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HOW HEAVY COMMERCIAL VEHICLE SUSPENSION RESPONDS TO VARYING LOAD CONDITIONS OVER UNEVEN INDIAN ROADS, AIMING TO REDUCE MECHANICAL FATIGUE AND IMPROVE TRANSPORT SAFETY

Mahir Shah

Student Researcher

Genesis Global School

Abstract

The business trucks constitute an important component in the transport of cargos, particularly in India where road transport covers more than 65 percent of the domestic freights. Other load conditions also include the various load conditions on uneven roads that subjects their suspension system to permanent mechanical load and hastens fatigue damage. Suspension components like springs, dampers, linkages and chassis connections have significant influence on stability, load distribution and transport safety. The research design employed in this paper is the exploratory research design which utilizes secondary qualitative data collected using scholarly journals, engineering reports and engineering industry publications. The suspension behaviour, variation of loads, road irregularities and mechanical fatigue followed patterns and the thematic analysis approach was chosen. These findings indicate that the unsteady cargo loads improve compression of the suspensions, alter the vibrations behavior, and increase the level of structural stress. The Indian road conditions discontinuities are well known to produce dynamic loads and shock forces that hastens component fatigue. The actions performed by the engineers to guarantee the correction of the issue, such as air and adaptive suspension systems, high-quality material and predictive maintenance plans, reveal a lot of success and are sure to prolong the operational safety and durability of the problem. The experiment supports the relevance of Mechanical Fatigue Theory, and Vehicle Dynamics Theory to investigate the behavior of suspensions in a realistic driving situation. These lessons may be employed to guide vehicle makers, transport

operators, road planners to optimize the design of the suspensions, reduce mechanical failures, enhance the security of the transportation whole.

Keywords: Heavy Commercial Vehicles; Suspension Systems; Load Variation; Road Irregularities; Mechanical Fatigue; Vehicle Dynamics; Air Suspension; Adaptive Suspension; Predictive Maintenance; Transport Safety

1. INTRODUCTION

1.1 Background

Commercial vehicles are heavy trucks that are the backbone of contemporary freight transport and logistics. These trucks facilitate the transportation of products over long distances, and also facilitate movement between production centers, ports, warehouses, and retail markets. The number of heavy trucks in India is necessitated by 65-70 per cent share of road transport in total freight transportation in the country and the efficiency of the supply chain (Sahu, Pani and Santos, 2022). These are the kind of vehicles, which are in a habit of bearing heavy loads over long routes and this means that the mechanical systems of these vehicles are subjected to heavy loads of operation. Suspension is one of the most important parts that make vehicles safe to operate. The suspension is constructed to absorb the shock caused by the irregularities of the roads and to ensure that the car remains stable throughout the motion. Not only does the suspension safeguard the vehicle structure, cargo, and the passengers, but also enhances the comfort and safety of the driver by mitigating vibration and mechanical impact (Krauze and Kasprzyk, 2020). The suspension system shares the load forces among the chassis and wheels, thereby enabling the vehicle to have traction and balance in dynamic driving conditions. Road quality has a strong influence on suspension performance, and unequal surfaces, potholes, and deformities cause repetitive shocks, accelerating fatigue, particularly in India, and this is why the examination of load response is necessary to increase durability and transport security.

1.2 Context of Heavy Vehicle Suspension Performance

Different types of suspension systems are used on heavy commercial vehicles depending on the design, the capacity of the vehicle to carry loads, and the needs of the operations. The leaf spring suspension is one of the most widely utilized systems; it is composed of layers of steel plates that are flexible to absorb road shock. Leaf spring suspension is the most common in heavy trucks due to its durability, simplicity, and heavy load carrying capacity. Another common mechanism is air suspension, in which compressed air is emitted into flexible air bags to hold the weight of the car, and raise/lower the height of ride (Jiregna and Sirata, 2020). Air suspension enhances comfort and can provide better load distribution. Hydraulic suspension systems are also used in some heavy vehicles, and the oscillations are regulated by hydraulic dampers that ensure stability during the movement. Weight can also have a critical impact, and freight might have to be redesigned to fit the type of shipment (Reda et al., 2024), and the creation of transport infrastructure often results in uneven roads and road anomalies, introducing new mechanical stimulus into the suspension system and affecting the performance of a car.

