

Suspension Characteristics and Status for Mid-Segment Passenger Vehicle: A Comprehensive Review

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Abstract

In the vehicle field, technology evolution has constantly augmented the boundaries of vehicle performance, comfort, as well as safety. Initially, the vehicle's driving comfort is determined by the Suspension System (SS) design, which transmits the force betwixt the vehicle and the ground. The suspension is one among the most critical systems contributing the vehicle advancements. Principally, the SS of a car connects important parts like the shock absorbers, struts, springs, and control arms to ensure smooth handling, stability, along with ride comfort. The force and reaction between the vehicle and the ground are transferred and controlled by the SS. This SS is important in mid-segment Passenger Vehicles (PV). Even though there are different kinds of SSs in vehicles, suspension plays an important role in mid-segment passenger cars, namely the Honda City, Skoda Slavia, Volkswagen Virtus, together with Maruti Ciaz, ensuring a balance of comfort and performance. The Suspension Characteristics (SC) are important for identification in this SS. SC are important in mid-segment PVs, confirming optimal comfort, handling, and stability for cars, namely the Honda City, Skoda Slavia, Volkswagen Virtus, along with the Maruti Ciaz. Thus, the review is conducted to investigate the SC for mid-segment PVs by analyzing the SS and its characteristics. The analysis reveals that passive systems remain cost-effective but limited in adaptability, while active systems provide superior performance at the expense of higher complexity and energy consumption. Semi-active and hybrid suspensions offer an optimal balance, making them suitable for mid-segment vehicles. This review contributes a comparative engineering perspective and identifies future research directions in intelligent suspension systems.

Keywords: Suspension system, multi-purpose vehicles, multi-utility vehicles, hybrid suspension system, mid-segment passenger vehicles, suspension characteristics, and ride comfort.

1. Introduction

Recently, due to different mechanical specifications, different vehicles have evolved. The important specifications are utilized in different models of the car among the different specifications of vehicles. Usually, a car is a 4-wheeled vehicle designed for passenger transportation along with commonly propelled by an internal combustion engine employing a volatile fuel. Because cars have motors and are composed of several simple machines that help to make them run, they are considered as complex machines [1]. Thus, revolutionary technological changes create a path for new innovations to overcome the complexity of car machines. Many latest innovations are created in different parts of cars as technology changes. These technological advancements offer multiple solutions for the benefit of car users. Among these different

parts, some are important for the car [2]. The SS is an important part of the car. This suspension helps to keep all wheels on the ground, especially when driving over uneven surfaces or during turns. This system also absorbs shocks from the road and reduces wear on other parts, such as tyres, brakes, and steering. In a car, the SS is accountable to stabilize along with controll the vehicle, permitting it to grip bumps as well as dips on the road. The SS aids to maximize the friction betwixt the tyres and the road, thus ensuring a comfortable ride and providing steering stability and good handling [3]. As the vehicle shakes and wobbles with severe vibrations that result in discomfort, vehicles without suspension are termed 'bone breakers'. Therefore, each vehicle must be equipped with an SS for absorbing vibrations, particularly on uneven road surfaces, as well as to support heavy passenger weights [4]. These SSs

play an important role in different types of advanced cars. Among the different types of advanced cars, mid-segment PVs have always been the Indian automobile market's higher-growth segment right from the very

first launch. This provides comfort for passengers riding inside the car in road conditions [5]. In Figure 1, the benefits of SC of mid-segment PVs are explained.

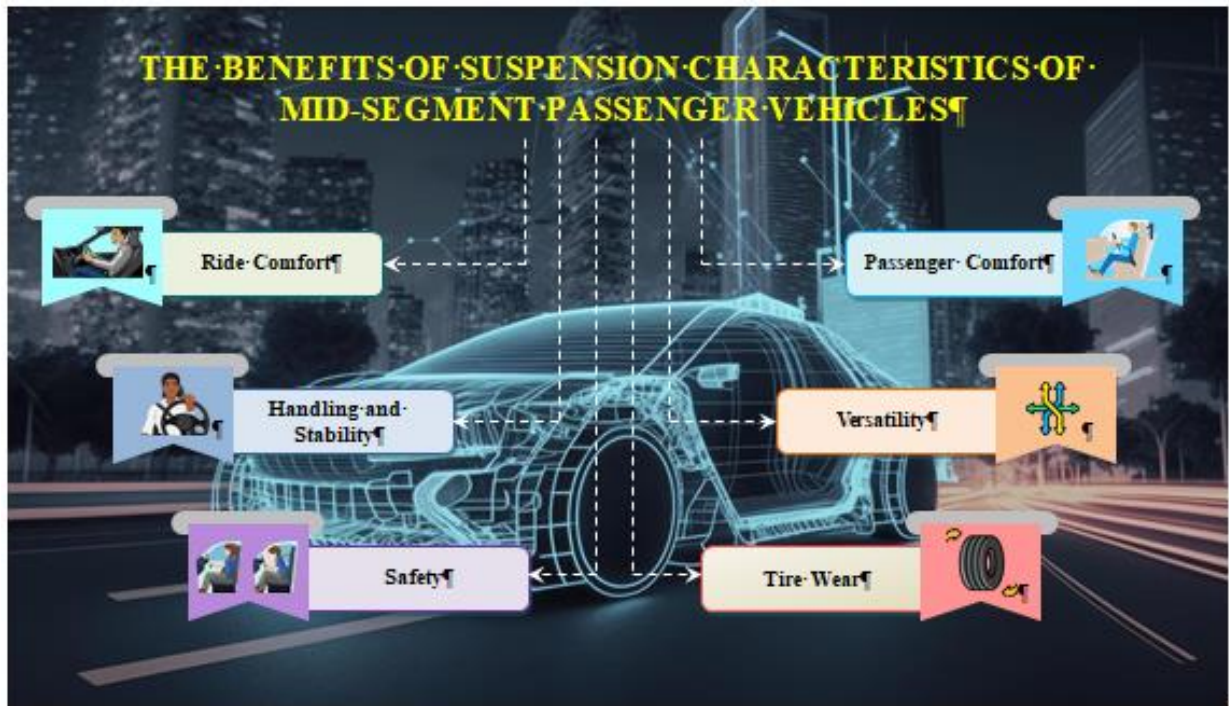


Figure 1. Benefits of suspension characteristics of mid-segment passenger vehicle

