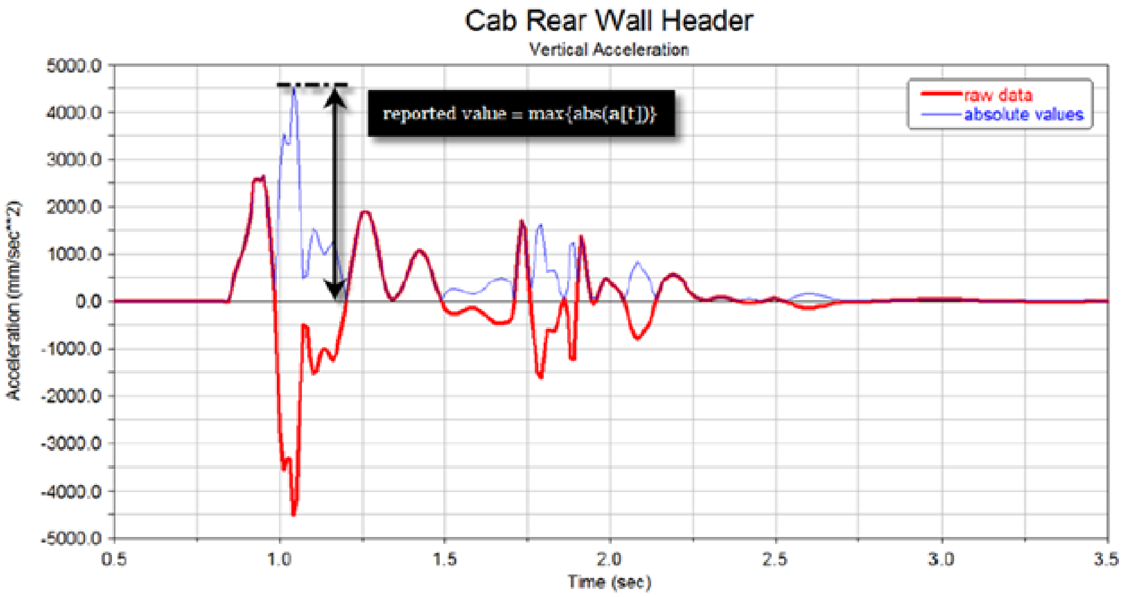

Fig. 7 Rear wall header acceleration absolute values on bumps

C. Comparative Analysis of Suspension Schemes

A comparative study was conducted using CAE to evaluate the performance of different cab suspension configurations. The proposed four-point coil spring system was compared against designs utilizing rubber mounts. The

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results, depicted in Fig. 8, clearly demonstrate the superior ride isolation provided by the all-spring configuration, as evidenced by its lower RQN values.

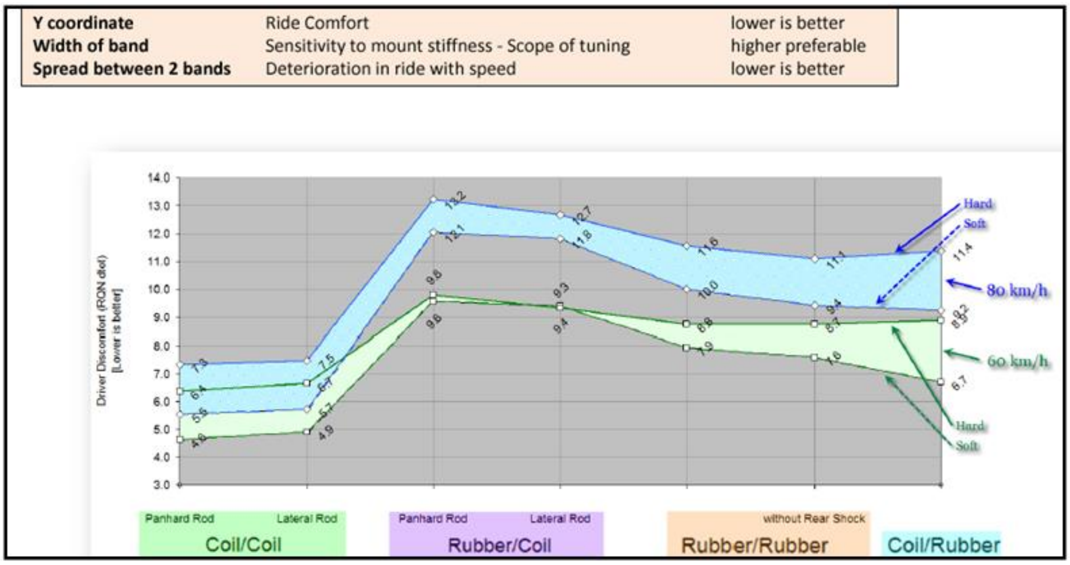

Fig. 8 Rough road RQN of various suspension schemes

The force-deflection characteristics of different suspension elements, shown in Fig. 9, further illustrate the benefits of coil springs, which offer a less stiff response compared to rubber mounts, leading to better vibration isolation.

