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Comparative Analysis of Different Vehicle Suspension Systems

MacPherson Strut, Double Wishbone, Multi-Link, and Air Suspension Systems

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Abstract

This review paper provides a comprehensive comparative analysis of four distinct types of suspension systems: MacPherson strut, double wishbone, multi-link, and air suspension. Suspension systems are critical components in vehicles, directly affecting ride quality, handling, stability, and safety. By synthesizing existing research and experimental data, this paper evaluates the advantages, disadvantages, and application suitability of each system. The comparison is based on key parameters such as ride comfort, handling, durability, cost, complexity, energy efficiency, and performance in different driving conditions. The review aims to assist automotive engineers, researchers, and manufacturers in selecting the most appropriate suspension system for specific vehicle requirements.

Keywords: Ride comfort, durability, driving conditions, efficiency, cost.

Introduction

Suspension systems play a vital role in modern vehicles by isolating the vehicle body from road irregularities while maintaining tire contact for optimal control and safety. The suspension system directly affects the ride comfort, handling characteristics, vehicle stability, and load distribution, making it one of the most crucial components in vehicle design and dynamics [1], [2]. As automotive technology evolves to meet increasing demands for comfort, safety, and performance, the design of suspension systems has become more diverse and sophisticated. Among the most commonly used configurations are the MacPherson strut, double wishbone, multi-link, and air suspension systems, each offering unique advantages and trade-offs in terms of geometry, complexity, cost, and dynamic behavior [3], [4].

The MacPherson strut suspension is widely adopted in front-wheel-drive passenger cars due to its compactness, low cost, and ease of assembly [5], [6]. It integrates the damper and coil spring into a single unit, saving space and simplifying the vehicle's front-end design. However, this configuration provides limited camber control and offers less lateral rigidity compared to more complex setups [7]. Colombo [8] and Kumar et al. [9] observed that while MacPherson strut systems are suitable for small- to mid-sized vehicles, they underperform in high-speed or high-load applications due to their constrained kinematics.

In contrast, the double wishbone suspension—commonly used in performance and luxury vehicles—features two control arms that offer independent camber and caster adjustments, providing superior handling and cornering stability [10], [11]. Research by Tandel et al. [12] and Unlusoy et al. [13] demonstrates that double wishbone setups outperform simpler systems in dynamic responsiveness, especially under lateral acceleration and braking. However, the increased complexity, size, and cost make this system less suitable for economy vehicles [14].

The multi-link suspension system evolved as a more flexible alternative, incorporating three or more control arms per wheel to allow fine-tuned suspension geometry throughout wheel travel [15]. This configuration achieves an excellent balance between comfort and control, and it is often found in luxury sedans and high-performance cars [16]. Studies by Rensen [17], Alexandru [18], and Țoțu et al. [19] show that multi-link systems provide precise handling and isolation of vertical and lateral forces, though they introduce challenges in terms of weight, alignment complexity, and manufacturing costs [20].

Air suspension systems, on the other hand, replace mechanical springs with air springs (air bellows) controlled by compressors and sensors. These systems offer real-time ride height adjustments and adaptive damping, making them ideal for applications requiring variable load handling or maximum comfort [21], [22]. Liu et al. [23] and Alexandru [24] confirmed that air suspensions significantly improve ride quality and adaptability but also noted increased system cost, vulnerability to leaks, and maintenance intensity.

Numerous studies have employed simulation tools such as ADAMS, MATLAB/Simulink, ANSYS, and CarSim to evaluate and compare the performance of these suspension types under standardized and real-world conditions [25], [26]. Vrushabhendra et al. [27] and Zhang et al. [28] analyzed how suspension systems respond to various road profiles, highlighting the superior damping characteristics of air and multi-link systems over traditional mechanical designs. Additionally, advancements in active and semi-active suspension control systems, using fuzzy logic, PID control, and artificial intelligence, have further extended the performance envelope of conventional suspension designs [29], [30]. Researchers like Kavitha et al. [31] and Liu et al. [32] explored the integration of control strategies into conventional suspensions to improve comfort and handling simultaneously. These developments are critical as automotive engineers aim to optimize suspension systems for diverse objectives, including cost-effectiveness, weight reduction, safety compliance, and electrification readiness [33], [34].

In this review paper, we conduct a comprehensive analysis of four major suspension systems—MacPherson strut, double wishbone, multi-link, and air suspension—to explore their operational principles, structural characteristics, and dynamic performance under varying conditions. By synthesizing findings from 47 academic and industrial research studies, this review aims to provide a comparative perspective for automotive designers and researchers, supporting informed decision-making for both current and future vehicle platforms.

