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Influence of the wheel assembly components on vehicle dynamics

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Abstract. The wheel assembly is a key element in transmitting forces between the vehicle and the road surface, having a major influence on the vehicle's stability, maneuverability, and passenger comfort. This paper presents a comparative analysis of the main structural components of the vehicle assembly, namely the rim, tire, bearing, and wheel hub. Various design solutions for rims are considered, including steel variants, aluminum alloys, and composite materials such as CFRP (Carbon Fiber-Reinforced Polymer), analyzing their influence on the sprung mass and dynamic behavior of the vehicle. Regarding the tire, the structural design, dynamic behavior, the influence of the tread profile on braking distance, as well as specific aspects for electric vehicles, such as torque fluctuations and the additional mass of the battery are investigated. For the wheel bearing, the literature proposes evaluations of stress distribution using simplified structural analysis models. In the case of the wheel hub, alternative geometrical configurations (3, 5, and 6 bolt holes) are evaluated and a life-cycle assessment is conducted, comparing conventional and electric vehicle configurations. The results offer a coherent overview of constructive solutions and their influence on vehicle dynamics within the context of technological transition.

Keywords: wheel assembly, structural solutions, conventional and electric vehicles, vehicle dynamics.

1. Introduction

The wheel assembly is one of the fundamental subsystems in vehicle dynamics, playing a crucial role in ensuring vehicle control, ride comfort, and the efficient transmission of forces between the vehicle and the road surface.

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Wheel assembly component structural optimization has emerged as a major topic of research and innovation due to the increasing performance and sustainability requirements in contemporary automotive engineering, especially in the context of electric mobility [14].

Through its main components, rim, tire, wheel bearings and wheel hub, the wheel assembly directly interacts with the suspension system, shaping the vehicle's response to road irregularities, cornering forces, braking, and acceleration [9, 15].

In recent years, the evolution of electric vehicles has induced new engineering challenges in wheel assembly design. Compared to conventional vehicles, electric vehicles exhibit significantly higher sprung masses, primarily due to the large battery typically mounted near or within the chassis [6, 7, 15]. Moreover, they are characterized by instantaneous torque delivery, which induces higher dynamic loads during acceleration phases [9], along with much stricter NVH (noise, vibration, harshness) requirements due to the necessity of a quieter powertrain [12]. Additionally, growing attention is being paid to energy efficiency, where every kilogram of rotating and sprung mass directly impacts driving range and tire rolling resistance [15].

According to [9, 15], the combination of instantaneous torque, frequent regenerative braking, and increased unsprung masses leads to amplified dynamic loading across all wheel assembly components, particularly the wheel bearings, tires, and wheel hub. These components are therefore subjected to increased mechanical and thermal stress, requiring advanced structural optimization and material selection solutions.

Furthermore, [6, 7] highlights that electric platforms shift the design trade-offs within the wheel assembly. Mass reduction strategies become significantly more critical (e.g., replacing steel with aluminum alloys or CFRP for rims), tires must balance low rolling resistance with the ability to accommodate large load variations, and wheel hub and wheel bearing must withstand higher radial and axial forces under more frequent loading cycles.

Although substantial research progress has been made in studying individual components of the wheel assembly, there is a lack of integrative syntheses analyzing how these structural differences affect the overall dynamic behavior of the vehicle, especially under the distinct loading conditions found in electric versus conventional platforms.

Therefore, this review aims to address this gap by synthesizing the structural characteristics of each component of the wheel assembly (rim, tire, wheel bearings and wheel hub), analyzing their individual and combined impact on vehicle dynamic response, and providing comparative insights between conventional and electric vehicles configurations.

By integrating recent findings from literature, computational modelling approaches, and experimental results, this work offers an updated perspective on the evolving role of the wheel assembly in modern vehicle dynamics, contributing to a deeper understanding of the design trade-offs and future research directions.

2. Wheel assembly components

2.1 Rim

The rim is the structural component of the wheel assembly that supports both static and dynamic loads generated under various operating conditions of the vehicle. A rim is a circular component capable of rotating around its axis, facilitating motion or transportation while supporting a load [1].

Among the requirements of a rim are strength and stiffness, especially during braking or cornering, as rims must withstand vertical and lateral loads. They need to be robust enough to resist deformation and potential damage under normal usage conditions. Additionally, since the rims are directly connected to the vehicle's unsprung mass, they must be as lightweight as possible, to ensure optimal damping of vibrations caused by road surface irregularities. Finally, rims must be properly balanced to rotate smoothly at high speeds without inducing vibrations or negative steering effects, thus improving vehicle handling and extending the service life of suspension components [1, 12, 13].