Mid-segment PVs can be called C-segment cars or executive cars. These C-segment cars show an accelerated trend in middle-class families. The middle-class family's increased income level motivates and fulfills the dream of owning a car by purchasing a C- C-segment car, which is much more appropriate for the Indian road conditions along with the financial capacity of the respondents' middle and low-middle category [6]. Some examples of mid-segment PVs include Honda City, Skoda Slavia, Volkswagen Virtus, Maruti Ciaz, Hyundai Verna, and Ford Focus. Yet, hybrid suspension is used in mid-segment PVs. Some of the examples of mid-segment PVs show advantages over the use of hybrid suspension. Some of them are proven to be more fuel efficient when analogized to conventional petrol/diesel vehicles owing to improvements in weight reduction, aerodynamics, along with a smaller engine. Likewise, the air spring part is easy to install in hybrid suspension vehicles.

Vehicles having a hybrid suspension are often adjustable with improved handling. It is also used to support vehicle weight while loading and continuously keeping the tires in contact with the road [7]. There are some characteristics of suspension in mid-segment PVs.

Some of them are suspension components, suspension geometry, suspension design, and suspension noise.

- **Suspension components-** The SS of a vehicle is made up of elastic elements, dampers, buffer blocks, guiding mechanisms, and lateral stabilizers. The suspension is armed with pneumatic tyres with diverse vibration characteristics.
- **Suspension geometry-** Harmonic force disturbs the tyre contact patch. The wheel axle's accelerations and suspension's specific points are obtained by the wheel camber, axle tilt, and roll center location [8].
- **Suspension design-** An aspect of automotive engineering, disturbed with designing the suspension for cars along with trucks, is automotive suspension design. The SS's design is important as it identifies how the vehicle transmits vibrations as of the wheels to the body [9].
- **Suspension noise-** The SS can generate noise, such as the flow of oil in the shock absorbers. The lower control arm with the control arm bushings, which connect the control arm with the vehicle frame, can cause suspension noises [10].

1.1. Research Gap

Existing literature lacks a structured and comparative analysis of suspension systems specifically for mid-segment passenger vehicles. In particular:

- Limited studies evaluate trade-offs between comfort, handling, cost, and complexity
- Lack of unified framework for comparing suspension architectures
- Insufficient focus on real-world constraints in emerging markets

1.2. Objectives and Contributions

This study aims to address these gaps through:

- Systematic classification of suspension systems
- Comparative evaluation using engineering performance metrics
- Identification of design trade-offs
- Assessment of suitability for mid-segment vehicles

Thus, this review briefly explains the investigations on SC for mid-segment PVs along with their types. In Figure 2, the review's architecture is explained.

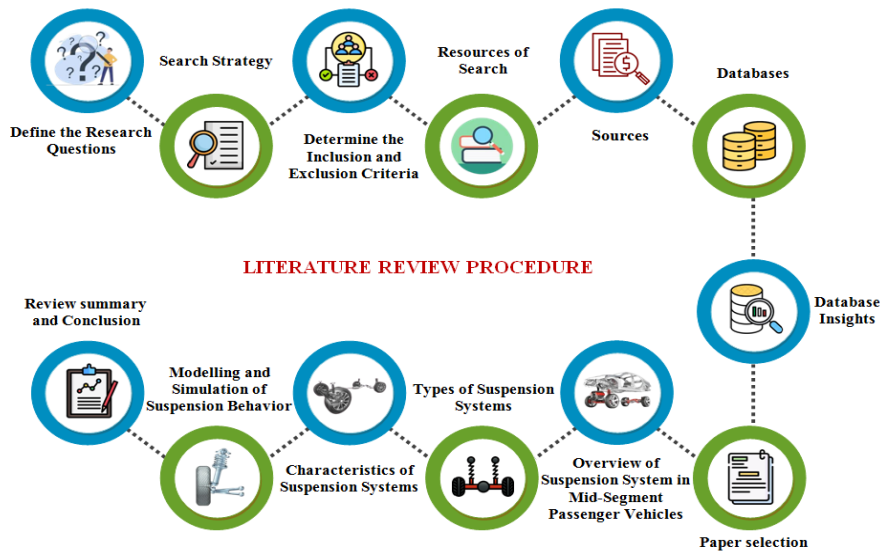


Figure 2. Architecture of the review

2. Creation of Research Questions and Article Selection Strategy

The research's focus is the Research questions (RQs). RQs should be clear, focused, concise, complex, and arguable. RQs help writers to focus the research by providing a path through the given sections. The specificity of well-developed RQs helps researchers to clarify doubts based on the given research.

2.1. Developed RQs

In this review paper, the well-organized RQs were developed. The RQs based on the SC for mid-segment PVs were created in this section. The section was organized and classified in a comparative format. Some of the RQs in this review paper were classified and explained in Figure 3.

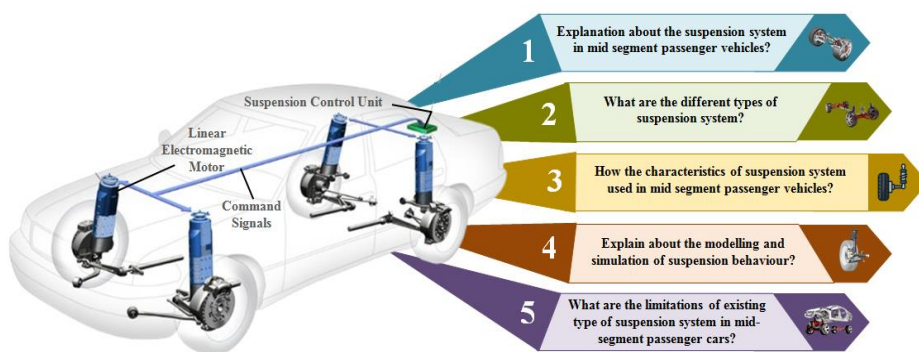


Figure 3. Developed RQs

2.2. Article Selection Strategy

It is the process of choosing the appropriate type for review. This process significantly influences the overall outcome and quality of the work. Different types of article selection in this research have a unique identity.