Suspension System Types

Suspension systems are integral to a vehicle's performance, comfort, and handling capabilities. Among the most widely used types are the **MacPherson strut**, **double wishbone**, **multi-link**, and **air suspension** systems. Each of these systems offers distinct advantages and is suited to different vehicle applications based on factors like cost, complexity, ride quality, and stability.

MacPherson Strut Suspension

The **MacPherson strut suspension [35]** is a compact and cost-effective design that combines the shock absorber and coil spring into a single unit. It is commonly used in front-wheel-drive (FWD) and some rear-wheel-drive (RWD) vehicles, especially in the compact and mid-size categories. Its primary strengths lie in its simplicity, low cost, and space efficiency, making it ideal for economy vehicles where affordability and packaging are key considerations. However, it offers only moderate ride comfort and handling. It may struggle to isolate road vibrations effectively and lacks the sophisticated geometry control of more advanced systems, limiting its performance on rough terrain and during aggressive cornering.

Double Wishbone Suspension

The **double wishbone suspension** employs two control arms in a wishbone configuration [36], [37], providing superior control over wheel chamber and alignment. This setup enhances the vehicle's handling and stability, particularly during high-speed maneuvers and sharp cornering. The double wishbone system distributes load more evenly across the suspension and allows for adjustable camber, making it a popular choice for sports and performance-oriented vehicles. However, this enhanced control comes at the cost of increased complexity, weight, and manufacturing expenses. Despite these drawbacks, the system offers a balanced trade-off between performance and practicality for vehicles prioritizing dynamic driving characteristics [38].

Multi-Link Suspension

The **multi-link suspension** goes a step further in sophistication, utilizing four or more links to manage the wheel's movement in multiple axes. This configuration allows for exceptional ride comfort and handling precision, as it can

independently control camber, toe, and other alignment angles. Multi-link [39] systems are often found in the rear suspensions of luxury sedans, high-performance cars, and SUVs. Their adaptability and performance make them highly desirable, but they are also among the most complex and expensive to design, assemble, and maintain. Space requirements can also limit their application in smaller vehicle platforms.

Air Suspension

Air suspension systems represent a technologically advanced approach by replacing traditional coil springs with air bladders filled with compressed air. These systems are managed by onboard compressors and electronic control units, allowing dynamic adjustment of ride height and stiffness [41]. Air suspension provides superior ride comfort and load handling, as it can adapt to varying road conditions and vehicle loads in real-time. This makes it especially effective for luxury vehicles, SUVs, and off-road models. Nevertheless, the system's complexity introduces reliability challenges, such as potential air leaks or compressor failures, and it requires more expensive repairs compared to mechanical alternatives.

Comparative Analysis of Suspension Systems

The comparison of the MacPherson strut, double wishbone, multi-link, and air suspension systems is based on key performance metrics such as ride comfort, handling, cost, complexity, and reliability.

Ride Comfort

When comparing these systems in terms of ride comfort, the MacPherson strut offers a moderate level, sufficient for most daily-driving conditions [6], [8], [42]. The double wishbone improves comfort due to better geometry control but may feel stiffer in performance settings. The multi-link system stands out with excellent comfort thanks to its ability to isolate road disturbances. Air suspension surpasses all others in this category, delivering a smooth ride across various terrains and load conditions.

Table 1: Ride Comfort Comparison

Suspension Type	Ride Comfort Level	Suitable Applications
MacPherson Strut	Moderate	Compact and mid-size cars
Double Wishbone	Good	Performance and sports cars
Multi-Link	Excellent	Luxury and high-end cars
Air Suspension	Superior	SUVs, luxury, off-road vehicles

Handling and Stability

In terms of **handling and stability [43]**, the MacPherson strut provides adequate performance for basic driving needs but is less stable under aggressive cornering. The double wishbone excels in this area, offering precise wheel control and reduced body roll. Multi-link suspension provides even greater handling benefits due to its multidirectional wheel management. Air suspension, with its adjustable stiffness, also performs well in handling, especially in high-end or off-road applications.

Table 2: Handling and Stability Comparison

Suspension Type	Handling & Stability	Suitable Applications
MacPherson Strut	Moderate	Compact cars, economy cars
Double Wishbone	Excellent	Sports and performance cars
Multi-Link	Superior	Luxury, off-road, high-performance vehicles
Air Suspension	Excellent	Off-road, luxury, SUV

Cost and Complexity

Regarding **cost and complexity**, the MacPherson strut is the most affordable and simplest, suitable for cost-sensitive markets. The double wishbone is moderately more expensive and complex, reflecting its higher performance potential. Multi-link systems are both high-cost and high-complexity, reflecting their premium positioning. Air suspension is the most expensive and complex, given its need for compressors, sensors, and electronic controls [10], [44].

