

ANALYSIS OF THE STRUCTURAL AND OPERATIONAL CHARACTERISTICS OF AUTOMOTIVE SUSPENSION SYSTEMS

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Abstract

This article presents an IMRAD-based analytical study of the structural and operational characteristics of automotive suspension systems. The suspension system forms an elastic and damping connection between the vehicle body and the wheels; therefore, it directly influences ride comfort, road holding, braking stability, cornering behaviour, tire wear and overall traffic safety. The research evaluates dependent, independent, semi-independent, pneumatic, passive, semi-active and active suspension concepts by comparing their design features, elastic and damping components, adaptability to road conditions, maintenance requirements and expected operational reliability. The methodological basis of the study is a theoretical and comparative analysis of suspension elements, technical functions, typical failures and conditional performance indicators, including stability, road adhesion, energy absorption and ride comfort. The results show that independent suspension provides better stability and road contact than rigid axle suspension, while semi-independent suspension offers a practical compromise between cost, compactness and operational performance. Semi-active and active suspension systems improve comfort and vehicle dynamics more effectively than passive systems; however, their use is limited by higher cost, greater complexity and more demanding service requirements. The study concludes that the correct selection, diagnosis and maintenance of suspension systems are essential for improving vehicle safety, reducing operational faults and extending the service life of suspension components.

Keywords: automobile, suspension system, shock absorber, spring, stabilizer, independent suspension, dependent suspension, semi-active suspension, active suspension, ride comfort, road holding, vehicle safety.

1. Introduction

The dynamic behaviour of a motor vehicle is determined not only by the powertrain, steering and braking systems, but also by the quality of the suspension system. The suspension is the mechanical, elastic and damping subsystem that connects the vehicle body or frame with the wheel assembly. During motion, the vehicle interacts continuously with uneven road surfaces, potholes, speed bumps, transverse waves and lateral forces generated in cornering. These external disturbances are transferred through the wheels to the suspension, where their influence must be reduced before they reach the passenger compartment and the load-bearing structure of the vehicle.

The main engineering task of a suspension system is to satisfy two partly conflicting requirements. First, the system must provide ride comfort by isolating the body from road-induced shocks and vibrations. Second, it must maintain reliable tire-road contact so that the vehicle remains controllable during acceleration, braking and cornering. A very soft suspension improves comfort on rough roads, but it can cause excessive body roll, pitch and heave. A very stiff suspension improves handling response, but it increases vibration and impact loads transmitted to the occupants and structural elements. Therefore, suspension design always requires a balanced compromise between comfort, handling, safety, cost and durability.

Traditional suspension systems are based on passive mechanical components, such as coil springs, leaf springs, torsion bars, shock absorbers, control arms and anti-roll bars. These elements

are simple and reliable, but their stiffness and damping parameters are fixed after design and manufacture. As a result, passive systems cannot fully adapt to different road profiles, vehicle loads and driving conditions. Modern automotive engineering increasingly applies pneumatic, semi-active and active suspension technologies to overcome these limitations. In semi-active systems, the damping characteristic may be adjusted according to road and vehicle conditions, while active systems use electronically controlled actuators to control the forces between the wheel and the body.

The structural choice of a suspension system depends on the vehicle category, its intended operating conditions and the priorities of the manufacturer. Heavy-duty vehicles and buses often use dependent suspension because of its simplicity, strength and load-carrying capacity. Passenger cars commonly use independent or semi-independent suspension because these configurations improve ride comfort and wheel control. Premium vehicles may use pneumatic or active systems to achieve a higher level of comfort, adaptable ride height and stable body posture in different operating modes.

The operational reliability of the suspension is also of major importance. Worn shock absorbers, cracked rubber bushings, loose ball joints, sagging springs, damaged stabilizer links and incorrect wheel alignment reduce vehicle stability and may increase stopping distance, noise, vibration, tire wear and accident risk. For this reason, suspension analysis must consider not only design schemes but also real service conditions, road quality, overload, speed regimes, climate, maintenance intervals and diagnostic procedures.

The aim of this article is to rewrite and develop the source materials into a coherent IMRAD-structured English research article. The specific objectives are: (1) to systematize the main structural types of automotive suspension systems; (2) to compare passive, semi-active and active suspension concepts; (3) to evaluate key operational indicators such as ride comfort, road adhesion, stability and energy absorption; and (4) to formulate practical recommendations for improving the reliability and safety of suspension operation.