1.3 Problem Statement

The roads on which commercial trucks are predominantly operated have bumps, potholes, and uneven surface. Simultaneously, freight transport is defined by a constantly altering load factor based on the mass and distribution of the goods (Rolt, Otto and Endale, 2020). These forces impose cumulative stress to the suspension parts, including springs, dampers, and chassis ties. Mechanical fatigue and potential component failure are associated with continuous exposure to varying load conditions. The failure of suspension system can cause road accidents, high maintenance, and shortened vehicle life. In this regard, the dynamics of suspension systems under random loads and non-homogeneous road surfaces must be perceived in a deeper way.

1.4 Rationale

Freight transportation in India is a sector that is quickly emerging due to the developing economy and by extension the augmentation of demand on road based logistic. Nevertheless, road infrastructure differs in terms of quality, subjecting heavy vehicles to undue mechanical stress during routine operations (Chandra, Christiansen and Fagerholt, 2020). The constant vibration and impact forces produced by an uneven road surface and by the heavy cargo loads must be absorbed by the suspension systems. Suspension component failure may undermine vehicle safety, introduce additional operating cost, and reduce transport efficiency. Experimental investigation of suspension behavior under different load conditions can yield information that can be useful in developing a better suspension, minimizing fatigue damage and providing safer transportation.

1.5 Aim

The aim of this study is to analyse heavy vehicle suspension responses to variable loads on uneven Indian roads for improved durability and safety.

1.6 Research Objectives

- To examine the influence of varying load conditions on suspension performance in heavy commercial vehicles.
- To analyse how uneven Indian road conditions affect suspension stress and mechanical fatigue.
- To investigate suspension technologies and engineering approaches used to improve durability and stability.
- To identify strategies that can reduce fatigue damage and enhance transport safety.

2. LITERATURE REVIEW

2.1 Heavy Commercial Vehicle Suspension Systems

The mechanical endurance of the vehicle in transit is aided by heavy vehicle suspension systems that hold springs, dampers, linkages and chassis connections, to stability, uniform load distribution, road shock absorption, vibration control and controlled road wheel movement. Thillikkani and Nataraj (2020) discovered that suspension components are involved in reducing the dynamic stresses that can be ascribed to changes in loads, directly affecting the fatigue life and structural integrity of heavy vehicles. They point out that in their study, the design of sound suspension overcomes the mechanical forces in the structural elements, thus minimizing the risk of early failure. Nevertheless, Lukoševičius et al. (2021) also believed that the performance of the suspension should also be evaluated in terms of vehicle stability especially during cornering and braking. The authors emphasize that a properly developed suspension system cannot guarantee the stability, unless the vehicle dynamics and weight distribution are considered with integration. The implication in this discussion is that the effectiveness of the suspension is not only a matter of component design but also the correlation between vehicle dynamics and structural load management.

2.2 Impact of Load Variation on Suspension Performance

Load variation has a substantial effect on heavy vehicle suspension because cargo weight and distribution alteration result in dynamic loading, which has been linked to stiffness, vibration behaviour, and structural stress of the suspension system components.

Stress analysis and advanced finite element analysis (FEA) methods reveal that different loads may considerably change the distribution of stresses through suspension structures (Borase et al., 2024). In their study, the researchers found a relationship between the cargo loads and the heightened compression of the suspension, as well as mechanical pressure on springs and structural joints. It implies that the improper design of a suspension can lead to increased material wear and structural corrosion. Instead, Shaikh et al. (2023) claimed that even in the case of variable loads, suspension design could be optimised to enhance fatigue life using available modelling tools. They note that their research findings indicate that computational modelling allows engineers to model real world loading conditions and to detect areas of critical stress levels before mechanical failure. In spite of this mechanical stress in the variability of loads, engineering optimisation and sophisticated modelling enhances the suspension stability, and effort in predictive design is needed to enhance performance in demanding freight transport circumstances of dynamic operation.

