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Modeling and Simulation of Active Suspension System for Road Vehicles and Sensitivity to Design Criteria for Energy Efficiency †

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Abstract

Active suspensions in automotive applications are designed to improve vehicle stability and comfort and reduce vibration transmission from the road surface. Active systems often include a dedicated actuator, and, to reduce their mass and energy absorption, it is a typical choice to rely on brushless electric motors with permanent magnets containing Critical Raw Materials such as Neodymium, a Rare Earth Element (REE), offering favorable power density values. Although these systems offer clear advantages in terms of ride quality and performance, their direct and indirect energy requirements, combined with their dependence on resource-intensive materials, raise concerns about life cycle sustainability: in other words, there is a trade-off between production impact (relevant for REE) and use impact (reduced by REE adoption). To address this issue, the research proposes a method to estimate energy consumption during the use phase of a vehicle through a dedicated parametric modeling and simulation framework; the aim is to evaluate the energy performance of active suspension systems under different road and driving conditions. The analysis explores how design parameters and operational choices affect energy consumption and efficiency. The simulation results reveal a marked sensitivity of system performance to road profiles and driving scenarios, highlighting the importance of holistic assessments during the early stages of design. The proposed framework represents a first step toward integrating circular design principles into the development of active suspensions. By combining technical and environmental perspectives, it supports the development of next-generation automotive components that balance comfort, performance, and sustainability.

Keywords: automotive; active suspension; circular design; Critical Raw Materials; design for efficiency; electric motors; energy management; permanent magnet; Rare Earth Elements; regenerative suspension

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1. Introduction

The automotive industry is currently undergoing a period of profound transformation, characterized by significant technological changes. Innovations in powertrain technologies, environmental sustainability, and autonomous driving are becoming progressively more complex and closely interconnected. In particular, following the implementation of the European Green Deal [1], manufacturers are preparing for a future predominantly characterized by vehicle electrification. As a result, vehicle design increasingly requires a holistic life cycle perspective [2] that considers not only performance but also the environmental, economic, and social implications of every design decision. These principles are in line with the circular design paradigm, which today is indispensable in all areas of engineering.

In the context of vehicle electrification, the efficiency of on-board auxiliary systems has become gradually more important. Modern subsystems are highly sophisticated and technologically advanced, but often require additional electrical power, which inevitably increases energy consumption during the use phase, a stage that contributes substantially to the overall impact of a car's life cycle [3]. Emerging technologies in this field are active and semi-active suspension systems.

Several factors drive technological progress in vehicle suspension systems. Traditionally, suspension design has been limited by a trade-off between ride comfort and road holding: passive suspensions rely on (although sophisticated) fixed stiffness and damping settings, optimized according to vehicle type to prioritize comfort or handling, or a compromise between the two. In contrast, semi-active and active suspensions aim to extend control of the vehicle's vertical dynamics by allowing variable stiffness and/or damping, or even near-complete control through actuator-generated forces between the sprung and unsprung masses, which are associated with energy consumption and conversion losses. Another relevant factor, particularly amplified by the growing production of electric vehicles (EVs), is related to acoustic comfort. In the absence of the Internal Combustion Engine (ICE) as the dominant source of noise, research in the field of noise, vibration, and harshness (NVH) is focusing on alternative factors that contribute to noise and vibration in the passenger compartment. Among these, the interactions between the road, suspension, and bodywork play a key role, as the suspension system acts as the primary filter for road-induced discomfort.

As a result, semi-active and active suspensions are increasingly being adopted, especially in premium vehicles, as a means of improving overall ride comfort and user experience. However, the integration of advanced suspensions often involves the use of brushless electric motors (EMs) that require components composed of Critical Raw Materials (CRMs) [4,5], such as permanent magnets (PMs), or Strategic Raw Materials (SRMs) [4,5], including copper. These motor technologies, in particular the axial flux type, provide advantages such as efficiency and high power density, which are both key needs for vehicle installation. In fact, for example, an increase in the suspension subsystem mass leads to an increment in the whole vehicle energy consumption: lightweighting is essential. High-performance permanent magnets are typically based on Rare Earth Elements (REEs), such as NdFeB alloys, which may contain Neodymium, Praseodymium, Dysprosium, and others. These materials are associated with significant environmental [6] and social [7] impacts due to the difficulties associated with their extraction and supply chain.

Another key aspect is the operational energy requirement of these suspensions, which, while smaller than the overall traction demand, is not negligible compared to other on-board auxiliary systems and can significantly affect vehicle range, particularly in electric vehicles. Therefore, as part of a holistic design framework, it is essential to critically evaluate which suspension technologies incorporate motors and/or systems that depend on CRMs and, where energy-intensive solutions are considered, to evaluate design choices in terms of efficiency, performance, and environmental, social, and economic impact. The parametric modeling and simulation system proposed here is part of such a design framework.

1.1. Automotive Suspension Systems Taxonomy Review

Automotive suspension systems are designed to meet multiple, often conflicting, objectives, including passenger comfort, structural integrity of the vehicle body, and optimal driving dynamics [8–10]. The suspension must support the static weight of the vehicle, dampen road-induced accelerations, and, consequently, mitigate the transmission of shocks to the chassis, thereby protecting both structural components and occupants [8–10]. In addition, it must effectively manage load transfers during dynamic maneuvers and static load variations, such as those resulting from passengers or additional loads [8–10]. A fundamental requirement is also to maintain continuous contact between the tires and the road, as this directly influences the vehicle's maneuverability, braking efficiency, and overall safety [8–10]. Suspension systems can be classified according to various criteria, such as structural architecture or functional mechanisms.

For this study, classification based on their operating principle was considered [8,9]:

- Passive suspensions.
- Semi-active suspensions.
- Active suspensions.