2.3. Selection Criteria

Inclusion Criteria:

- Studies published between 2015–2024
- Focus on suspension systems and vehicle dynamics
- Peer-reviewed journal and conference papers

Exclusion Criteria:

- Studies limited to unrelated vehicle segments
- Non-technical or conceptual-only discussions

A total of approximately **120 papers** were initially identified, out of which **55 high-quality studies** were selected for detailed analysis.

2.4. Resources of Search

Selecting the correct search and identifying the important proof for the presented research is the main objective of the resource search. Search resources focus on the areas of the search and the selection of correct relevant articles. In Table 1, the search resources, such as sources, databases, database insights, and paper selection are explained.

Table 1. Description of sources, databases, database insights, and paper selection

Sources	The related studies were taken from academic search engines, such as IEEE Xplore, Elsevier, Springer, as well as Google Scholar. Thus, the data correlated with the objective of the research within the time frame (2015 to 2024).
Databases	Important databases, including Scopus, Science Citation Index Expanded (SCIE), as well as Web Of Science (WOS), were used to identify the papers.
Database insights	Emerald was found to be distinct from other important databases. Scientific journals and conference proceedings were available in, Emerald; so, they were the best resource for researchers.
Paper selection	40 papers were selected for this review. Based on the given criteria, the papers were selected and identified.

After analyzing the search details, the literature survey's search outcome is described briefly in Figure 4.

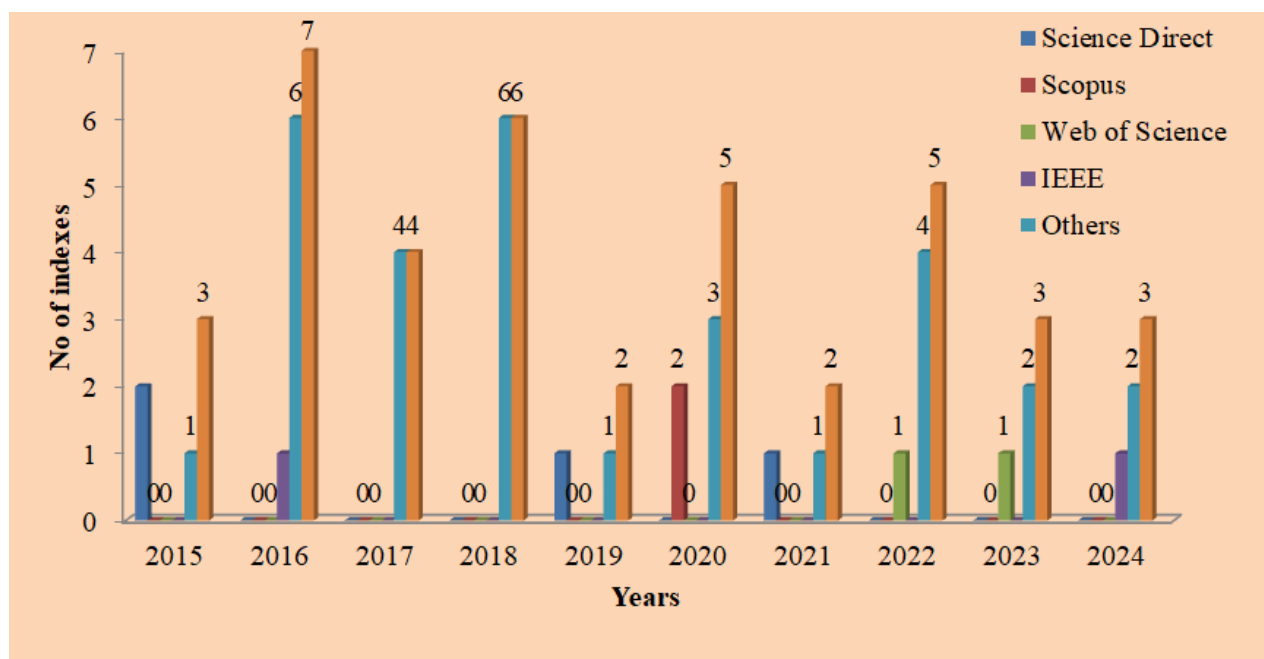


Figure 4. Search outcomes

3. Literature Review

In vehicles, the suspension serves as a pivotal connection point, permitting the wheel to move up as well as down for conserving proper placement with the road surface. In absorbing shocks and vibrations, a key role is played by the suspension control arm, offering stability during cornering and supporting the vehicle's weight. The SS is important in the mid-segment PV. The cars offer more space, comfort, and luxury features. Therefore, this review explains the overview of the SS in mid-segment PVs with the significance of Multi-purpose vehicles (MPVs) and their suspension along with the Multi-Utility Vehicles (MUVs) on the SS. Next, a detailed examination of the types of SSs available in mid-segment PVs is analyzed to identify how SS acts on different types of vehicles. Further, the characteristics of the SS in the mid-segment PV are also analyzed to examine the ride comfort, handling and stability, load distribution, and vehicle dynamics. Finally, the modeling and simulation of suspension behavior are also examined in this comprehensive review.

3.1. Overview of Suspension System in Mid-Segment Passenger Vehicles

A system of (i) tires, (ii) tire air, (iii) springs, (iv) shock absorbers, along with (v) linkages, which attach a vehicle to its wheels as well as allow relative motion, is encompassed in the SS [11]. A car suspension operates on the force dissipation principle. It encompasses converting the force into heat, which neglects the impact on the car's body [12]. Components like springs, shock absorbers, and struts are deployed by SS for attaining the damping effect. Mid-segment PVs are also known as MPVs. The cars are designed to offer optimum practicality along with comfort for enormous passengers. MUVs focus on providing maximum interior space and comfort for passengers and cargo. A car classification, which merges elements of road-going passenger cars with features as of off-road vehicles like raised ground clearance along with 4-wheel drive, is SUV [13].