2.3 Influence of Uneven Road Surfaces

Mechanical wear on heavy commercial vehicles over time, repeat shock, greater vibration to the vehicle, high stress cycles in the suspension parts, and mechanical wear due to uneven road conditions, such as potholes, cracks, and uneven road surfaces, all mechanically deteriorate.

In line with Choudhary et al. (2024), vehicle safety and dynamical stability is directly dependent on the road surface conditions and pavement geometries. They found that pavement quality affects the stability of the vehicle and the risk of accidents because of sudden shock loads and vibration forces. These results emphasize the importance of road infrastructure quality as a factor of vehicle safety and suspension integrity. On the contrary, Thangavel and others (2025) held that vehicles can react better to harsh road conditions despite these conditions when improved structural and driving engineering is employed. In their research, they propose that a complex of progressive structural design and effective suspension systems could be introduced to enhance vehicle resiliency under the conditions of poor road infrastructure. The quality of the roads is an important aspect of the suspension performance; short-term solutions can be provided through the development of advanced vehicles and long-term solutions can be provided through infrastructure development.

2.4 Mechanical Fatigue in Heavy Vehicles

The phenomenon of mechanical fatigue exerts tension on the design of a heavy vehicle because the suspension parts become subjected to the cycles of repetitive stresses; the continuous loading and unloading initiate the development of microcracks and structural collapse and exposure to the dynamic forces of road irregularities and load variations.

According to Thillikkani and Nataraj (2020), fatigue life prediction plays a crucial role in identifying how a suspension component is vulnerable to different load conditions. Their effort illustrates that unless fatigue behaviour is well addressed during the design phase, cyclical stress cycles can reduce the operational life of suspension structures by several years. The prediction Sound fatigue models can consequently guide engineers to enhance the suspensions durability and maintenance planning. Conversely, Zhou and Chang (2022) felt that fatigue analysis should involve the whole body of the vehicle and not individual parts of the suspension. Their study of rear axle fatigue observes that how the stress is distributed to the interrelated parts of the vehicle can affect the failure mode and mechanical life. The suspension systems play a significant role in fatigue behaviour, yet the total life of the vehicle is a holistic decision-making process that accounts all the structural components.

2.5 Suspension Technologies and Engineering Innovations

Other new technologies in vehicle suspension, such as air, adaptive, load-sensing, and vibration detection, improve the stability of heavy vehicles, minimize mechanical wear and tear, extend service life, and offer improved ride comfort in varied loading condition.

According to Jiregna and Sirata (2020), the conventional suspension systems can potentially work in straightforward load absorption but might not be flexible to meet the demands of contemporary transportation. They observe that the traditional suspension systems cannot bear the dynamic load changes and challenging road conditions. Alternatively, Mei et al. (2025) suggested that complex suspension technologies, including adaptive suspension and intelligent control systems, have meaningful contributions to vehicle performance. These systems automatically modify the degree of suspension stiffness and damping properties to suit the road conditions and vehicle loads, thus enhancing the safety and longevity. Suspension engineering is moving towards adaptive technology, as compared to passive systems, in order to enhance efficiency, fatigue reduction, and safety in heavy vehicle transportation.

2.6 Theoretical Framework

This study was conceptually founded on the Mechanical Fatigue Theory and Vehicle Dynamics Theory, which offer theoretically-based knowledge on how heavy commercial vehicle suspension systems behave under different conditions.

A. Mechanical Fatigue Theory

The Mechanical Fatigue Theory describes the gradual degradation of materials under cyclic loading. Repeated stress cycles of the mechanical components cause microscopic cracks to appear in the material structure (Zhang et al., 2022).