Regarding the classification of automotive rims (table 1), they can be grouped into steel disc rims (fig. 1a), cast or forged light alloy rims (fig. 1b), and spoke-type metal rims (fig. 1c) [1].

Currently, the most used materials for rims (table 2) are steel, lightweight alloys (aluminum, magnesium), and, in high-performance applications, composite materials such as CFRP. The choice of material directly influences the unsprung mass, structural stiffness, and dynamic behavior of the vehicle. Steel rims offer low costs and robustness; however, their main disadvantage is the high mass, which negatively affects the suspension response. Lightweight alloys (especially aluminum) are preferred in electric vehicles to reduce mass and improve the efficiency of NVH systems and energy consumption. In motorsport, forged magnesium and heat-treated aluminum ensure an optimal combination of low weight and stiffness under extreme conditions. CFRP composite materials provide the best characteristics for improving dynamic behavior, but at a high cost, making them suitable for hyper cars or prototype vehicles [1, 4, 5, 6, 7, 8, 10, 12, 15].

Table 1. Types of wheel rim [1].

Rim type	Advantages	Disadvantages
Steel disc rims	Low cost	High weight
	Robust	Poor thermal dissipation
	High impact resistance	Reduced performance at high travel speeds
	Simple construction	Higher costs
Light alloy rims	Reduced weight	Prone to corrosion
	Efficient thermal dissipation	Possibility of cracking upon impact
	Increased stiffness	
	Resistance to vibrations and fatigue	
Spoked metal rims	Structural flexibility	Requires frequent maintenance and fine tunning
	Efficient load transmission	Incompatible with tubeless tire

Table. 2. Types of materials used for rims [1, 4, 5, 6, 7, 8, 10, 12, 15].

Material	Advantages	Disadvantages
Steel	Predictable behavior under standard conditions	Slow suspension response
	Robust	Reduced grip under dynamic conditions
	High impact resistance	Reduced performance at high speeds
	Simple construction	Higher costs
Aluminum	Reduced weight	Corrosion vulnerability
	Efficient thermal dissipation	Possibility of cracking upon impact
	Increased stiffness	Energy-intensive manufacturing
	Better NVH characteristics	
Magnesium	Extremely low weight	Prone to corrosion
	Reduced rotational inertia	High cost
	Efficient vibration damping	Brittle under impact
CFRP	Significant reduction in usprung mass	Direct transmission of shocks due to excessive stiffness
	Excellent handling	

Fig. 1. Types of wheel rim, adapted from [1]: a) steel disc rim; b) cast or forged light alloy rim; c) metal spoked rim.

2.2 Tire

The tire is the contact element between the vehicle and road surface, directly influencing the dynamic behavior, the efficiency of active safety systems, and vehicle handling. Its performance determines the ability to transmit forces (traction, braking, steering), as well as to absorb shocks and ensure overall vehicle stability [1, 4, 5, 6, 7, 8, 9, 13].
The performance requirements imposed on modern tires are presented in table 3:

Table. 3. Functional requirements of the tire and its impact on vehicle dynamics [1, 12, 13].

Functional requirements	Dynamic impact
Low rolling resistance	Increased energy efficiency
Optimal contact with the road surface	Directional stability, effective braking
Shock absorption capacity	Comfort and vibration isolation
Wet performance	Safety against aquaplaning and improved braking
Durability and structural stability	Reliability, predictability of wear

Regarding tire construction, three fundamental types of tire construction are widely used today, the radial tire, the bias-ply tire, and the bias-belted tire, which combines a bias-ply structure with additional belts placed beneath the tread. These three types of tires are illustrated in figure 2 and comparatively presented in table 4 [5].

a) b) c)

Fig. 2. Radial and bias-ply tires: a) tires with crossed carcass cord plies (bias-ply); b) tire with crossed carcass cord plies and belt reinforcement (bias-belted); c) radial tires (radial-ply), adapted from [5].

Table. 4. Comparative characteristics between tire types [5].

Tire type	Advantages	Dynamic limitation
Bias-ply	High ride comfort, robustness	Low stability, uneven wear
Bias-belted	High stiffness and directional stability	Uneven wear
Radial	Excellent stability, low wear	More sensitive sidewalls

The radial construction features an architecture that allows for high sidewall flexibility, offering enhanced comfort, but also high directional stability, ensured by the rigid belts made of textile or steel materials placed along the circumference between the casing and the tread, at angles of approximately 20° to the rolling direction [5].
The tire is equipped around its entire contour with grooves and geometric channels, along with additional sipes that form contact edges. The main function of the integrated tread pattern, resulting from vulcanization, is to effectively evacuate water, mud or snow from the contact area with the road surface [1, 5, 9, 12].
To highlight the importance of tread depth in road safety and breaking performance, figure 3 illustrates the major impact that the tread pattern has during braking on wet surfaces, while table 5 shows the correlation between tread depth and braking distance [12].