Figure 1 shows some classic configurations of quarter-car models of the three types of suspension. It should be noted that these suspension models are sometimes represented with other configurations. For example, semi-active suspensions may also have a passive damper in parallel. Furthermore, active suspensions can be represented without the passive damper in parallel, or have a configuration with the actuator in series with the passive suspension.

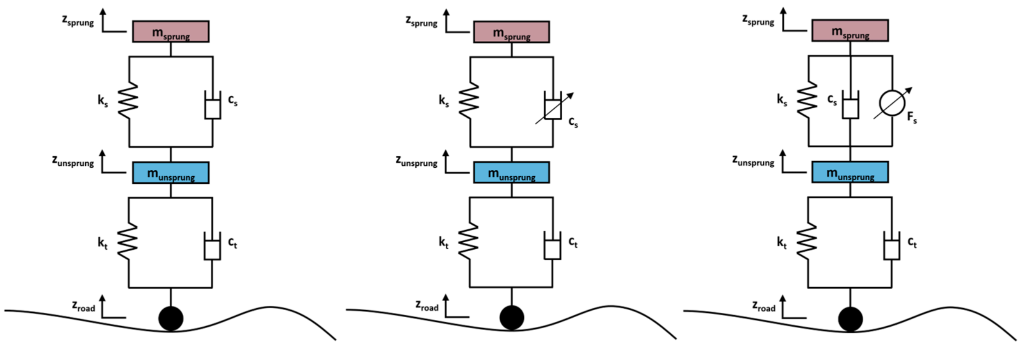

Figure 1. Quarter-car model of suspension systems: (**a**) Passive; (**b**) semi-active; and (**c**) active.

1.1.1. Passive Suspension Systems

Passive suspension systems are mainly mechanical assemblies consisting of an elastic element, such as a spring, combined with a damping device, usually a hydraulic or gas shock absorber [8,9]. These components are arranged in parallel between the unsprung mass (the wheel and support structure) and the sprung mass (the vehicle body) [8,9]. Their widespread use in automotive engineering is mainly due to their structural simplicity, robustness, and low production cost. The compromise between ride comfort and dynamic handling inherently determines the performance of passive suspensions. For example, better vibration isolation would require soft springs with relatively low damping, while stability under variable load conditions and aggressive maneuvers requires stiffer springs and higher damping coefficients [8,9]. Tire-road grip is also improved by increased damping, but this often comes at the expense of passenger comfort [8,9]. The fundamental limitation of passive suspension lies precisely in its inability to vary design choices relating to spring stiffness and damping characteristics during changing operating conditions [8,9]. As a result, the system can only respond reactively to external inputs without exercising any active control. Improvements are therefore limited to optimizing the geometry of the system and the design of components and materials [8,9], for example, to achieve non-linear damping performances. Damping, in fact, is typically obtained by laminating oil in calibrated orifices, which would approximate an ideal damper with a constant coefficient; through mechanical devices (e.g., one-way valves, movable plates, and similar devices) such a lamination factor is modified depending on direction and speed of the damper terminals. Despite these limitations, passive suspension remains the most widely used solution in road vehicles due to its compactness, affordability, and proven reliability [8,9].

1.1.2. Semi-Active Suspension Systems

Semi-active suspension systems essentially share the same basic mechanical configuration as passive suspension, consisting of springs and shock absorbers, but incorporate the ability to modulate the damping coefficient in real time [8–10]. This feature allows the suspension to adapt its response to different driving conditions: cushioning can be increased when cornering, accelerating, or braking to reduce roll and pitch, while it can be attenuated when driving in a straight line and in a steady state to improve driving comfort. Compared to fully active suspension, semi-active systems offer the advantage of significantly lower power consumption, as external power is only needed to modulate damping characteristics and not to generate control forces directly. However, their functional limitations are not negligible: they cannot adjust the ride height, nor can they eliminate roll and pitch in steady-state conditions [8–10]. As a result, while semi-active suspension provides a balanced compromise between comfort, handling, and energy efficiency, it remains intrinsically constrained by its reliance on passive mechanical elements [8–10]. Semi-active actuators are usually of the following types [10,11]:

- Servo/Solenoid valve dampers.
- Magnetorheological (MR) and electrorheological (ER) dampers.
- Electromagnetic dampers.

The shock absorbers of servovalves and solenoid valves regulate the flow of hydraulic fluid through electronically controlled valves, controlling orifice areas, offering rapid response, and benefiting from consolidated industrial maturity [10,11]. Magnetorheological (MR) and electrorheological (ER) dampers exploit field-sensitive non-Newtonian fluids whose viscosity (or apparent viscosity) changes under magnetic or electrical stimuli, allowing precise and continuous damping modulation with high mechanical reliability [10,11]. Electromagnetic dampers, by contrast, generate resistive forces controllable via electromagnetic induction using permanent magnets or electromagnets without relying on hydraulic fluids, providing rapid response and potentially lower fluid-related maintenance, but introducing requirements associated with power electronics and thermal management; their high cost remains a barrier to widespread implementation in conventional vehicles [10,11].

A wide range of control strategies have been developed for semi-active suspension systems, among which those considered “classic” are skyhook and groundhook control, as well as the hybrid formulation of the two. The skyhook scheme models a virtual damper connected between the vehicle body and an inertial reference frame, aiming primarily at the suppression of body vibration. In contrast, the groundhook scheme assumes a shock absorber acting between the wheel and the ground, with the goal of minimizing dynamic tire-load variations to improve road holding [11,12]. The latter can therefore be considered the dual formulation of the former, and their combination provides the basis for several advanced semi-active suspension controllers. After classical methods, “modern” control methods are present in the literature. Among these is Optimal control, which usually uses algorithms such as Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG). In addition to Optimal control, Model Predictive Control (MPC), Robust Control, and Adaptive Control are also included in modern methods. The latest control methods are the “intelligent” ones, which include Fuzzy-logic Control, Neural Network Control, and Bio-Inspired Optimization Algorithms [11,12].