Zongyi, et al. [14] elucidated vibration-damping optimization for the power assembly SS centered on the ant colony algorithm in MPVs. For vibration damping optimization design in engine SS, the ant colony algorithm was used. It could control the SS's highest order inherent frequency within the obligatory range; also, it could make the decoupling rate along the

Z axle. The highest order of the SS was reduced to 18.31Hz.

Zheng, et al. [15] defined the MPV SS simulation and optimization grounded on ADAMS. Here, the common analysis method of the kinematic characteristics of the suspension on wheels was conducted. When the wheels were balanced within the design limits, the optimization results of the toe angle were acceptable. The optimization design was limited for the evaluation process.

Jyoti, [16] elucidated Hyundai Motors India Limited's positioning towards market leadership. The study was conducted on Hyundai Motors India Limited for identifying the market leadership. Thus, in the automobile sector, huge Foreign Direct Investment (FDI) took place as well as almost every major automobile firm entered the Indian market. Station wagon bodies had stronger chassis and SSs. This study was limited to some of the global factors, namely (A) foreign demand, (B) exchange rates, along with (C) trade barriers.

Li, et al. [17] defined the MPV vehicle's total drag coefficient grounded on the Lightning Searching Algorithm (LSA). Here, the front suspension, wheelbase, and rear suspension-based characteristics were analyzed based on LSA. As per the results, the LSA contributed to the greatest performance enhancement, with an average relative error minimized as of 5.45% to 2.83%. The parameters had a lower impact on the drag coefficient in (A) hood tilt angle, (B) front overhang, (C) approaching angle, (D) departure angle, along with (E) car height.

Murat, et al. [18] defined SS parameters' optimization for an SUV. For reducing the vehicle response for the bump passing maneuver and optimizing values, a regression model was built. As per the outcome, the maximal pitch angle along with vertical acceleration was minimized by 3.4% and 9.4%, respectively. The optimized coefficients' effect was not evaluated regarding vehicle driving dynamics.

3.2. Types of Suspension Systems

A vehicle's SS is referred to as the group of mechanical components, which attach the wheels to the frame or else body [19]. Active, passive, and hybrid suspensions are the diverse sorts of SSs. The first one is a sort of automotive suspension, which deploys an onboard control system for controlling the vehicle's wheels and axles' vertical movement [20]. For counterbalancing

the test objects' mass, passive SSs deploy a system of counterweights, springs, along with pulleys. The hybrid suspension combines the passive dampers' simplicity with the electromagnetic active suspension's performance. The study related to this suspension is explained as follows,

Duc & Tuan, [21] defined the vehicle's stability when employing the active SS. For controlling the active SS's operation, the Optimization Sliding Mode Control (OSMC) was wielded. The sprung mass's maximal together with average values were minimized when the OSMC was applied under normal oscillation situations. Wheel separation phenomenon could be limited.

Phalke & Mitra, [22] elucidated the comparison of passive along with semi-active SSs by Matlab Simulink meant for diverse road profiles. To detect optimal along with robust system in diverse road conditions, the semi-active SS with a Proportional-Derivative-Integrator (PID) controller was presented. Results showed that the PID controller in the semi-active SS improved the performance much better than the passive SS. Here, the deployed derivative slowed the rate of change of the controller output.

Hui, et al. [23] defined a coordinated adaptive backstepping tracking control's design for a nonlinear uncertain active SS. For identifying the vehicle body's virtual controller design stability, the backstepping and Lya- punov stability theory were used. The controller design's inaccuracies led to the active suspension control system's instability. This study had limited suspension mechanism structures.

3.3. Characteristics of Suspension Systems

The vehicle SS's predominant role is to minimize the vertical acceleration, which is transmitted to the vehicle body, safeguarding comfort directly in the lane [24]. Thus, the SS purposes are to preclude road shocks as of being transmitted to the vehicle's components, to guard the vehicle from road shocks, as well as to sustain the vehicle's stability during pitching or else rolling while the vehicle is in motion [25]. Some characteristics of suspension in mid-segment PVs are suspension components, suspension geometry, suspension design, and ride comfort and suspension noise [26]. In Table 2, the articles linked with the SS characteristics are explained.

Table 2. Articles related to the Characteristics of suspension systems

Authors' Names	Objectives	Characteristics	Outcomes	Limitations
Suresh, et al. [27]	Appraising the passenger's seat vibrations on the irregular road surface was the goal.	Ride Comfort	As per the FFT analyzer's output, the employed software along with the plots of passenger seat responses, was attained regarding displacement, velocity, along with acceleration.	The passengers per volume or else area and the amount of insulation material were limited.
Keunuk, et al. [28]	To appraise the structural strength subjected to arbitrary forces employing several shapes of cross-member reinforcements.	Ride comfort	As per the results, stiffness along with driving stability factors like (i) smooth road shake, (ii) impact hardness, as well as (iii) memory shake were identified.	The ride comfort was performed just centered on the vibration produced by acceleration below dynamic conditions.
Santosa, et al. [29]	To present a technique for detecting rollover probability in SUVs and MPVs.	Load distribution	As per the results, the safety rating was determined in the SUVs and MPVs along with the load distribution characteristics.	Only limited information was available for the analysis of load distribution.
Chihua, et al. [30]	To examine the dynamics simulation based on	Vehicle dynamics	It had better engineering value as well as was apt for	The computational cost and time were limited

Authors' Names	Objectives	Characteristics	Outcomes	Limitations
	super element modelling for increasing dynamics simulation efficiency.		dynamics problems of vehicle bodies.	for structural optimization.
Yueru, et al. [31]	To analyze the acceleration/deceleration characteristics for the representation and simulation of the traffic flow, especially in MPVs.	Vehicle dynamics	The results showed that the vehicle dynamics were identified in MPVs.	There was a long charging time along with limited driving distance due to the limitations of battery technology.