2. Materials and Methods

The study was carried out using a theoretical, comparative and analytical methodology. The source materials contained two related manuscripts on automotive suspension systems: one extended article with an abstract, introduction, methodology, results, discussion and conclusion, and one shorter analytical article containing a methodological sequence, a comparative table and a diagram of suspension indicators. These materials were consolidated and rewritten in English according to the IMRAD format.

The analysis focused on the following groups of suspension characteristics: structural layout, elastic element type, damping element, stabilizer function, operating conditions and control method. The evaluation also considered operational criteria such as ride comfort, road holding, cornering stability, structural complexity, maintenance convenience, reliability and typical service failures.

The research did not involve new laboratory measurements. Instead, it systematized the technical information, comparative values and engineering indicators presented in the source materials. The numerical values used in the comparative tables are treated as conditional analytical indicators for comparing suspension types rather than universal values applicable to every vehicle. Such an approach is suitable for a review-analytical article, educational research and preliminary engineering assessment.

The analytical procedure consisted of five stages: structural analysis, operational analysis, comparative performance assessment, interpretation of failure mechanisms and development of practical recommendations. Structural analysis examined the functions of springs, shock absorbers, control arms, stabilizers, rubber-metal joints and bearings. Operational analysis assessed the

influence of road profile, vehicle load, driving speed and maintenance quality. Comparative assessment used normalized or score-based indicators for stability, road adhesion, energy absorption and comfort.

Table 1. Main criteria used in the analytical comparison

No.	Criterion	Assessment indicator	Practical significance
1	Structural layout	Dependent, independent and semi-independent suspension	Selection according to vehicle type and intended operation
2	Elastic element	Coil spring, leaf spring, torsion bar or air spring	Ride comfort and load-carrying ability
3	Damping element	Shock absorber type and technical condition	Effectiveness of vibration suppression
4	Stabilizer	Reduction of body roll in cornering	Improvement of lateral stability
5	Operating conditions	Road quality, load, speed and climate	Wear rate and service life of suspension parts
6	Control method	Passive, semi-active and active suspension	Adaptability, comfort and handling performance

For the comparative analysis of dependent, independent and semi-independent suspension types, four indicators were used: stability index, road adhesion index, energy absorption and comfort score. The coefficients of stability and adhesion were expressed as relative values between 0 and 1, energy absorption was expressed as a percentage, and comfort was scored on a 1 to 10 scale. For graphical presentation, all values were normalized to a percentage scale.

3. Results

3.1. Main structural elements of the suspension system

The suspension system consists of several elements that work as one dynamic system. Each element has a specific function, and the failure of even a single component can reduce comfort, control accuracy and safety. The spring or leaf spring accepts vertical loads and elastic deformation caused by road irregularities. The shock absorber dissipates the energy stored in the spring and prevents long-lasting body oscillations. Control arms guide the wheel trajectory, while bushings and joints provide movable connections and reduce noise and vibration.

The stabilizer bar is especially important during cornering. When the vehicle body tends to roll to one side, the stabilizer generates a restoring torsional force that reduces excessive lateral inclination. This improves driver confidence and decreases the risk of loss of control during sharp manoeuvres. Support bearings, ball joints and other connecting elements ensure correct movement of the suspension and influence steering accuracy.

Table 2. Suspension elements and their operational functions

Element	Main function	Operational significance
Coil spring or leaf spring	Receives and stores road impact energy elastically	Provides ride smoothness and load support
Shock absorber	Dissipates oscillation energy and controls rebound	Reduces excessive body vibration and improves tire contact
Control arms	Determine wheel movement relative to the body	Influence steering response and wheel alignment stability
Anti-roll bar	Reduces body roll during cornering	Improves lateral stability and handling

Bushings and silent blocks	Provide elastic movable joints	Reduce noise, vibration and harshness
Ball joints and support bearings	Transfer steering and suspension loads	Affect steering accuracy and service safety

3.2. Classification of suspension systems by structural layout

From the structural point of view, automotive suspension systems can be divided into dependent, independent and semi-independent systems. In a dependent suspension, the left and right wheels of the same axle are rigidly connected. When one wheel moves vertically, it influences the position of the opposite wheel. This configuration is simple, durable and suitable for high loads, which explains its use in trucks, buses and some off-road vehicles. Its main disadvantage is lower ride comfort and weaker road holding compared with independent designs.