1.1.3. Active Suspension Systems

Active suspensions are systems that, via an electronically controlled actuator, generate additional forces to improve the dynamic behavior of the vehicle [8–10]. This type of suspension scheme uses sensors, control algorithms, and actuators (hydraulic or electric) to adapt to road and driving conditions continuously [8–10]. When the actuator operates in parallel to the spring, the suspension is classified as high-bandwidth, controlling both sprung and unsprung mass. In contrast, when operating in series, the suspension has a low bandwidth and mainly controls the sprung mass. Typical frequencies of the sprung mass range between 1 and 2 Hz for passenger vehicles, though compact and sporty cars may reach up to 2.5 Hz, while those of the unsprung mass generally lie between 10 and 15 Hz [8–10]. The main advantage of active suspension lies in its ability to overcome the inherent trade-off between driving comfort and vehicle stability found in passive and partly semi-active suspension. The actuator reduces vehicle body acceleration, compensates for rolling, pitching, and lifting movements, and can adjust ride height to improve aerodynamics and efficiency at high speeds.

While these systems offer superior performance, they require significant power input and additional energy conversion devices, such as hydraulic pumps or electric motors, thus impacting the vehicle's overall energy efficiency [8–10].

The actuators usually used are [10]:

- Hydraulic or pneumatic actuators.
- Electromagnetic actuators.
- Electromechanical actuators.

Each type of actuator has specific advantages and limitations in terms of response speed, force capacity, integration complexity, and energy efficiency, making the choice of actuator a crucial aspect in the design of active suspension systems.

As regards control systems, several methods are present in the literature, including Proportional-Integrative-Derivative (PID) control, H-infinite, other methods already presented in the part relating to semi-active suspensions, or even control methods in combination with the other mechatronic systems of the vehicle [13].

One of the most interesting features of active suspension systems in the context of design for sustainability is their potential for energy regeneration through the same mechanism that provides actuation [14]. This capacity represents a possible solution to the considerable energy requirements typically associated with such suspensions. While active systems offer excellent dynamic performance, they do so at the expense of higher power consumption, which can lead to higher fuel consumption in conventional vehicles or reduced driving range in electric vehicles.

Several studies have addressed the opportunity of energy regeneration using suspension systems by exploring different system architectures [15] and controls [16], including electromechanical [17] and electromagnetic (or hybrid) [18] designs, with experimental modeling and validations ranging from bench tests [19] to multi-objective optimization approaches [20]. However, the use strategies of active suspensions remain a highly open field of research, making them an ideal case for integrating system design into a more holistic perspective, which considers not only the use phase but also the production phases and end-of-life.

1.2. Work Structure and Objectives

The document is structured as follows. Section 1 examines the state-of-the-art of automotive suspension systems and outlines their taxonomy. Section 2 describes the proposed parametric model and the set of design variables used. Section 3 reports the results of the simulations obtained by varying the road conditions and the design parameters of the actuator. Section 4 provides a critical discussion of the results, addressing both the strengths and limitations of the proposed approach, and identifies directions for future research.

The first goal of this work is to initially present an overview of the current design technologies of automotive suspension systems and highlight the possible connection with the principles of circular design. Next, a parametric simulation model is presented for evaluating the energy consumption of active suspension systems in road vehicles. The model was developed to be part of a broader framework that integrates suspension performance with energy efficiency and the environmental, social, and economic sustainability of design decisions, not only in the use phase, but also in production and end-of-life phases. The final objective of this work is twofold: (i) to formulate a flexible parametric model that allows systematic comparisons between different suspension and actuator models, and (ii) to demonstrate its applicability through simulation studies with variable road profiles and design configurations.

2. Materials and Methods

The model presented in this work was developed using MATLAB and Simulink (version R2024b) [21]. The objective is to represent a quarter-car model of an active suspension system, specifically a suspension actuated mechanically through an electric motor and a ball screw mechanism. This choice is motivated by the fact, as highlighted in the Introduction, that such electromechanical actuators are among the most promising solutions for future vehicles. Consequently, they require investigation from both the perspective of circular design and the perspective of design for efficiency, given their capability not only to consume energy to actuate the suspension but also to regenerate energy under certain operating conditions. The modeling approach is based on the reference scheme illustrated in Figure 1c, which represents a quarter-car model where the suspension is composed of three parallel elements: a passive spring, a passive damper, and a controllable force actuator. The actuator is modeled as a Permanent Magnet Synchronous Motor (PMSM) that drives a ball screw mechanism, converting the motor's rotary motion into a linear actuation force applied to the suspension. The following subsections provide a detailed description of the modeling approach for each component, together with the main parameters used in the case studies presented.

2.1. Road Profile

The reference standard for characterizing one-dimensional road profiles is ISO 8608 [22]. It specifies a spectral description in terms of the displacement Power Spectral Density (PSD) $G_d(n)$ (m^3), where n is the spatial frequency (cycles/m). Within this framework, different surface conditions, from very smooth pavements to rough terrain, are classified by two parameters: the PSD level at a reference spatial frequency n_0 and the spectral slope ("waviness") w. Over the range of interest, ISO 8608 models the PSD as a power law (with n_0 = 0.1 cycles/m and, for typical roads, $w \approx 2$) [23]:

$$G_d(n) \;=\; G_d(n_0)\left(\frac{n}{n_0}\right)^{-w} \tag{1}$$

For the present work, synthetic road profiles consistent with ISO 8608 were generated using a sum-of-sines approach. A MATLAB script constructs vectors of amplitude A_k, angular frequency ω_k, and phase ϕ_k for $k = 1, \ldots, K$. The amplitudes are chosen to match the target PSD in each finite band Δn_k centered at n_k, namely, as follows:

$$A_k = \sqrt{2G_d(n_k)\Delta n_k} \tag{2}$$

The phases are independent and uniformly distributed $[0, 2\pi)$. The temporal excitation follows from a constant vehicle speed V, via $f_k = Vn_k$ and $\omega_k = 2\pi f_k$. The synthesized realization is reported in Equation (3) and reproduces the target PSD. The harmonic method is widely used in the literature because it is transparent, parameterizable, and effective for generating statistically consistent profiles [23,24]:

$$z(t) = \sum_{k=1}^{K} A_k \sin(\omega_k t + \varphi_k) \tag{3}$$

Three profiles were synthesized to represent ISO 8608 classes B, C, and D, i.e., three distinct values of $G_d(n_0)$ at the reference frequency, with identical slope w. This isolates the effect of increasing roughness level while keeping the spectral decay unchanged. Figures 2 and 3 report the generated profiles as functions of distance x and time t, respectively (with $x = Vt$, $V = 20$ m/s). Figure 4 provides a PSD-level check: the PSD recovered from the synthesized amplitudes is plotted against the ISO 8608 target at the same band centers. Agreement within the discretization error confirms that the construction enforces the prescribed spectral content by design.

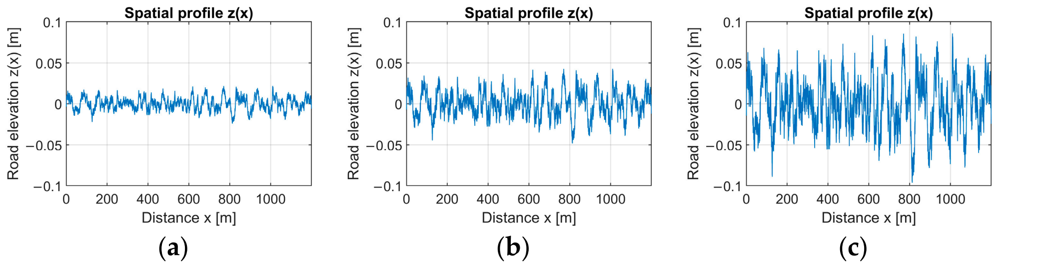

Figure 2. Road profile—z(x): (**a**) ISO class B; (**b**) ISO class C; and (**c**) ISO class D.

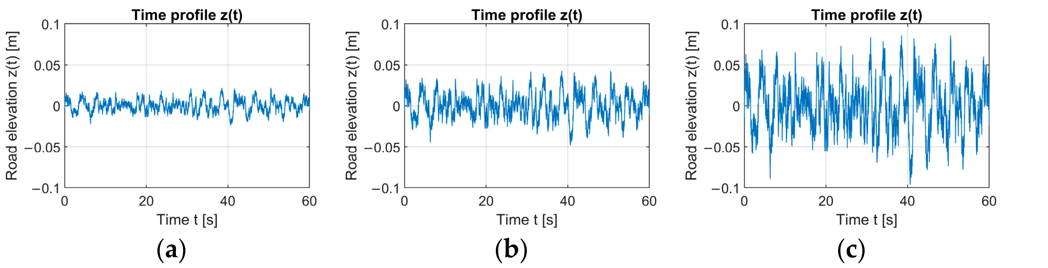

Figure 3. Road profile—z(t) at 20 m/s: (**a**) ISO class B; (**b**) ISO class C; and (**c**) ISO class D.

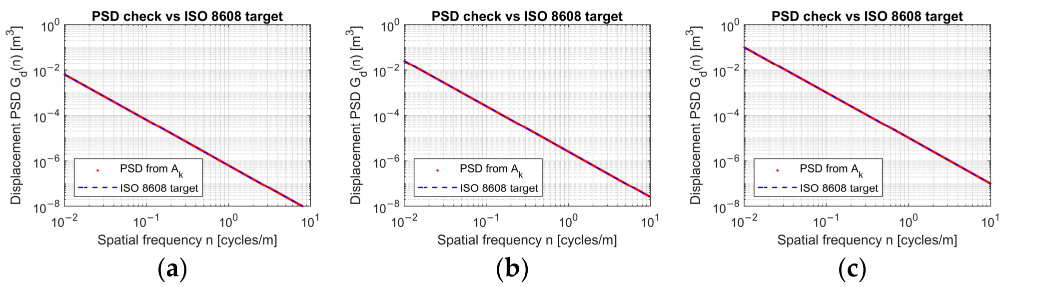

Figure 4. PSD-level check: (**a**) ISO class B; (**b**) ISO class C; and (**c**) ISO class D.

2.2. Quarter-Car Model

The quarter-car model employed in this study is a two-degree-of-freedom (2-DOF) system, consisting of a sprung mass and an unsprung mass. The model is implemented in the Simulink environment, primarily using the Simscape library. The wheel is represented by a parallel spring-damper configuration, which connects the road surface to the unsprung mass, reproducing the tire's stiffness and deflection characteristics. Between the unsprung and sprung masses, three parallel elements were used: the actuator of the active suspension and two components representing the passive suspension, namely a spring and a viscous damper. Several sensors are placed within the system to measure both absolute and relative displacements of the components. These signals are then processed to compute the control inputs for the electric motor driving the actuator. The main simulation parameters correspond to a hypothetical C-segment electric vehicle and are summarized in Table 1.

Table 1. Quarter-car model main parameters.