Shenjin & Yuping, [32] defined the Driver-Adaptive Stability Control Strategy for SUVs. To simulate the SUV vehicle dynamics, the SMC-centric differential braking (DB) controller model was designed. As per the results, the resulting yaw rate's peak values were minimized with the skills' augmentation. The data collection for the suspension identification was limited.

Kexiang, et al. [33] defined the economic benefits as well as the adaptability of different Electric Vehicles (ELV), such as MPV powertrain topologies. Here, the control methods were used for the examination of the comfort of riding in MPVs. The powertrain topology depended mainly on the vehicle's total mass. The differential control of the wheels when the vehicle operated in complex conditions was not analyzed.

Amron, et al. [34] defined the influence of (A) brand image, (B) brand trust, (C) product quality, along with (D) price on the consumer's buying decision of MPV cars. For attaining primary data regarding the ride comfort in MPVs, questionnaires were employed. As per the outcome, competitive prices had a key and favourable effect on buying decisions. Here, the data for identifying the passengers' ride comfort in MPVs was limited.

Rinu, et al. [35] defined a combined big data analytics along with Fuzzy decision-making trial along with an evaluation laboratory to improve the responsiveness of automotive supply chains in SUVs. As per the results, in SUVs, the ride comfort characteristic was identified with the decision-making trial together with the evaluation laboratory. Yet, when modeling the car interior and engine, this process would cost a huge time along with computational power.

3.4. Modelling and Simulation of Suspension Behavior

The modeling and simulation of suspension behavior in mid-segment PVs or hybrid suspensions involves creating computational models to analyze and predict the dynamic responses of the SS under various conditions. These models typically incorporate elements, such as springs, dampers, and control arms, and are used to simulate real-world scenarios like road bumps, potholes, and high-speed maneuvers [36]. eEngineers can evaluate the performance of different suspension designs, optimize parameters for improved ride comfort and handling, and develop advanced control strategies for semi-active or active SSs by using software tools like MATLAB/Simulink. This process helps in achieving a balance between comfort, stability, and safety, ultimately enhancing the overall driving experience for passengers [37].

Simulation Tools Used in Suspension Analysis

Multi-Body Dynamics (MBD) software is a tool that allows the simulation of the motion and interaction of the vehicle suspension. MBD software helps to study the dynamics, kinematics, vibrations, and stability of vehicle SSs. In this study, the MBD software is used for the analysis.

Sarang, et al. [38] elucidated the integrated approach for air SS's development for an SUV category vehicle deploying analytical as well as experimental tools. To implement an air SS in SUV pickup category vehicles, a robust virtual modeling methodology was used. As per the results, the standard deviation values for a few vital measured parameters, like driver seat Z direction acceleration and chassis Z direction acceleration, were identified. The vehicle's ride performance via air springs' pressure setting was difficult to attain in the default vehicle SS.

Adam, et al. [39] defined road vehicles' higher-speed driving stability under crosswinds centered on aerodynamic, along with vehicle dynamic parametric sensitivity analysis. To appraise stability performance in SUV's early design phases, the robust virtual methods were wielded. As per the results, for minimizing the yaw moment to the negative peak value, the front as well as rear axle side forces worked together. Here, the wielded optimization software limited the crosswind stability.

Wonjo, [40] defined an electronic stability control development for enhanced vehicle handling employing co-simulation. To augment vehicle handling, the Non-Singular Fast Terminal Sliding Mode (NFTSM) was wielded. As a result, the maximum lateral displacement was higher at $t = 1.07$ seconds. The NFTSM limited the desired yaw rate at the friction.

The analysis indicates a clear shift from passive to adaptive suspension systems. Mid-segment vehicles require:

- Cost-effective solutions
- Improved ride comfort
- Moderate complexity

Hybrid and semi-active systems meet these requirements effectively. However, challenges remain in:

- Control system design
- Energy efficiency
- Integration with vehicle electronics

4. Summary of the Review

Augmenting a vehicle's overall performance is the SS's primary function as it cruises down the road. Moreover, it aids in absorbing bumps in the road along with offers a safe as well as comfortable ride. In modern vehicles, the wielded 2 most common types of SSs are independent suspension along with solid axle suspension. Superior ride comfort, handling, and traction are provided by independent suspension like MacPherson strut, as well as double wishbone designs. Yet, solid axle suspension, like leaf spring as well as solid axle coil spring, excels in hefty-duty applications along with off-road environments. SS's choice relies on specific requirements, vehicle type, along with intended use. Vehicle owners could make informed

decisions to augment their driving experience by recognizing every SS's characteristics and advantages.

The serviceability assessment's main problem is the steel suspension footbridge, which is performed via dynamic testing as well as numerical simulations. The experimental part involves structural response's operational model testing and measurement under diverse group crossing of pedestrians. The footbridge exhibits complex dynamic characteristics (that is., '2' couples of closely spaced modes as well as '5' modes in the frequency range of 1.9–3.0 Hz), along with the maximal accelerations encouraged by pedestrians along with joggers, turn out to be in the discomfort range.

Thus, the active SS's proper design by considering its present limitations is vital. The Magnetorheological (MR) dampers have considerably improved automotive SSs by offering adaptable damping characteristics regarding varying road conditions along with driving dynamics. The evolution's comprehensive analysis, as well as MR damper integration in semi-active SSs, needs to be conducted. An optimal balance is presented by semi-active systems by incorporating the simplicity inherent with active systems' adaptability characteristic while mitigating substantial energy consumption.

The suspension spring material's most common type is steel because of its sheer strength, durability, along with affordability. This strong, rigid material could withstand heavy impacts and loads as well as resist deformation.

The best software for suspension analysis can depend on the specific needs, such as the type of vehicle, the level of detail required, and the budget. Some of the top options widely used in the industry are ADAMS (MSC Software), SolidWorks, MATLAB/Simulink, CarSim, Altair HyperWorks, ANSYS, Simpack, and OpenModelica. This software considers factors like ease of use, integration with other tools, cost, and specific analysis capabilities. A combination of these tools may also be beneficial for comprehensive analysis and design optimization.