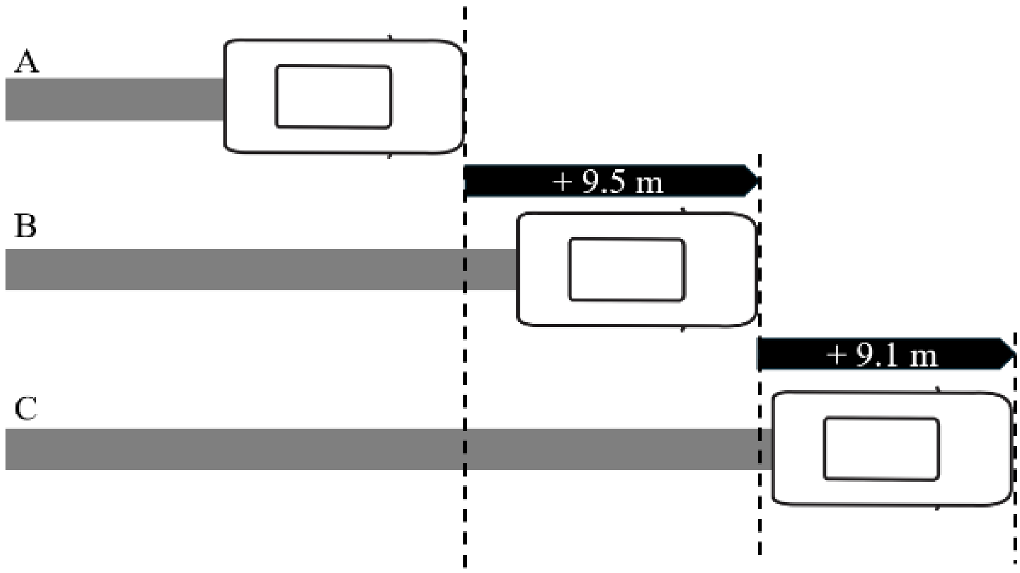

Fig. 3. Braking distance from 80 km/h on wet pavement as a function on tread depth adapted from [12].

As an interpretation and its impact on vehicle dynamics, as the tread depth wears down, the braking distance increases significantly, which reduces the vehicle's ability to respond effectively in various critical situations (e.g., emergency braking, sudden obstacles, etc.). From the perspective of vehicle dynamics performance and vehicle safety, although the legal minimum tread is 1.6 mm, it is recommended that tire replacement be considered at 3 mm [12].

Table. 5. Comparative analysis of braking distance from 80 km/h under defined conditions [12].

Analyzed scenario (see. fig. 3)	**Tread depth [mm]**	**Braking distance [m]**
A	8	42.3
B	3	51.8 (+22% compared to new tire)
C	1.6 (legal limit)	60.9 (+44% compared to new tire)

2.3 Wheel bearings

Wheel bearings provide the connection between the hub and the knuckle, allowing the wheel to rotate freely while supporting the vertical, longitudinal, and lateral loads transmitted through the tire during driving. From a dynamic perspective, they contribute significantly to directional stability, braking efficiency, and suspension response, being considered a key element in the unsprung mass of the wheel assembly [11, 15].

In performance applications (motorsport) or for electric vehicles, stringent requirements are imposed, such as reduced weight, which helps lower the moment of inertia and improve suspension response, high axial rigidity to minimize play, minimal internal friction, and high reliability under severe conditions to withstand shocks, vibrations, and high temperatures [11, 15].

The study [11] demonstrated through a combined LPM-FEM approach that a standard bearing (6007-2RS1), mounted on a lightweight vehicle, can reach its load limits under real dynamic conditions (obstacle crossing, 13.3 kN).

Moreover, [11] highlighted a stress distribution on the central plane perpendicular to the bearing axis, with maximum stresses localized in ball 0 (2.13 GPa), a value close to the yield strength of material (SAE 52100). Additionally, [11] pointed out that the stressed volume is located well below the surface, with an ellipsoidal shape, indicating efficient use of the material in real configurations.