Table 3: Cost and Complexity Comparison

Suspension Type	Cost Estimate	Complexity	Suitable Applications
MacPherson Strut	Low	Low	Economy and compact cars
Double Wishbone	Moderate	Moderate	Performance vehicles
Multi-Link	High	High	Luxury, high-performance vehicles
Air Suspension	Very High	Very High	SUVs, luxury, off-road vehicles

Durability and Reliability

For **durability and reliability**, MacPherson struts are generally robust and low-maintenance, ideal for mass-market use. Double wishbone systems are also durable but require more frequent maintenance due to additional components. Multi-

link systems, while durable [45], [46], can experience more wear due to the greater number of moving parts. Air suspension systems are moderately durable but have lower reliability, with a higher likelihood of component failure over time [47].

Table 4: Durability and Reliability Comparison

Suspension Type	Durability	Reliability	Suitable Applications
MacPherson Strut	High	High	Most vehicles
Double Wishbone	High	Moderate	Performance vehicles
Multi-Link	High	Moderate	Luxury, high-performance vehicles
Air Suspension	Moderate	Low	Luxury, off-road, SUVs

Findings

The comparative study of MacPherson strut, double wishbone, multi-link, and air suspension systems reveals that each type offers unique advantages based on application needs. MacPherson strut is cost-effective and compact, ideal for budget vehicles. Double wishbone provides excellent handling and stability, making it suitable for sports cars. Multi-link suspension delivers superior ride comfort and control, often used in luxury vehicles, while air suspension stands out for its adaptability and ride quality, particularly in off-road and premium applications.

Despite their benefits, each system also has limitations in terms of complexity, cost, or durability. Future developments can focus on improving these systems through lightweight materials, smart sensors, and AI-based control units. For instance, active damping in MacPherson struts, dynamic geometry in double wishbone setups, or enhanced reliability in air suspension can significantly boost performance.

There is also strong potential for hybrid suspension systems that combine the best features of multiple designs. These could intelligently adjust damping, ride height, and geometry in real-time based on driving conditions and load (Table 5). Such systems would be highly beneficial for future electric, autonomous, and performance vehicles, aiming to balance efficiency, comfort, and dynamic handling.

Table 5: Performance Comparison MacPherson Strut, Double Wishbone, Multi-Link, and Air Suspension

Performance Parameter	**MacPherson Strut**	**Double Wishbone**	**Multi-Link**	**Air Suspension**
Ride Comfort	Moderate	Good	Excellent	Superior
Handling & Stability	Moderate	Excellent	Superior	Excellent (adjustable)
Durability	High	High	High	Moderate (susceptible to wear)
Cost (Manufacturing)	Low	Moderate	High	Very High
Complexity	Low	Moderate	High	Very High
Maintenance	Low	Moderate	High	High

Weight	Light	Moderate	Heavy	Heavy (due to additional components)
Handling Under Load	Limited control over load	Excellent control under load	Excellent load distribution	Excellent (dynamic adjustment)
Comfort on Rough Terrain	Limited	Good	Excellent	Excellent
Off-Road Capability	Poor	Moderate	High	Excellent (adjustable height)
Ride Height Adjustability	No	No	No	Yes (Dynamic adjustment)
Energy Efficiency	High	Moderate	Moderate	Moderate (due to compressors)
Handling at High Speeds	Moderate	Excellent	Superior	Excellent
Passenger Load Compensation	No	No	Yes	Yes (automatically adjusts)