Parameter	Value	Unit
m_{sprung}	450	kg
$m_{unsprung}$	50	kg
k_{tire}	200	kN/m
c_{tire}	150	Ns/m
$k_{suspension}$	18	kN/m
$c_{suspension}$	1500	Ns/m
$c_{skyhook}$	8000	Ns/m
$c_{groundhook}$	3000	Ns/m

2.3. Control

The control strategy adopted in this work is a hybrid skyhook–groundhook scheme [25,26]. The primary objective of the skyhook control is to enhance ride comfort by generating a damping force that emulates a virtual damper connected to an inertial reference fixed in the "sky". On the contrary, the goal of the groundhook control is to improve road holding and vehicle handling, ideally by generating a damping force proportional to the velocity of the unsprung mass relative to the road surface (the "ground").

The hybrid formulation, reported in Equation (4), combines these two strategies through a weighting factor $\alpha \in [0, 1]$, which allows for adjustment between comfort-oriented behavior ($\alpha \to 1$) and stability-oriented behavior ($\alpha \to 0$), depending on the operating conditions:

$$F_d = -\alpha c_{sh}(\dot{z}_s - \dot{z}_u) - (1 - \alpha) c_{gh}(\dot{z}_u - \dot{z}_r) \quad (4)$$

where $\dot{z}_s$, $\dot{z}_u$, and $\dot{z}_r$ are, respectively, the vertical velocity of the sprung mass, unsprung mass, and road, according to the scheme in Figure 1c. Instead, c_{sh} and c_{gh} are the equivalent damping gains for skyhook and groundhook control law, as reported in Table 1. In addition to the hybrid skyhook–groundhook scheme, the model incorporates several signal-conditioning and control mechanisms designed to ensure a physically consistent system behavior. These measures account for both the kinematic constraints of the suspension mechanisms and for the robustness of the control action, thereby improving the realism and reliability of the overall system response. The force demanded by the controller is ultimately converted into the corresponding torque requirement for the control of the electric motor. This torque is then transmitted to the linear actuator through the ball screw mechanism, which ensures the transformation of rotary motion into the desired linear actuation.

2.4. Actuator Block

The actuator subsystem is connected in parallel with the passive suspension and converts motor torque into linear motion. The motor is primarily represented by the Simscape "Motor & Drive (System Level)" block. The actuator subsystem is particularly flexible, as it allows for minor adjustments that enable the simulation of different electromechanical or electrohydraulic couplings between the electric motor and the suspension. The parameters of the linear component are primarily related to frictional losses. For this reason, a ball screw mechanism was adopted, as it ensures high efficiency in both forward and reverse motion. In this study, the screw lead was set to $L = 0.010$ m/rev to match the suspension speed during oscillations and the expected motor speed. The motor part of the model represents the most relevant aspect for this work, as it directly relates to the themes of circular design and sensitivity to design choices. Electric motors used in active suspensions must provide high performance to minimize net energy consumption and ideally enable energy regeneration under specific operating conditions. However, the choice of materials, assembly methods, or the use of recycled permanent magnets can significantly affect the environmental, social, and economic impacts of the product throughout its production and end-of-life phases. These alternatives, on the other hand, may reduce motor efficiency, a key parameter for assessing life cycle impact, as the actuator is an active component that continuously consumes or regenerates energy.

The literature shows that permanent magnets can be recycled and reused with only minor changes in performance [27], particularly affecting losses in the efficiency map at low speeds and high torques [28]. One of the objectives of this study is to evaluate the effect of such performance losses on the energy consumption of the active suspension across different road profile scenarios. The “Motor & Drive” block enables the integration of efficiency models or experimental datasets, expressed as functions of torque and speed. These datasets may be obtained through complex CFD simulations or more simplified analytical calculations [29].

2.5. Case Study

The simulation tests of the model are based on the three generated road profiles, evaluated with two versions of an Axial Flux Permanent Magnet (AFPM) electric motor, one of which featured a modified efficiency map. The two maps represent a hypothesis of a reference electric motor and a modified motor in which different design choices have been implemented during production, such as, for example, the use of permanent magnets composed, in part, of secondary raw materials. Figure 5 shows the two efficiency maps used in the simulations.

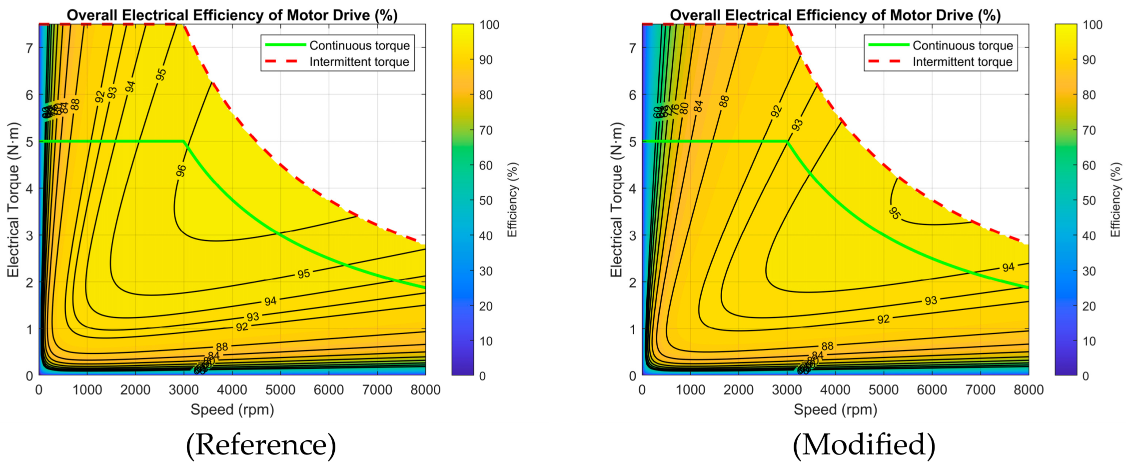

Figure 5. AFPM electric motor efficiency maps—reference and modified.