In an independent suspension system, each wheel is connected to the vehicle body separately. The movement of one wheel has less influence on the opposite wheel. This improves the ability of the tire to follow road irregularities, increases ride comfort and provides more accurate control of wheel geometry. Independent suspension is therefore widely used in passenger cars and high-performance vehicles.

Semi-independent suspension combines some advantages of dependent and independent layouts. It is often used on the rear axle of compact and medium-size passenger cars. This type is relatively inexpensive, compact and easy to service. However, its dynamic performance is limited compared with fully independent suspension, especially at high speeds, under heavy loads or on highly uneven road surfaces.

Table 3. Comparative characteristics of structural suspension types

Suspension type	Advantages	Limitations	Typical application
Dependent suspension	Simple, strong and high load capacity	Lower comfort, larger unsprung mass and limited wheel independence	Trucks, buses and off-road vehicles
Independent suspension	High comfort, better handling and better road contact	More complex and more expensive	Passenger cars and premium models
Semi-independent suspension	Low cost, compact design and easy maintenance	Limited dynamic ability compared with independent suspension	Urban and compact passenger cars
Pneumatic suspension	Adjustable height and high comfort	Higher cost and service complexity	Premium cars, buses and special vehicles
Active suspension	Highest level of body control and adaptability	Very expensive and technically complex	High-class and advanced vehicles

3.3. Passive, semi-active and active suspension systems

Suspension systems may also be classified according to their control characteristics. Passive suspension is the traditional solution based on mechanical springs and shock absorbers with fixed parameters. It is inexpensive, mechanically reliable and easy to maintain, but it cannot change its damping or stiffness characteristics in response to road conditions or driving style.

Semi-active suspension changes the damping force of the shock absorber according to the operating mode. The system does not add large external forces to the suspension, but it modifies

the energy dissipation process. Magnetorheological dampers are one of the most important examples: the viscosity and resistance of the damper fluid can be changed by a controlled magnetic field. This allows a semi-active suspension to improve comfort and road holding without the high energy consumption typical of fully active systems.

Active suspension uses actuators to generate controlled forces between the vehicle body and the wheel assembly. It can actively reduce heave, pitch and roll, maintain a stable body posture and adapt to changing road and load conditions. However, active suspension requires sensors, electronic control units, actuators, a power supply and complex control algorithms, which increases cost, energy demand and maintenance requirements.

Table 4. Comparison of passive, semi-active and active suspension systems

Indicator	Passive suspension	Semi-active suspension	Active suspension
Structural simplicity	High	Medium	Low
Cost	Low	Medium	High
Ride comfort	Medium	High	Very high
Handling and stability	Medium	High	Very high
Energy consumption	Very low	Low	High
Maintenance complexity	Low	Medium	High
Adaptability to road conditions	Low	High	Very high

3.4. Comparative indicators of suspension performance

The comparative indicators show that independent suspension has the best combination of stability, road adhesion, energy absorption and comfort among the three traditional structural groups. Semi-independent suspension provides an intermediate level of performance, while rigid axle suspension has lower comfort and road holding but remains useful where strength and load capacity are priorities.

Table 5. Conditional comparative indicators of suspension systems

Suspension type	Stability coefficient	Road adhesion coefficient	Energy absorption, %	Comfort score (1-10)
Independent suspension	0.85	0.90	75	9
Semi-independent suspension	0.70	0.75	60	7
Rigid axle suspension	0.60	0.65	50	6