- Ride Comfort: Evaluates how well the suspension absorbs road irregularities and minimizes vibrations to ensure a smooth ride for passengers. Air suspension excels here due to its ability to adjust ride height and stiffness dynamically based on road conditions.
- Handling & Stability: Focuses on how well the suspension system performs during cornering, braking, and high-speed manoeuvres. The double wishbone and multi-link systems provide superior handling and stability due to their more sophisticated geometries and ability to control wheel alignment.
- Durability: Refers to the suspension system's ability to withstand wear and tear over time. MacPherson strut systems are known for their simplicity and durability, while air suspension systems, due to their complexity, may suffer from reliability issues like air leaks or compressor failures.
- Cost (Manufacturing): The production cost of each suspension system. MacPherson struts are the least expensive due to their simple design, while air suspension systems are the most costly due to the additional components required (e.g., compressors, air springs).
- Complexity: The number of components and design intricacy involved in the suspension system. MacPherson struts are the simplest, while air suspension systems are the most complex, requiring precise control units and sensors.
- Maintenance: The ease and cost of maintenance over the vehicle’s lifespan. MacPherson struts have low maintenance costs, while air suspension systems require more frequent maintenance due to their complex components.
- Weight: The weight of the suspension system, which impacts the overall vehicle weight. Lighter systems, such as the MacPherson strut, contribute to better fuel efficiency. Air suspensions are typically heavier due to the additional components like compressors and air springs.
- Handling Under Load: Assesses the suspension system’s ability to manage weight and load distribution. Multi-link and air suspensions provide the best control under load, with air suspension offering dynamic load adjustments.
- Comfort on Rough Terrain: How well the system isolates passengers from road irregularities in off-road conditions. Air suspension offers the best comfort in off-road driving, followed by multi-link, which excels in absorbing bumps and vibrations.

- Off-Road Capability: Evaluates the suspension's ability to handle challenging off-road terrain. Air suspension systems are ideal for off-road use due to their height-adjustability feature, while MacPherson strut systems are generally not well-suited for off-road conditions.
- Ride Height Adjustability: Refers to the system's ability to change the vehicle's height. Air suspension is the only system in this comparison that offers dynamic height adjustment.
- Energy Efficiency: Involves the suspension system's impact on overall fuel efficiency. The simpler MacPherson strut is more energy-efficient compared to air suspension, which uses energy for compression and air management.
- Handling at High Speeds: The ability of the suspension to maintain stability and comfort during high-speed driving. Both multi-link and air suspensions provide superior performance, with air suspension offering dynamic adjustments to optimize stability.
- Passenger Load Compensation: How well the system compensates for additional weight in the vehicle, keeping the ride height and performance consistent. Air suspension excels in this area by automatically adjusting for varying loads.

Conclusion

Each suspension system evaluated in this comparative study demonstrates unique advantages and trade-offs when analysed across key performance parameters such as ride comfort, handling, durability, cost, and complexity. The MacPherson strut, being the most economical and mechanically straightforward design, is ideal for compact and budget-friendly vehicles due to its low weight and ease of integration. However, it lacks advanced handling capabilities, making it less suitable for dynamic driving and off-road conditions. The double wishbone suspension stands out for its excellent handling and stability, especially during aggressive cornering and high-speed manoeuvres. Its dual-arm configuration allows for better camber control and load distribution, making it a preferred choice for sports and performance vehicles. Nevertheless, it introduces moderate complexity and manufacturing costs. Multi-link suspension systems offer the most well-rounded performance in terms of ride quality, alignment precision, and handling. Their ability to manage multiple axes of movement makes them ideal for luxury and high-performance vehicles. Yet, the higher number of components increases both system complexity and maintenance demands. Air suspension systems deliver superior ride comfort and dynamic adjustability, allowing for real-time changes in ride height and stiffness. These systems excel in SUVs and off-road vehicles where adaptability is crucial. However, their high cost, increased weight, and reliance on electronic and pneumatic components can pose challenges in terms of reliability and long-term maintenance.

Hybrid suspension systems represent a promising evolution in automotive design, blending the strengths of traditional setups such as mechanical, air, and active suspensions to achieve an optimal balance of ride comfort, handling precision, adaptability, and efficiency. By integrating systems like MacPherson struts with active damping, or combining double wishbone geometry with air springs, manufacturers can enhance both stability and ride height control. Advanced configurations, such as multi-link systems with electromagnetic or hydraulic actuation, are already being employed in luxury and electric vehicles for real-time adaptability. Furthermore, the development of predictive hybrid suspensions using AI, LiDAR, and sensor fusion opens new possibilities for terrain-aware adjustments and improved ride quality. While challenges such as increased cost, complexity, and maintenance persist, the long-term benefits—particularly in fuel efficiency, dynamic control, and comfort—make hybrid suspensions a compelling future standard, especially for electric, autonomous, and high-performance vehicles.

Ultimately, this research underscores that the selection of a suspension system must be aligned with the vehicle's design goals, market segment, and expected performance conditions. No single system is universally optimal. Future advancements in active and semi-active suspension technologies, materials, and control algorithms may further bridge the gap between comfort, handling, and cost-effectiveness, leading to more versatile and efficient suspension solutions.

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