The objective of simulations is to verify that the developed parametric model can simultaneously ensure an acceptable level of ride comfort and road holding, while also enabling an intelligent use of energy, both consumed and regenerated, by the electric motor driving the active suspension actuator. By achieving this, the model would be ready to be integrated into a broader framework aimed at assessing the effectiveness of design choices from an eco-design perspective. Figure 6 represents the quarter-car model and the various subsystems in the MATLAB/Simulink environment.

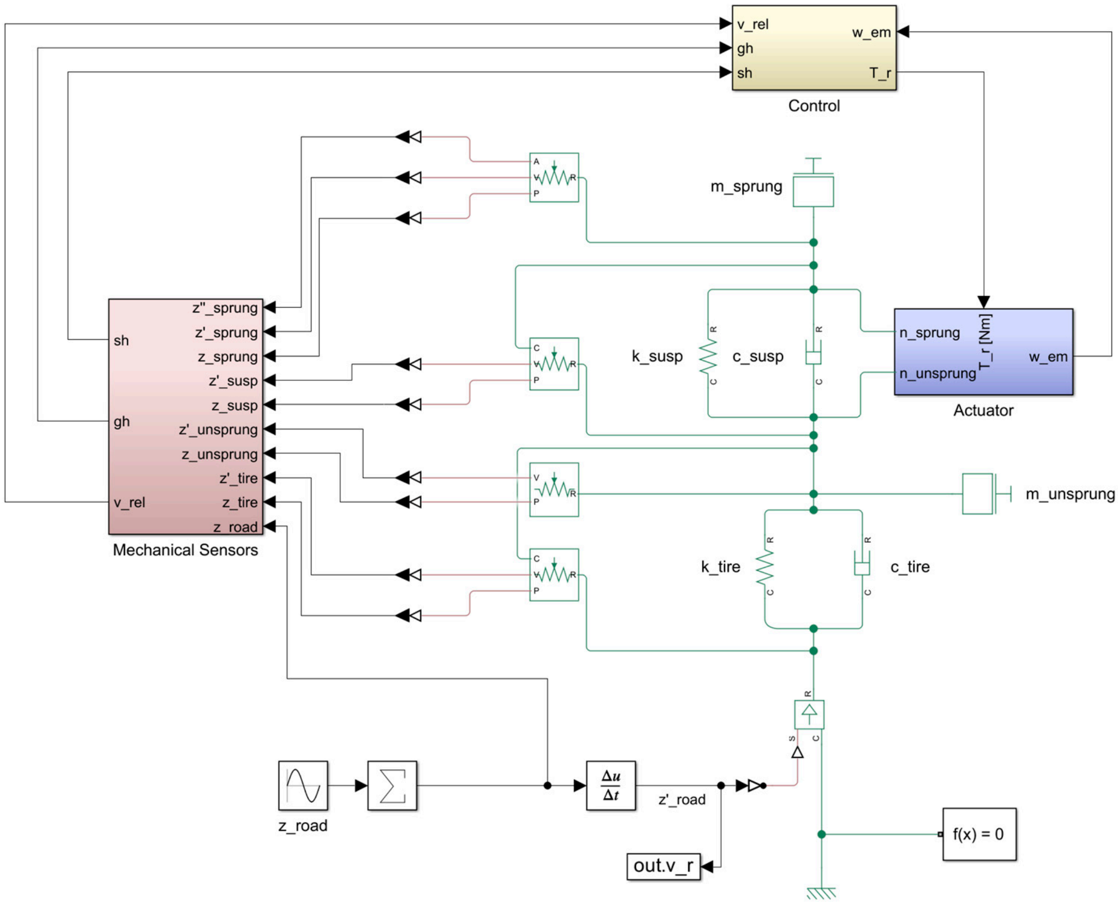

Figure 6. Active suspension system quarter-car model in Simulink environment.

3. Results

The simulations conducted in this study had two objectives. First, to evaluate the performance of the suspension and verify that it was consistent with the results reported for comparable models in the literature, while showing a realistic response characteristic of a quarter-car model. Second, to quantify the energy consumption of the modeled active suspension system, including regenerative effects, and thus establish a basis for future comparisons between alternative component designs, drive architectures, and motor technologies with different characteristics.

3.1. Suspension System Performance

The first analysis focused on the dynamic performance of the modeled system as described in the Methods section. Specifically, it was verified that driving comfort and road holding were consistent with those expected from an active suspension. For this purpose, the vehicle's response to an ISO 8608 Class C road profile (representing an average roughness) was simulated, and the transmissibility of road excitation to (i) the displacement of the suspended mass (bodywork) and (ii) tire deflection was estimated. The corresponding frequency response functions (FRFs) were estimated in MATLAB using the "tfestimate" function, which implements the Welch average periodogram method [30]. The resulting amplitude-frequency curves (Figure 7) show similar trends to the results reported in the literature for comparable active suspension models [10].

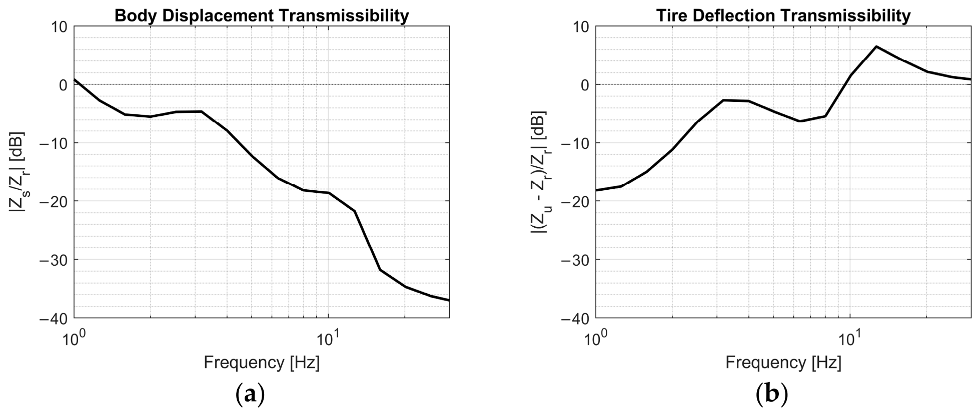

Figure 7. Frequency response of the active suspension system: (**a**) from road profile to body displacement; and (**b**) from road profile to tire deflection.