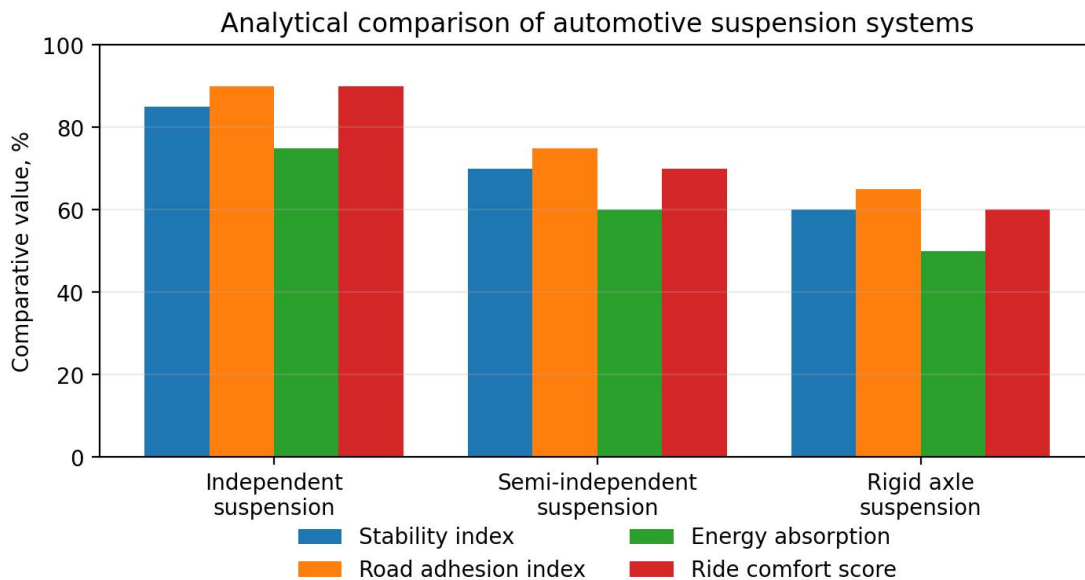


Figure 1. Normalized analytical comparison of stability, road adhesion, energy absorption and ride comfort.

According to the normalized comparison, independent suspension reaches 85% for stability, 90% for road adhesion, 75% for energy absorption and 90% for comfort when the 1-10 comfort scale is converted into a percentage scale. The semi-independent solution remains acceptable for compact and urban vehicles because it provides moderate performance at lower cost. Rigid axle suspension is less effective in comfort but may still be preferable in vehicles that require structural strength and load-carrying capacity.

Table 6. Reported improvement of semi-active and active systems compared with passive suspension

Indicator	Semi-active suspension, %	Active suspension, %
Reduction of body displacement	44	56
Reduction of body acceleration	65	40
Reduction of tire deformation	6	6
Increase in working stroke	17	9

The values in Table 6 demonstrate that semi-active and active suspension systems can considerably improve selected comfort and road-contact indicators compared with passive suspension. However, the efficiency of each system depends on the vehicle model, road profile, control algorithm, damper characteristics and the evaluation criterion selected by the researcher.

3.5. Operational factors and typical suspension failures

The service life of suspension components depends strongly on operating conditions. Rough roads, excessive load, high speed over uneven surfaces, frequent hard braking, aggressive cornering and insufficient maintenance accelerate the wear of shock absorbers, bushings, ball joints, springs and stabilizer links. Temperature variation, dust, moisture and road chemicals also affect rubber and metal parts.

A small suspension defect may create a chain of negative effects. For example, a worn shock absorber cannot control spring oscillation effectively. As a result, the tire may lose stable contact with the road, the braking distance may increase, the vehicle may become less stable in cornering

and tire wear may become uneven. Similarly, worn bushings and joints may produce knocking noise, increase steering play and disturb wheel alignment.

Table 7. Common suspension failures, symptoms and causes

No.	Failure type	Typical symptoms	Main causes
1	Shock absorber failure	Continuous body oscillation, longer braking distance and oil leakage	Oil leakage, valve wear and overheating
2	Worn silent block	Noise, squeaking and impact sounds	Rubber cracking, ageing and overload
3	Ball joint failure	Steering play and knocking noise	Dust penetration, lack of lubrication and mechanical impact
4	Spring sagging or breakage	Reduced body height and uneven vehicle posture	Metal fatigue, corrosion and overload
5	Stabilizer link or bushing wear	Knocking during cornering or on rough roads	Rubber bushing wear and repeated impact loading
6	Incorrect wheel geometry	Uneven tire wear and unstable steering	Bent control arm, worn joints or improper adjustment

4. Discussion

The results confirm that the suspension system should be considered a safety-critical system rather than only a comfort-related mechanism. A well-designed suspension improves passenger comfort, but its more important function is to preserve tire-road contact and vehicle stability. This is especially important during emergency braking, lane changes and high-speed cornering, where the vertical load distribution between tires changes rapidly.