A steel alloy's helical cylindrical coil spring is chosen as an advanced method for designing a hybrid suspension special type. Steel alloy is wielded as it has high strength, lower durability, ease of availability, along with cost attractiveness when weighed against other composite materials.

Some of the methods of optimization or AI ML frameworks given by various authors in enhancing/predicting SC are explained. To augment model performance, accuracy, and efficiency, AI optimization techniques are essential. Hyperparameter tuning, regularization, pruning, quantization, and gradient descent optimization are the key techniques. These techniques help to minimize overfitting issues,

speed up training, and augment generalization. Thus, in this type of hybrid suspension, the analysis of characteristics is important. This review explains the SS of the mid-segment PVs, the characteristics of the SS, the types of the SS, and the modeling and simulation of the suspension behavior. In Figure 5, the diagrammatic representation of the questions and the related answers in the particular section is explained.

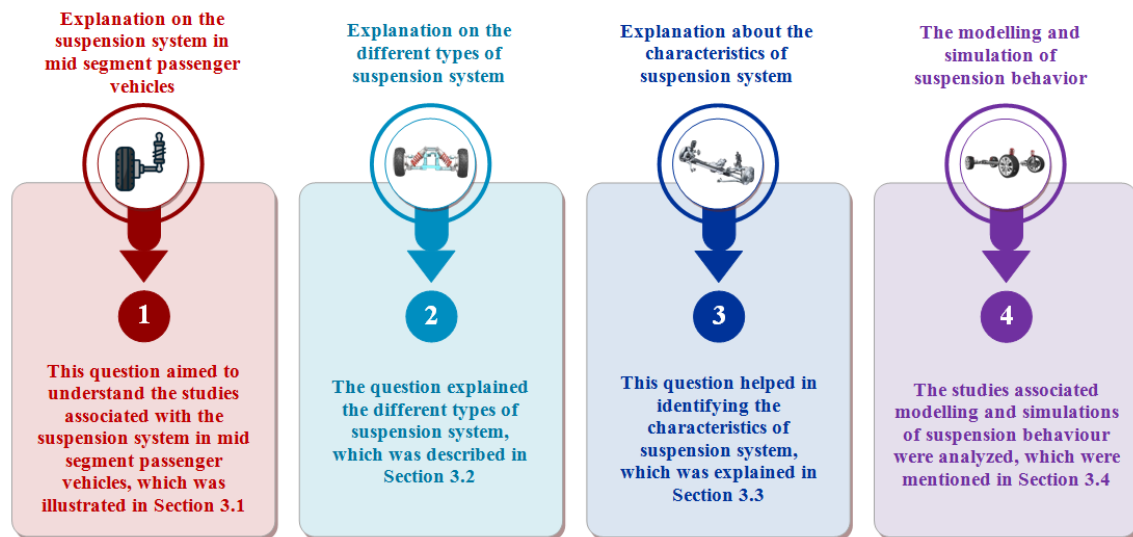


Figure 5. Summary of the review

This review gives an explanation of the SS, the problems that occur in the SS, and the solutions for the related challenges. Thus, the SS in mid-segment vehicles provides the essential damped spring opposing force while being compressed. Springs bear the vehicle's weight. Dampers oppose the spring movement, dissipating their energy along with averting them from bouncing without control.

5. Limitations of the Existing Type of Suspension System in Mid-Segment Passenger Cars

Here, some of the limitations of the existing type of SS in mid-segment passenger cars are analyzed. Initially, the vehicle's driving comfort is detected by the SS's design, which transmits the force betwixt the vehicle as

well as the ground. There are diverse sorts of vehicle SSs in mid-segment PVs. Active SSs, which offer key benefits for ride comfort while driving, are a few of them. Yet, no proof is provided in some studies that driver comfort could be predicted while adopting a few present recommendations. Also, in some studies, it is identified that enlightening cabin comfort is an engineering challenge as the 1st commercial vehicles are designed. Now, the options for further enhancement employing passive suspension devices are limited. Yet, numerous semi-active as well as active alternatives are available. Here, the latter offers the biggest performance gains both regarding cabin comfort and attitude-behavior; but, it also requires development.

5.1. Comparative Evaluation

Table 3. Suspension Comparison

Type	Advantages	Limitations	Cost	Complexity	Suitability
Passive	Low cost, simple	Limited adaptability	Low	Low	Entry-level
Semi-active	Improved comfort	Moderate control	Medium	Medium	Mid-segment
Active	High performance	Expensive, complex	High	High	Premium
Hybrid	Balanced performance	Design complexity	Medium	Medium	Mid-segment

5.2. Engineering Trade-offs

Suspension design involves balancing competing requirements:

- **Comfort vs Handling:** Softer suspensions improve comfort but reduce stability
- **Performance vs Cost:** Advanced systems enhance performance but increase cost
- **Complexity vs Reliability:** More control leads to higher maintenance challenges

Semi-active and hybrid systems offer the most practical compromise.

5.3. Limitations

- Limited availability of real-world experimental data
- Variability in evaluation metrics across studies

5.4. Future Scope

- AI-based suspension control systems
- Integration with autonomous driving
- Real-time adaptive suspension tuning

6. Conclusion

This study presented a structured and analytical review of suspension systems in mid-segment passenger vehicles. The findings highlight that while passive systems remain economical, they are insufficient for modern performance requirements. Active systems offer superior performance but are constrained by cost and complexity. Semi-active and hybrid suspensions emerge as optimal solutions, providing a balance between ride comfort, stability, and affordability. Future advancements in intelligent control systems are expected to further enhance suspension performance.