In the same analysis, it was assessed whether the accelerations of the suspended mass (bodywork) and the dynamic forces of the tires, respectively indicators of ride comfort and road holding, are consistent with the scientific literature and increase with road surface irregularity. Three simulations were performed using the three ISO 8608 profiles (classes B, C, and D, from smoother to more uneven surfaces), and the root mean square (RMS) of the parameters was evaluated for each case. The numerical results are in line with suspension systems expectations [31] and show the expected increase from class B to class D, as indicated in the two graphs in Figure 8.

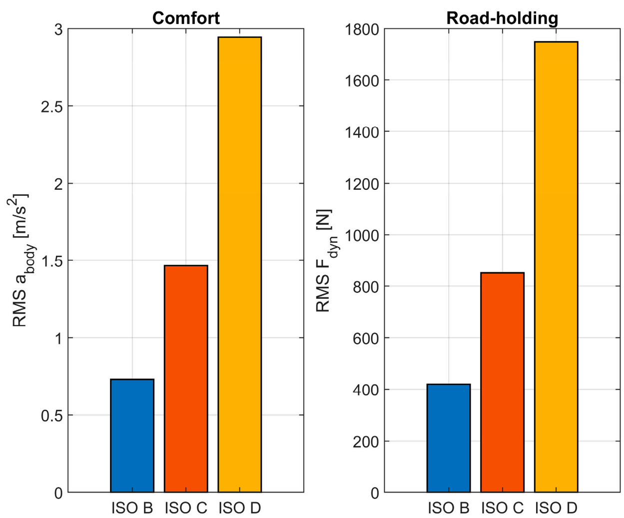

Figure 8. Comfort and road-holding on different road profiles.

3.2. Energy Consumption

After verifying that the suspension model responded adequately to the imposed inputs, a second series of analyses was conducted. For each ISO 8608 road class taken into consideration (B, C, and D), simulations were performed for both the reference and modified motor configurations. The instantaneous electrical power of the actuator was evaluated during each driving cycle; as can be seen in Figure 9, particularly in the case of class D, the peak values are near 400 W. Specifically, in Figure 9, the positive peaks indicate the electrical consumption of the active suspension. In contrast, the negative peaks correspond to the phases in which the actuator operates in a generative manner, recovering energy. Figure 10, on the other hand, shows the cumulative net energy (consumed minus regenerated) over the simulation for both configurations. The disparity between the two becomes more pronounced as the roughness of the road increases.

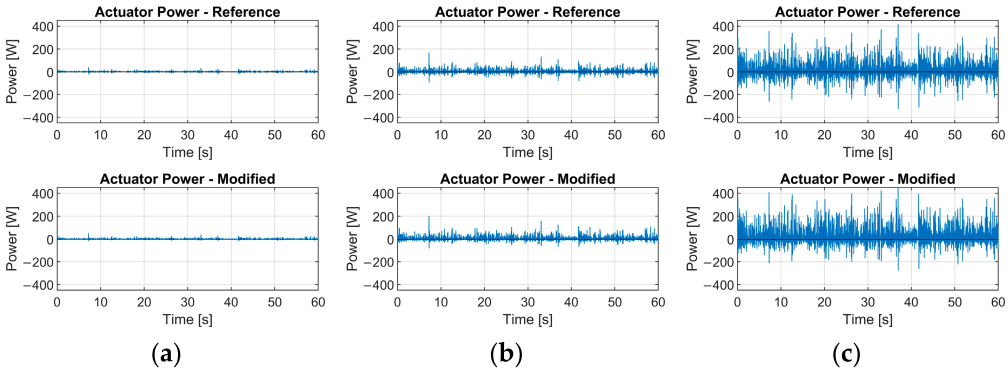

Figure 9. Actuator power on road: (**a**) ISO class B; (**b**) ISO class C; and (**c**) ISO class D.

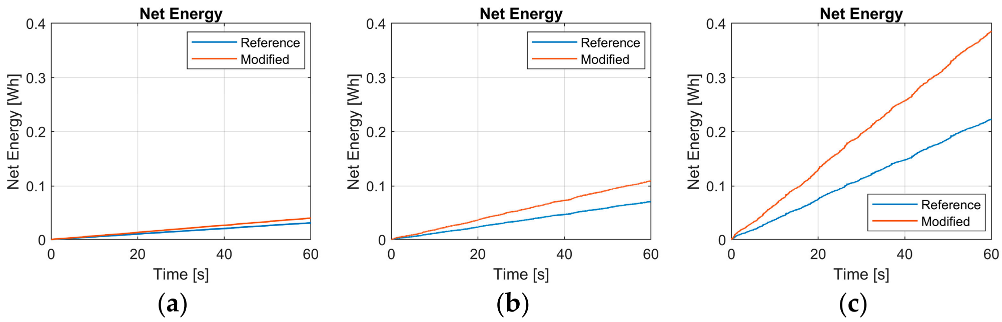

Figure 10. Net energy used on road: (**a**) ISO class B; (**b**) ISO class C; and (**c**) ISO class D.