The comparison of structural layouts shows that no single suspension type is best for all vehicles. Dependent suspension remains valuable for heavy-duty applications because it is mechanically robust and can carry high loads. However, its higher unsprung mass and interdependence of wheel movement reduce comfort and road adhesion. Independent suspension offers superior handling and comfort, but it requires more components, more precise manufacturing and more careful maintenance. Semi-independent suspension is a balanced solution for many passenger cars because it is cheaper and easier to service while still providing acceptable performance for normal urban operation.

The comparison of passive, semi-active and active systems shows the general direction of modern suspension development. Passive systems are still widely used because of their low cost and reliability. Semi-active systems provide a better balance between comfort, adaptability and energy consumption. They are especially promising because they can improve damper behaviour without the full complexity of active actuators. Active suspension has the greatest technical potential, but its cost and complexity limit its use mainly to high-class or specialized vehicles.

The data also indicate that suspension performance must be interpreted with respect to the operating environment. For regions where roads are uneven and vehicles are often used with variable loads, durability and serviceability may be more important than maximum comfort. In such conditions, simple and strong suspension designs may be more practical than sophisticated systems that require expensive diagnostics and repair. At the same time, regular technical inspection becomes essential for all suspension types.

From the maintenance point of view, the most important preventive actions are checking shock absorber performance, replacing worn bushings and joints on time, controlling spring condition, inspecting stabilizer links and adjusting wheel alignment. These measures improve safety and reduce secondary failures. For example, timely correction of wheel alignment prevents uneven tire wear; replacing worn bushings reduces noise and restores correct wheel movement; and checking shock absorbers improves braking stability.

The study has several limitations. The comparative numerical values used in the article are analytical indicators based on the source materials and should not be considered universal experimental constants. Actual suspension performance depends on vehicle mass, tire characteristics, suspension geometry, damper calibration, road profile, speed and load. Future studies should include instrumented road tests, laboratory vibration tests and mathematical modelling using quarter-car, half-car and full-vehicle models to obtain more precise quantitative conclusions.

5. Practical recommendations

Table 8. Practical recommendations for suspension operation and maintenance

No.	Recommendation	Expected result
1	Check shock absorbers at regular service intervals	Improved braking stability and reduced body oscillation
2	Replace worn silent blocks and ball joints in time	Reduced noise, vibration and steering play
3	Adjust wheel alignment after suspension repair or strong impact	Reduced tire wear and improved directional stability
4	Avoid overloading the vehicle beyond the recommended mass	Longer service life of springs, bushings and dampers
5	Choose driving speed according to road quality	Lower impact load on suspension components
6	Inspect stabilizer links and bushings during seasonal maintenance	Improved cornering stability and reduced knocking noise
7	Use components that match the vehicle model and load conditions	Restored design performance and improved operational reliability

6. Conclusion

The analysis of the structural and operational characteristics of automotive suspension systems shows that suspension design has a direct influence on ride comfort, road adhesion, handling stability, braking performance and vehicle safety. The suspension system must reduce the impact of road irregularities while maintaining reliable contact between the tires and the road surface.

Dependent suspension is simple, strong and suitable for vehicles with high load requirements, but its comfort and dynamic performance are lower than those of independent suspension. Independent suspension provides better wheel control, ride comfort and road holding, which explains its wide use in modern passenger vehicles. Semi-independent suspension offers a practical compromise for compact and urban cars because it combines acceptable performance with lower cost and easier service.

Passive suspension systems remain widespread because they are reliable and inexpensive, but they cannot adapt to changing road conditions. Semi-active systems improve comfort and stability by controlling damping characteristics, while active suspension systems provide the highest level of dynamic control. Nevertheless, the application of semi-active and active systems depends on cost, energy consumption, control complexity and service infrastructure.

Operational conditions such as road quality, vehicle load, speed, climate and maintenance quality strongly affect suspension service life. Typical failures of shock absorbers, bushings, ball joints, springs and stabilizers can reduce safety and increase tire wear. Therefore, systematic diagnosis, timely replacement of worn components and correct wheel alignment are necessary for safe and efficient vehicle operation.

Overall, the correct selection and maintenance of automotive suspension systems can improve vehicle safety, extend the service life of components, reduce operational failures and increase comfort for drivers and passengers. Further research should include experimental measurements and dynamic modelling to refine the quantitative relationships between suspension parameters and vehicle performance.

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