As an interpretation of the results obtained from the combined LPM-FEM simulations, it is emphasized that wheel bearings represent a critical element in the dynamic behavior of the vehicle. Under real load conditions, the stresses developed in the contact zones reach values close to the material's yield limit, suggesting intensive utilization of the load-carrying capacity. The increased loading directly affects braking precision, directional stability, tire wear through consistent load distribution, as well as safety during critical maneuvers.

2.4 Wheel hub

The wheel hub is an essential element of the wheel-suspension assembly, ensuring wheel mounting and the transmission of drive and brake torque, as well as vertical and lateral forces to the bearings [1, 2, 3, 9, 12, 15].

Being subjected to variable loads during operation, the geometry and material of the wheel hub directly influence vehicle dynamic behavior and safety, as the wheel hub ensures proper wheel centering and supports multiple loads such as torsion, vertical load, and lateral forces caused by cornering [1, 2, 3, 9, 12, 15].

According to [2], three configurations of the wheel hub (with 3, 5, and 6 mounting holes) were designed and analyzed using CAD-FEM methods. Based on the results, the design with 6 mounting holes shows the lowest deformation (0.11 mm), a uniform stress distribution, and higher safety factors, with reduced deformations in the contact area with the shaft.

On the other hand, in study [3], the environmental footprint of steel and aluminum alloy hubs is evaluated comparatively for electric and conventional vehicles using the ReCiPe methodology for Life Cycle Assessment (LCA). This method allows aggregation of environmental effects (such as climate change, toxicity, resource depletion, etc.) into a single score, expressed in ReCiPe points, thus facilitating the comparison of different design and technological scenarios.

The results presented in figure 4 indicate that, for electric vehicles, wheel hubs made of aluminum alloys generate an environmental impact 15.57% lower compared to those made of steel. Also, structural optimization of steel hubs achieves a 15% reduction in the ReCiPe impact score, while process optimization delivers an even higher level of performance, with an environmental impact 32.58% lower than standard steel [8].

Regarding the overall comparison between vehicle types, figure 5 highlights that steel wheel hubs used in electric vehicles produce an environmental impact 21.86% lower than if they were used in conventional vehicles. Similarly, for aluminum alloy hubs, the difference is 17.35% in favor of electric vehicles, while for optimized variants (structural and process), the impact is reduced by up to 21.86% for electric vehicles [3].

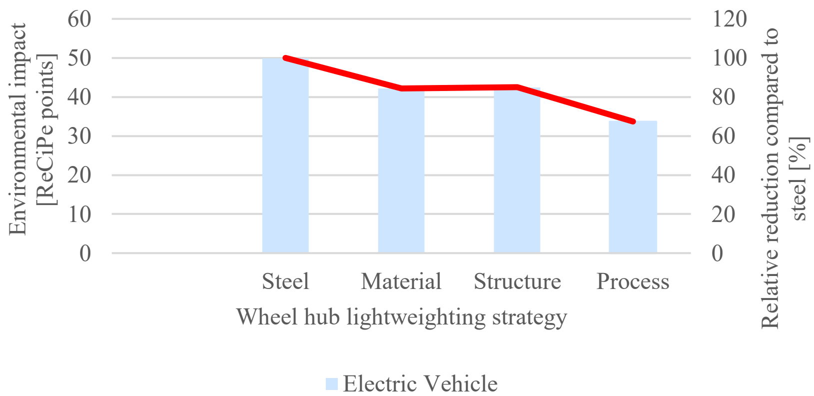

Fig. 4. Environmental impact of wheel hubs for electric vehicles using different lightweighting methods, adapted from [3].

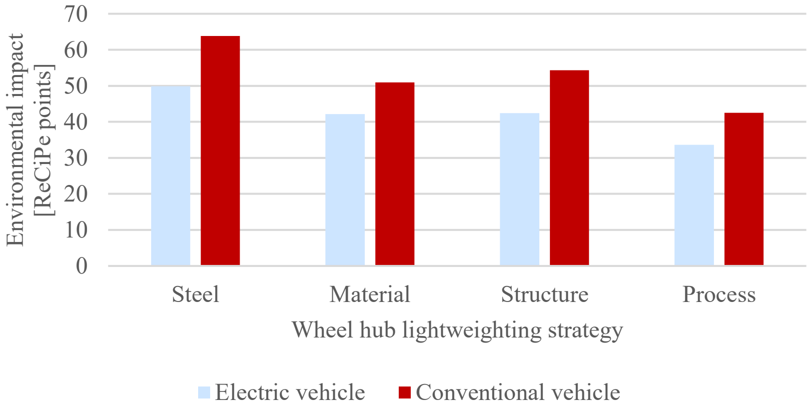

Fig. 5. Environmental impact of wheel hubs using different lightweighting methods, by vehicle type, adapted from [3].