Although the absolute energy requirement for simulation is modest, it refers to a single wheel and a simulation lasting only 60 s for a car going 20 m/s. Extending the assessment to the entire vehicle (four wheels, four suspensions) and realistic driving distances, non-negligible totals are obtained, as summarized in Table 2. For each operating condition, both the energy used and the net energy (considering regenerative events) are reported. The metrics are presented per wheel in Wh/km and, to facilitate interpretation at the vehicle level, in Wh/100 km for the entire vehicle.

Table 2. Use phase energy consumption results.

Parameter	Unit	ISO Class B		ISO Class C		ISO Class D	
		Ref.	Mod.	Ref.	Mod.	Ref.	Mod.
Energy used per km	Wh/km	0.031	0.037	0.096	0.119	0.361	0.452
Net energy per km	Wh/km	0.026	0.033	0.059	0.091	0.186	0.322
Full vehicle energy used per 100 km	Wh/100 km	12.45	14.69	38.43	47.48	144.33	180.81
Full vehicle net energy per 100 km	Wh/100 km	10.28	13.22	23.48	36.54	74.33	128.72

The results indicate that the overall energy requirement is moderate. This result is plausibly influenced by the efficiency of the mechanical chain, which is assumed to be relatively high. Furthermore, the presented simulations use a quarter-car model at constant speed, which tends to be conservative compared to real-world operation, where the dynamics of the entire vehicle introduce additional excitation through variations in speed, lateral acceleration, and the associated roll and pitch movements. These factors can increase the work of the suspension and thus increase energy requirements compared to the estimates reported here. Different choices for motor type, efficiency, ball screw pitch, and further construction parameters would lead to different energy consumption results. Consequently, it is confirmed that active suspensions should be designed not only for dynamic performance (driving comfort and road holding), but also for efficiency, through component sizing, control, and actuation strategy, and machine selection, and evaluated for sustainability throughout their entire life cycle, including considerations related to energy during use and at the end of their life.

4. Discussion and Conclusions

This work had multiple objectives. First, to examine the state-of-the-art in automotive suspensions, with a particular focus on active and semi-active suspension concepts, their drive options, and the associated energy requirements, which can significantly affect the range of battery electric vehicles (BEVs). Second, to develop a flexible simulation model of an active suspension that allows for simple studies on quarter-car models and rapid exploration of alternative design choices, both from a mechanical standpoint and, in particular, from the standpoint of the drive subsystem.

In this study, the actuator was modeled as an electromechanical unit: an Axial Flux Permanent Magnet Synchronous Motor (AFPMSM) driving a ball screw transmission mounted in parallel with the passive elements. The modeling framework, however, is modular and can be adapted with minimal effort to other motorized drive schemes. The model had to (i) reproduce the canonical performance indicators and trends reported in the literature for ride comfort and road holding and (ii) quantify the net energy exchange (consumed minus regenerated) as the design parameters varied.

Validation confirmed that the model produces comfort and handling metrics with consistent trends. Energy behavior was therefore evaluated for three ISO 8608 road profiles (classes B, C, and D) and for two design variants, referred to as "Reference" and "Modified", to capture plausible differences in motor efficiency maps. For example, consider those that could result from alternative magnetic materials or recycled content, which, according to the literature, could reduce efficiency in high-torque and low-speed regions of the efficiency map. The simulations revealed frequent actuator events, with instantaneous electrical power occasionally near 400 W in the case of the most uneven road profile. They also demonstrated that regenerative operation can almost offset consumption, resulting in relatively modest net energy requirements over short time horizons.

These results underscore that the efficiency of the entire electromechanical chain is critical: the bidirectional mechanical efficiency (drive/reverse) of the ball screw and the torque-speed efficiency map of the motor are both decisive factors. However, even with regeneration, travel-scale energy, when aggregated over four wheels and realistic durations, becomes non-negligible for calculating the driving range of electric vehicles. Consequently, active suspensions are industrial products that should be designed not only for dynamic performance but also for efficiency, and evaluated from a life cycle perspective that includes energy in the use phase, the impact of production, and the end-of-life phase.

Overall, the proposed model meets the initial objectives: it is suitable for integration into a broader framework for multi-criteria assessment of performance and life cycle sustainability (environmental, economic, and social) throughout the entire life cycle of an industrial product. As such, it can support both designers and non-specialist stakeholders in comparing alternative suspension and actuation solutions with a holistic view at the system level.

Future work will prioritize: (i) extending the set of actuators to include, for example, electrohydraulic systems or actuators built with different technologies; (ii) moving from a quarter-car model to a full-vehicle model to capture roll/pitch dynamics and diagonally coupled architectures; and (iii) increasing fidelity through Hardware-in-the-Loop (HiL) simulations and experimental correlation.

In conclusion, the results indicate that active suspensions can deliver the expected dynamic benefits while keeping net energy costs manageable, provided that the drivetrain is optimized and evaluated within a clear life cycle framework.

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Abbreviations

The following abbreviations are used in this manuscript:

REE	Rare earth element
EV	Electric vehicle
ICE	Internal combustion engine
NVH	Noise, vibration, and harshness
EM	Electric motor
CRM	Critical raw material
PM	Permanent magnet
SRM	Strategic raw material
MR	Magnetorheological
ER	Electrorheological
LQR	Linear quadratic regulator
LQG	Linear quadratic Gaussian
MPC	Model predictive control
PID	Proportional integrative derivative
PMSM	Permanent magnet synchronous motor
ISO	International standard organization
PSD	Power spectral density
DOF	Degree of freedom
CFD	Computational fluid dynamics
AFPM	Axial flux permanent magnet
FRF	Frequency response function
RMS	Root mean square
BEV	Battery electric vehicle

AFPMSM	Axial flux permanent magnet synchronous motor
HiL	Hardware-in-the-loop

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