A set of components connecting a vehicle's wheels to the rest of the car is the SS. Its only resolution was keeping the car stable by absorbing each external force applied on the wheels owing to undulations on the road, speed breakers, or else other obstacles. This SS was more important in mid-segment PVs like cars. More space, comfort, and luxury features were offered by cars. To accommodate a family of five comfortably for long drives, hybrid suspension cars were designed. The Honda City, Toyota Corolla, and Hyundai Verna are some popular mid-size cars. In these mid vehicles, the evaluations of SC were necessary. Suspension geometry, suspension design, suspension types,

comfortable ride, and suspension noise are the characteristics of the suspension in mid-segment PVs. These characteristic investigations analyzed the influence of the rubber bushings and other elastic connections on the behavior of the suspension. The limitation was that the SSs were complex and needed refined control algorithms and sensors, which could enhance the probability of technical problems and maintenance needs. Thus, researchers must consider this significant limitation in the future to find the optimum solution to sort out the technical problems. Likewise, these problems will be noticed and overcome by using various advanced techniques for an effective SS in vehicles.

References

- [1] Ozlem Simsekoglu, Trond Nordfjaern and Torbjorn Rundmo, "The role of attitudes, transport priorities, and car use habit for travel mode use and intentions to use public transportation in an urban Norwegian public", *Transport Policy*, vol. 42, pp. 1-8, 2015.
- [2] Ananda Prasad Rao M, "Advanced Automotive Technologies", *International Journal of Science and Research*, vol. 11, no. 6, pp. 1-5, 2022.
- [3] Yurlin D, "Intelligent systems of the vehicles' suspension", *IOP Conference Series: Materials Science and Engineering*, vol. 315, no. 1, pp. 1-11, 2018.
- [4] Mohamad Amiruddin Bin Ismail, Irdayanti binti Mat Nashir, Sethuprakash V, Kazuma Sekiguchi and Lee Soyoung, "Design of Magnetorheological Suspension of Cclass car segment using Spencer model for education", *Central Asia and the Caucasus*, vol. 22, no. 5, pp. 1-8, 2021.
- [5] Karunakar B, "Indian Passenger Vehicle Industry: Strategic Analysis with Focus on the Big Four Firms", *NMIMS Journal Of Economics And Public Policy*, vol. 11, no. 1, pp. 1-27, 2017.
- [6] Victor Charles J, Kathiravan C and Velaudham C, "Consumer Expectation towards C- Segment Cars in Chennai City", *Journal of Exclusive Management Science*, vol. 5, no. 9, pp. 1-50, 2016.
- [7] Narayan S, Ali Sulaiman Alsagri and Vipul Gupta, "The Design And Analysis Of Hybrid Automotive Suspension System", *International Journal of Mechanical and Production Engineering Research and Development*, vol. 9, no.4, pp. 1-7, 2019.
- [8] Zlatin Georgiev and Lilo Kunchev, "Study of the vibrational behaviour of the components of a car

- suspension", MATEC Web of Conferences, vol. 234, pp. 1-6, 2018.
- [9] Anirban C Mitra, Tanushri Soni, Kiranchand G. R, Shaizam Khan and Nilotpal Banerjee, "Experimental Design and Optimization of Vehicle Suspension System", Materials Today: Proceedings, vol. 2, pp. 1-10, 2015.
 - [10] Rajin Vhora, "Automotive Noise And Vibration Control", International Journal of Advance Research and Innovation Ideas in Education, vol.4, no. 6, pp. 1-6, 2018.
 - [11] Bilal Abduraxman, Peter Hubbard, Tim Harrison, Christopher Ward, David Fletcher, Roger Lewis and Ben White, "Acceleration-based friction coefficient estimation of a rail vehicle using feedforward NN: validation with track measurements", Vehicle System Dynamics, vol. 62, no. 12, pp. 1-21, 2024.
 - [12] Harus Laksana Guntur, Wiwiek Hendrowati and Skriptyan N. H Syuhri, "Designing hydro-magneto-electric regenerative shock absorber for vehicle suspension considering conventional viscous shock absorber performance", Journal of Mechanical Science and Technology, vol. 34, no. 1, pp. 1-13, 2020.
 - [13] Omar M. F, Ghazali R, Saadon I. M, Aripin M. K, Sam Y.M and Soon C. C, "Optimal Control for Sport Utility Vehicle System Using Linear Quadratic Integral Control Approach", Journal of Telecommunication, Electronic and Computer Engineering, vol. 10, no. 4, pp. 1-7, 2018.
 - [14] Zongyi Xing, Xinrong Liu, Yang Zhao, Yong Qin and Limin Jia, "Optimization of Vibration Damping for the Power Assembly Suspension System Based on Ant Colony Algorithm", International Journal of Simulation, Systems, Science and Technology, vol. 21, no. 5, pp. 1-5, 2016.
 - [15] Dongchen Qin, Junjie Yang, Qiang Zhu and Peng Du, "Simulation and Optimization of MPV Suspension System Based on ADAMS", Proceedings of the World Congress on Structural and Multidisciplinary Optimization, pp. 1-5, 2015. https://web.aeromech.usyd.edu.au/WCSMO2015/papers/1149_paper.pdf
 - [16] Jyoti Kainth and Tanmay Mathur, "Hyundai Motors India Limited: positioning towards market leadership", Emerald Emerging Markets Case Studies, vol. 6, no. 1, pp. 1-20, 2016.
 - [17] Li Yang, Shuyun Jiang, Jun Zhang and Chuanbo Liu, "A novel prediction model of total drag coefficient of an MPV vehicle based on LSA optimization", Journal of Physics: Conference Series, vol. 2816, pp. 1-8, 2024.
 - [18] Murat Otkur, Narjes Alshammari, Noura Abdullah, Danah Alkandari, Hanan Thyab and Latifah Alduwaisan, "Optimization of Suspension System Parameters for a SUV", Proceedings of the 8th World Congress on Mechanical, Chemical, and Material Engineering, vol. 137, pp. 1-8, 2022.
 - [19] Shiping Wen, Michael Z. Q Chen, Zhigang Zeng, Xinghuo Yu and Tingwen Huang, "Fuzzy Control for Uncertain Vehicle Active Suspension Systems via Dynamic Sliding-Mode Approach", IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 47, no. 1, pp. 1-11, 2016.
 - [20] Sono Bhardawaj, Rakesh Chandmal Sharma and Sunil Kumar Sharma, "Development of multibody dynamical using MR damper based semi-active bio-inspired chaotic fruit fly and fuzzy logic hybrid suspension control for rail vehicle system", Journal Multi-body Dynamics, vol. 234, no. 4, pp. 1-22, 2020.
 - [21] Duc Ngoc Nguyen and TuanAnh Nguyen, "Evaluate the stability of the vehicle when using the active suspension system with a hydraulic actuator controlled by the OSMC algorithm", Scientific reports, vol. 12, no.1, pp. 1-15, 2022.
 - [22] Phalke T. P and Mitra A. C, "Comparison of passive and semi-active suspension system by MATLAB SIMULINK for different road profiles", IOSR Journal of Mechanical and Civil Engineering, pp. 1-6, 2016. <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=0f7682e6a0671d73009cd7b36520b351155d6dde>
 - [23] Hui Pang, Xu Zhang, Jianan Chen and Kai Liu, "Design of a coordinated adaptive backstepping tracking control for nonlinear uncertain active suspension system", Applied Mathematical Modelling, vol. 79, pp. 1-16, 2019.
 - [24] Mohd H Ibrahim, Raja M. Raja M, Nor A. I Mazlan, et al., "Rapid Upper Limb Assessment among Malaysian Multi-Purpose Vehicle's Driver", Current Journal of Applied Science and Technology, vol. 42, no. 5, pp. 1-7, 2023.
 - [25] Mohammad Firdaus Mohammed Azmi, Mohammad Al Bukhari Marzuki and Mohd Arzo Abu Bakar, "Vehicle Aerodynamics Analysis Of A Multi Purpose Vehicle Using Cfd", vol. 12, no. 7, pp. 1-7, 2017.