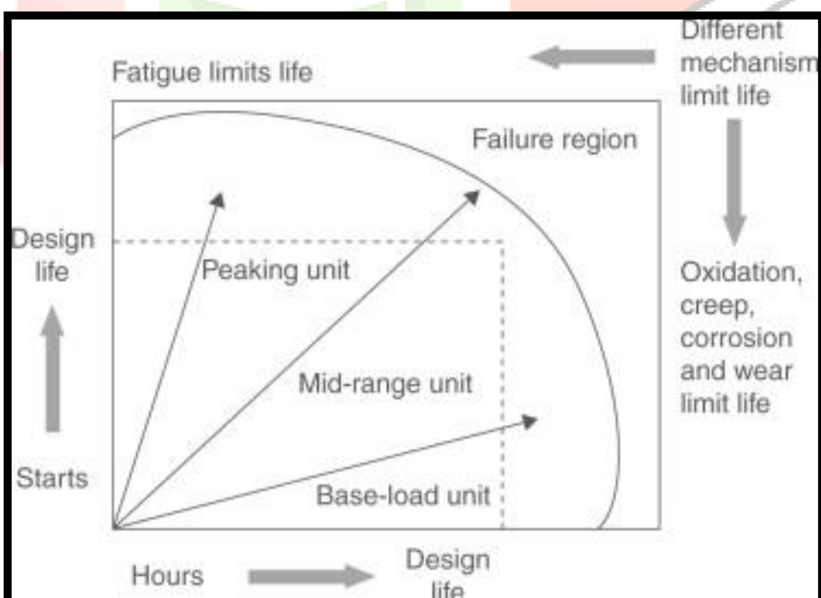

Figure 1: Mechanical Fatigue Theory

(Source: Lee et al., 2022)

Over time, such cracks spread, and structural failure occurs. Commercial vehicles with heavy loads expose the springs, dampers, and linkages to cyclic loads associated with road undulations and cargo variability across the suspension (Lee et al., 2022). The paper can use the Mechanical Fatigue Theory to examine how repeated accumulation of stress affects the existence and supportability of suspension membership. This theoretical framework enables the study to quantify the role of dynamic loading conditions in fatigue damage and mechanical degradation.

B. Vehicle Dynamics Theory

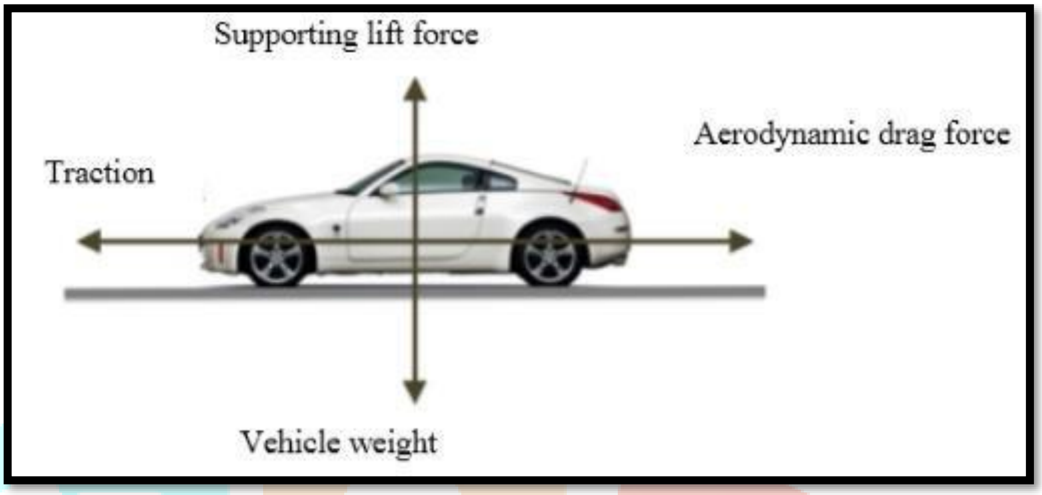

Figure 2: Vehicle Dynamics Theory

(Source: Diep, Nguyen and Tran, 2020)

The second theory is Vehicle Dynamics Theory that considers forces acting on a moving vehicle and the interaction of the suspension system, tyres and road surface (Diep, Nguyen and Tran, 2020). This theory assists in understanding the effect of load distribution, road irregularities, and vehicle motion on the suspension behaviour. Vehicle Dynamics Theory is applied in the context of the present research as a method of explaining the response of suspension systems to different loads and non-homogeneous roads that are typical to the Indian transport environment (Park et al., 2023).