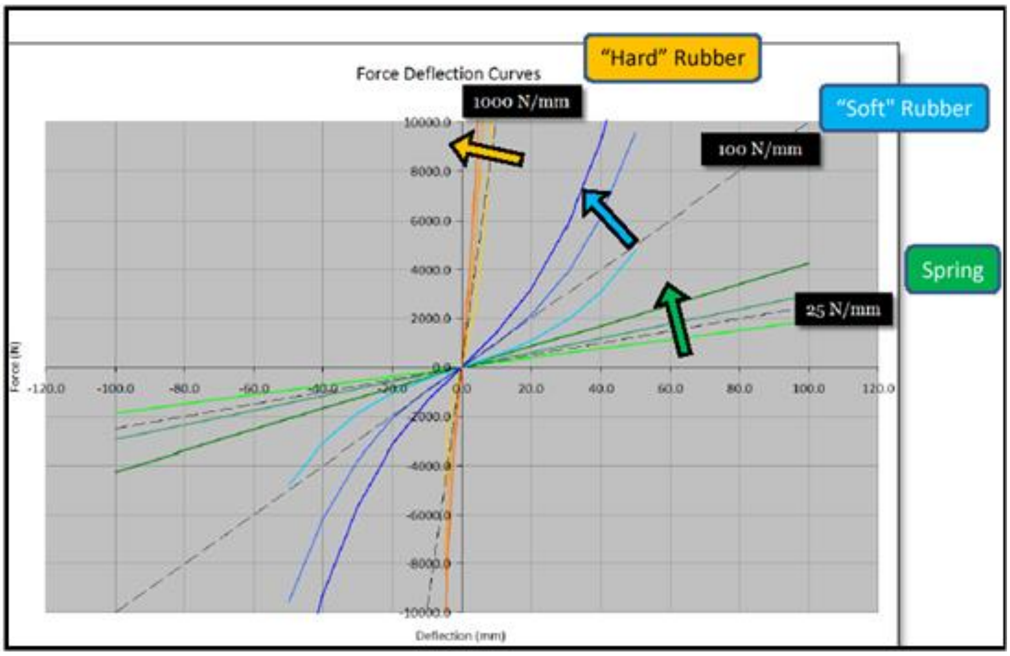

Fig. 9 Force deflection curves of various suspension options

IV. CONCLUSION

This paper has successfully outlined a systematic process for the design and virtual validation of a coil-spring cab suspension system for a heavy commercial vehicle. The process commenced with a clear definition of design constraints and objectives, proceeded through the calculation of static and dynamic loads, and established a target natural frequency of 2 Hz based on vehicle dynamics principles to ensure optimal vibration isolation. Detailed spring design yielded specific parameters for front and rear springs that effectively balanced performance requirements with packaging and cost

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constraints. The final four-point coil spring design was rigorously validated through Multi-Body Dynamics analysis. The simulation results confirmed that the system provides satisfactory ride quality, with RQN values ranging from 6.5 to 7.5 under various operating conditions. The comparative analysis conclusively justified the selection of coil springs over rubber mounts for this specific application. This study demonstrates that an integrated design approach, which combines fundamental theoretical calculations with advanced computer-aided engineering tools, is a highly effective strategy for developing optimized, cost-effective cab suspension systems that contribute to enhanced driver comfort and productivity.

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Prasad Kulkarni is Manager – Body Structures at Mahindra Integrated Business Solutions (formerly Mahindra Automotive North America), with over 25 years of global experience in the automotive industry and structural design. His expertise lies in crashworthiness engineering, lightweighting innovations, and advanced manufacturing technologies for passenger vehicles and battery electric platforms.

His career spans major OEMs in both India and the United States, covering passenger cars, commercial vehicles, and the latest generation of electric vehicles (EVs). Over the course of his career, Prasad has led structural design programs across the complete vehicle development cycle, from concept to production validation, with a strong focus on occupant protection and EV structural safety. He has worked on platforms aligned with Bharat NCAP, Euro NCAP, and FMVSS standards, pioneering the integration of hot-stamped steels, aluminum, and AI-driven optimization into safer, lighter, and more sustainable vehicle architectures.

He is currently leading the BIW structure design for a modular "Born Electric" SUV platform at Mahindra, focusing on battery pack integration and occupant safety.

An internationally recognized expert, Prasad is passionate about shaping the future of crash-safe, sustainable mobility and contributing to the global engineering community through thought leadership and industry insights.

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Research and Professional Interests

- Crash-Safe and Lightweight BIW Architectures for Electric Vehicles
- AI-Driven Design Optimization and Material Selection
- Advanced Manufacturing Processes for High-Strength Steel and Aluminum
- Global Vehicle Safety Regulations and Homologation
- Sustainable and Frugal Engineering Design Practices
- Design for Manufacturability (DFM) and Assembly (DFA)