- [26] Nazri Huzaimi Zakaria, Usha J, Sivaraos, Ruthrabathi S and Raguvaran M. J, "A Comprehensive Analysis on Aerodynamic Characteristics of a MPV Spoiler", *International Journal of Engineering Research and Technology*, vol. 9, no. 10, pp. 1-9, 2020.
- [27] Suresh Abasaheb Patil and Indrajit Dinkar More, "On-Road Ride Comfort Test and Simulation Analysis of Passenger Cars with Emphasis on Indian Suburban and Rural Road Conditions", *SAE Technical Papers*, pp. 1-12, 2016. <https://10.4271/2016-01-1680>
- [28] Keunuk Chung, Yeonghoon Lee and Jinwook Lee, "The Analysis of Stiffness and Driving Stability in Cross-Member Reinforcements Based on the Curvature of a Small SUV Rear Torsion Beam Suspension System", *Applied Sciences*, vol. 13, pp. 1-15, 2023.
- [29] Santosa S. P, Jusuf A, Gunawan L, Abu Kassim K. A, Hakim M. L and Wiranto B. P. E, "Rollover Risk Probability Analysis for SUVs and MPVs in the ASEAN Market", *Journal of the Society of Automotive Engineers Malaysia*, vol. 2, no. 3, pp. 1-14, 2018.
- [30] Chihua Lu, Wenxin Yang, Hao Zheng, Jingqiang Liang and Guang Fu, "The Application of Superelement Modeling Method in Vehicle Body Dynamics Simulation", *SAE Technical Paper*, pp. 1-7, 2016. <https://10.4271/2016-01-8050>
- [31] Yueru Xu, Yuan Zheng and Ying Yang, "On the movement simulations of electric vehicles: A behavioral model-based approach", *Applied Energy*, vol. 283, pp. 1-11, 2021.
- [32] Shenjin Zhu and Yuping He, "A Driver-Adaptive Stability Control Strategy for Sport Utility Vehicles", *Vehicle system dynamics*, vol. 55, no. 8, pp. 1-24, 2017.
- [33] Kexiang Wei, Hongguang Zhou, Xiong Shu, Songlin Xie and Konlayutt Punyawudho, "Research on Economic Benefits and Adaptability of Different ELV Powertrain Topologies", *IEEE Access*, vol. 12, pp. 1-12, 2024.
- [34] Amron Amron, "The Influence of Brand Image, Brand Trust, Product Quality, and Price on the Consumer's Buying Decision of MPV Cars", *European Scientific Journal*, vol. 14, no. 13, pp. 1-12, 2018.
- [35] Rinu Sathyan, Parthiban P, Dhanalakshmi R and Amrita Minz, "A combined big data analytics and Fuzzy DEMATEL technique to improve the responsiveness of automotive supply chains", *Journal of Ambient Intelligence and Humanized Computing*, vol. 12, pp.1-15, 2020.
- [36] Duc Ngoc Nguyen and Tuan Anh Nguyen, "A Novel Hybrid Control Algorithm Sliding Mode-PID for the Active Suspension System with State Multivariable", *Complexity*, vol. 2022, pp. 1-14, 2022.
- [37] Walelign Wudu Bezabh, Ayitenew Mogninet Getaneh and Mequanint Birhan, "Simulation of Control System for a Half-Car Suspension System for Passenger Vehicle Application by Designing an LQR Controller", *Qeios*, pp. 1-15, 2023. <https://doi.org/10.32388/SGEORJ>
- [38] Sarang Bire, Prashant R Pawar and Saraf M, "Integrated Approach for Development of Air Suspension System for a SUV Category Vehicle Using Analytical and Experimental Tools", *SAE Technical Paper*, pp. 1-7, 2017. <https://www.sae.org/publications/technical-papers/content/2017-26-0340/>
- [39] Adam Brandt, Bengt Jacobson and Simone Sebben, "High speed driving stability of road vehicles under crosswinds: an aerodynamic and vehicle dynamic parametric sensitivity analysis", *Vehicle System Dynamics*, vol. 60, no. 7, pp. 1-25, 2022.
- [40] Wonjo Jung, "Development of an Electronic Stability Control for Improved Vehicle Handling using Co-Simulation", *Thesis, University of Windsor*, 2020.