2.7 Research Gap Identified

The current literature on vehicle suspension systems and fatigue behaviour in controlled laboratory settings is already abundant. Nonetheless, the majority of research publications have concentrated on simulated test conditions that may be not always reflective of actual operating conditions. Few studies have been carried out on the behaviour of suspension systems in the interplay of variable load conditions and non-regular road infrastructure especially in developing nations like India. most engineering research has not been carried out on the combined effect of road surface irregularities and dynamic cargo loading.

3. MATERIALS AND METHODS

3.1 Research Design

This research paper follows a pattern of ***exploratory research design*** to explore the responsiveness of heavy commercial vehicle suspension systems to different load conditions and uneven roads. Exploratory research fits into research when the object of study is a complex problem with partial or limited information (Makri and Neely, 2021). Variation in loads, roughness of roads, vibration forces, and mechanical fatigue all act in concert with vehicle suspension systems. Exploratory design, in such a manner, allows the researcher to explore these interacting factors and build a more elaborate understanding of suspension behaviour within operating parameter.

The exploratory method proves to be especially effective in the analysis of engineering issues that incorporate numerous technical and environmental aspects. The pros of this design are that it is a flexible design and enables us to extrapolate on the results of many technical studies and engineering tests. It also aids in the exploration of new fields of research where empirical findings can still be growing (Al-Ababneh, 2020). Alternate research design options were also discussed but not chosen. This is due to the fact that survey-based research techniques tend to be employed in behavioural or social research and cannot be applied to research of mechanical engineering systems like vehicle suspension performance.

3.2 Data Sources

This study has used the ***secondary data sources*** to analyse how heavy commercial vehicle suspension systems behave under different operative conditions. Secondary data is data that has already been gathered and shared by researchers, engineers and institutions. Various data sources were used in the current work: academic journal articles, engineering research papers, vehicle testing reports, transport authority publications, and industry reports of vehicle dynamics and suspension system performance (Taherdoost, 2021). Secondary data also makes sense since a lot of technical information and experimental results would be accessible without requiring extensive lab work to do it. Numerous engineering research projects already conducted simulations of large scale, fatigue analysis and stress modelling of the suspension components, which can be synthesised and incorporated into the analysis. The second benefit of secondary data use is that it is economical and time saving because the study will be able to tap into a richer pool of tested scientific data. This study did not choose primary data collection since the field research on testing heavy vehicle suspension systems would involve specialised equipment, test setups, and substantial funding (Ajayi, 2023). Additionally, the main experimental test is not possible within the framework of this study due to time limitations.

3.3 Inclusion and Exclusion Criteria

The literature used in the study also entails scholarly research covering heavy commercial vehicle suspension systems, fatigue studies, and the role of road conditions in vehicle development over the past fifteen years. The loss of other material literature on passenger vehicles, non-technical reports and irrelevant car parts was also abandoned to guarantee that the relevance and reliability of the literature proliferate.