3. Comparative analysis and application trends

With the accelerated transition toward electromobility, the components of the wheel assembly, as well as its interaction with the suspension system, must meet significant different requirements compared to vehicles equipped with internal combustion engines (table 6). Critical factors such as unsprung mass, instantaneous torque, thermal management, and NVH become key priorities in the design of associated components, namely the rim, tire, wheel bearings, and wheel hub.

Table. 6. Comparative analysis between electric and conventional vehicles from the perspective of structural and functional performance

Component	**Major Demands**		**Optimization trends for electric vehicles**
	Conventional vehicles	**Electric vehicles**	
Rim	Mechanical rigidity, low cost, brake heat dissipation	Reduced mass, efficient heat dissipation, rigidity for high torque	Lightweight alloys, forged rims, CFRP
Tire	Shock absorption, efficiency on mixed road surfaces	High NVH requirements, accelerated wear, handling higher additional loads (battery)	EV-dedicated tires, nanomaterials, sensors
Wheel bearings	Support for static and moderate dynamic loads	Handling increased loads, minimal friction, high durability and reliability	Low-friction bearings, advanced lubrication
Wheel hub	Efficient torque transfer and vertical load support	Mass optimization, structural stiffness, reduced environmental impact (LCA)	Aluminum, steel optimized via process and LCA

Unlike conventional vehicles, electric vehicles feature large, heavy batteries, which increase the load on the suspension system and unsprung components, while the instantaneous torque delivered by electric motors requires higher stiffness in wheel hubs and rims to prevent deformation or axial slip. Furthermore, the absence of engine noise means that any structural imperfection of vibration becomes more noticeable to occupants (accentuated NHV effect).

4. Development trends

Composite materials such as CFRP can be used in rims, suspension arms, and even wheel hubs, providing a significant weight reduction (up to 50%) and remarkable structural rigidity. In [9], it is demonstrated that CFRP rims reduce deformation and structural stress by over 30% compared to steel rims, showing significant potential for electric vehicles

Another development involves the use of intelligent tires equipped with integrated sensors that measure pressure, temperature, real-time grip, and wear. These systems can dynamically assist the response of ESP or ABS and alert the driver to aquaplaning hazards [13].

For wheel bearings, one development direction is the use of special greases and surface treatments to reduce energy losses. Additionally, in [3], dynamic loads exceeding
13 kN were simulated on wheel bearings, highlighting the need for advanced fatigue resistance solutions.

According to study [8], using aluminum instead of steel reduces environmental impact by 15-20%. However, combining it with optimized processing (LCA) can further reduce the impact by up to 32%, thus emphasizing both structural and ecological optimization of the wheel hub.

5. Conclusions

The wheel assembly and its interaction with the suspension system play a fundamental role in vehicle dynamics, as it is the subsystem that ensures direct contact between the vehicle and the road. The analyzed components (rim, tire, wheel bearing, and wheel hub) directly influence the vehicle's stability, handling, and occupant comfort, as well as its response in cornering maneuvers.

Rims significantly contribute to unsprung mass, having a direct impact on suspension response. Transitioning from steel to lightweight alloys or CFRP provides clear dynamic benefits by reducing weight and improving thermal dissipation. In the case of electric vehicles, lightweight rims become a technological necessity to compensate for the additional battery mass and maintain good energy efficiency.

Tires represent the first interface with the road and play a critical role in filtering vibrations, transferring forces, and ensuring vehicle stability. Particularly for electric vehicles, characterized by higher unsprung mass and the absence of internal combustion engine noise, correct tire selection is essential for maintaining comfort and traction.

Wheel bearings, although seemingly simple, influence braking precision, steering rigidity, and overall dynamic behavior. In modern applications, especially for electric vehicles, they must combine high structural rigidity with minimal friction to support higher loads while reducing energy losses.

The wheel hub acts as the central node for transmitting torque and lateral forces. Its structural and material optimization enables weight reduction and a lower ecological footprint, with beneficial effects on the vehicle's dynamic performance.

At the same time, the use of advanced composite materials and the integration of smart technologies, such as sensors for real-time monitoring of tire and bearing behavior, represent strategic direction for development. These solutions can significantly contribute to enhancing dynamic performance, optimizing energy consumption, and reducing environmental impact, particularly in the context of the transition toward electric mobility.

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