3.4 Data Analysis

Literature gathered was analysed thematically through the ***thematic analysis*** which is the qualitative method of analysis that establishes patterns and themes that persistently re-emerge in the outcomes of research. Thematic analysis enables the researcher to generalise the outcomes of various studies and congregate them into significant themes according to the purposes of the research (Finlay, 2021). The analysis was in steps. The first stage was the coding of the corresponding information about the chosen literature, specifying the main ideas connected with the suspension behaviour, loading change, road conditions, and fatigue mechanisms. Second, these coded concepts were clustered into more broad themes that reflected similarities across literature. Third, the connection between the specified themes was examined to interpret the impact of various factors on the suspension performance under heavy commercial vehicle use (Coker, 2022). Thematic analysis was selected due to its suitability to ensure qualitative literature synthesis and enable a systematic interpretation of complex technical information. Other analytical tools did not involve statistical meta-analysis and studies used in these techniques had different research designs and could not be quantitatively compared.

4. RESULTS AND DISCUSSION

Theme 1: Impact of Load Variation on Suspension Behaviour

The articles under review confirm that the change of load is a defining variable that affects the behaviour of heavy vehicle suspension systems. A research article by Thillikkani and Nataraj (2020) examined the life of fatigue in heavy vehicle suspension parts and revealed that high load cases cause the compression and stress of structure members like springs and joints. Their fatigue predictive algorithm suggests that repeated loading cycles increase mechanical damages and decrease service life of the suspension. Likewise, Lukoševicia et al. (2021) investigated vehicle stability taking into consideration the behavior of the suspension with regard to diverse loads during operations. The experiment revealed that increased loads change patterns of vibration response and affect vehicle stability, especially braking and turning. Greater loads cause greater vertical forces and changes in forces between wheels, both of which have a direct impact on suspension dynamics. These results conclude that dynamic load change is a conclusive factor in the differentiation of the suspension behaviour and the mechanical stress distribution of heavy commercial vehicles. Results are consistent with literature review which indicates that load variation influences the suspension stress and vibration behaviour, and as such, it provides a direct response to objective one of the study.

Theme 2: Influence of Uneven Indian Road Conditions

The literature review shows that asymmetry of roads results in substantial dynamic forces on heavier commercial vehicles. Under the investigation by Biswas et al. (2021) concerning the road surface conditions and traffic behaviour of urban road in India, it was noted that the stability of vehicle movement depends on the pavement irregularities and side friction factors. The poor-road surfaces elevate forces on the vehicle structures and mechanical stresses on the suspension components. Likewise, Kotagi et al. (2020) investigated the traffic conditions in undivided roads in India and found that the mixed traffic flow, along with the uninformed state of the roads, results in unpredictable vehicle movement and weight change. These jiggly movements create dynamic loads that increase vibration and mechanical shock on the suspension system. Surface distortions and potholes provide sudden vertical forces amplifying stress cycles within suspension components, which encourages fatigue damage and structural degradation. Findings validate the arguments in the literature review that rough road surfaces enhance vibration and stress cycles, which qualifies objective two of road impact.

Theme 3: Engineering Solutions to Improve Suspension Durability

Suspension technology is an engineering technology that is very major in enhancing the durability and vibration control of heavy vehicles. Kumar et al. (2023) designed a model of suspension systems with natural rubber substances and demonstrated that better material properties would play a crucial role in mitigating vibration transmission. Their findings show that an increase in damping material can effectively absorb the road shocks and decrease suspension member stresses. Likewise, Shaikh et al. (2023) employed modelling and simulation to investigate suspension systems to improve fatigue life. They discovered that suspended settings and better load distribution mechanisms could greatly increase component life. Air suspension and adaptive damping are the technologies aimed at enhancing the vehicle stability by adjusting the suspension to responsiveness to the load states and the anomalies present on the road. These are the engineering solutions that show the effectiveness of suspension design to minimize mechanical load and promote long-term vehicle operation. The results enhance literature review discussion by demonstrating that technological improvements are a contributing factor to long life of suspension, vibration damping, which addresses the third objective directly.

Theme 4: Strategies to Reduce Mechanical Fatigue and Improve Safety

Different researchers believe that mechanical fatigue and operational safety of transport can be minimized by various measures. Thillikkani and Nataraj (2020) pointed to the significance of fatigue life prediction models that can be used to determine the critical points of stress within the suspension components. Properly foreseen fatigue helps engineers to re-engineer structural elements and choose materials that can endure recurring cycles of loading. Moreover, the issue of fatigue management in safety critical transportation systems was mentioned in a paper by Wingelaar-Jagt et al. (2021), where the significance of fatigue monitoring and preventive maintenance, as well as early warnings about risks related to fatigue, were stated. They carry out a study on aviation safety, and the concepts of fatigue monitoring and predictive risk management might be applied to vehicle engineering. Strategies that can be applied under medical intervention, like better material design, active maintenance programs, as well as technology that monitors road conditions, can greatly minimize mechanical failures and enhance safety performance of heavy transportation vehicles. Findings enrich the current literature on fatigue mechanisms, illustrating practical measures to minimize the effects of fatigue or deal with objective four on safety improvement.

Discussion

This paper shows that load change and road condition play a major role in determining the performance of heavy commercial vehicle suspension systems, not mentioning the sustainability itself. This discussion shows that the successional loads, relative to cargo loads, augment compression and vibrational freqs, thereby augmenting load on springs, dampers, and structural connections (Sahu, Pani and Santos, 2022). Likewise, non-homogenous road surfaces cause impulsive shock loads and cyclic stresses that expedite mechanical wear on suspension components. These observations indicate that the design is not the only factor that influences the performance of suspension but heavily depends on the circumstances of operation like the road conditions and freight loading patterns.

Comparing to the literature, similarities and some further insights can be provided. According to Thillikkani and Nataraj (2020), an essential factor that influences fatigue life of suspension systems is cyclic loading. They identify that applicability of fatigue prediction models is crucial in comprehending the effects of stress accumulation in component failures. The current research findings support this argument, as it suggests that in the condition where loading variables are controlled to change, it leads to higher stress concentration in suspension structures. Conversely, Lukoševičius et al. (2021) assumed that the suspension performance analysis should be conducted, first of all, through the prism of vehicle stability and dynamics. Although their study considered vehicle balance and stability during a moving mode, the current research demonstrates that the interaction of road irregularities and load changes add to a more complex pattern of stress that affects stability and structural fatigue. This means that the suspension durability might not be completely comprehended in the absence of the compounding effects of road infrastructure and operational loading conditions.

Principally, the findings validate the applicability of Mechanical Fatigue Theory, which describes the progressive weakening of suspension materials through repeated stress cycles. The conclusions are also in favor of Vehicle Dynamics Theory because the suspension response is delicate to the interaction among vehicle motion, load distribution and the road surface conditions. Managerial implications of the findings are also available (Lee et al., 2022). In vehicle manufacturers, the findings demonstrate the need to create adaptive based systems of suspensions with the ability to respond to changing loads and uneven roads. In the case of transport companies, they could adopt predictive maintenance, which will detect the weariness of suspensions before mechanical breakdowns occur (Shah, Mittal and Lotwin, 2025). Infrastructure planners need to work on the quality of roads to ensure that vehicles are safe.

5. CONCLUSION

The analysis was of the response of heavy commercial vehicle suspension systems to different load configurations in poor Indian roads, to decrease mechanical stress and improve transportation safety. The test established that the changes in loads amplify the compression of the suspension, loads on springs and dampers, and variation of vibration pattern, accelerates the normal wear and tear of critical parts. Dynamic loads such as uneven road surfaces and potholes increase the intensity of the stress cycles and structural degradation possibilities. The application of the latest suspension technologies (air and adaptive systems) was discovered to enhance the distribution of loads and vibration, as well as the life of the component. Predictive maintenance, optimized material design, and monitoring of road conditions are other steps applicable in minimizing mechanical fatigue and maximizing reliability. The research contribution to the literature is that it incorporates the interaction between variability of loads and actual Indian road conditions, which is commonly neglected in the lab experiments. The proposals are bettering road quality and proactive maintenance schemes and to adopt adaptive suspension designs will enhance the lifespan of suspensions and to make transportation safer.

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