A Comparative Analysis of Inerter Integration in Suspension Systems

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Abstract. Recent advancements in automotive suspension systems have markedly enhanced vehicle safety, comfort, and dynamics. An notable innovation is the integration of the inerter, which improves stability and comfort by damping vibrations. The inerter, a two-terminal inertial element, generates a resistance force proportional to the relative acceleration between its terminals, quantified by the inertance constant in kilograms (kg). This research explores the dynamics of an SUV passenger vehicle using a 14-degree-of-freedom (DOF) vehicle model that incorporates an inerter along with traditional springs and dampers. Utilizing VI-CarRealTime and MATLAB/SIMULINK for simulations, the study aims to identify optimal inertance values. The objective is to elucidate the improvements in suspension performance due to the inerter under various road conditions, ultimately determining the best comfort configuration for the vehicle.

Keywords: Vehicle Dynamics, Vehicle Suspension, Inerter, VI-CarRealTime, SIMULINK

1 Introduction

Ensuring a safe, smooth, and comfortable ride for vehicle occupants relies heavily on the effectiveness of automotive suspension systems. This system plays a critical role in absorbing shocks from the road surfaces. The interaction between tires and the road often generates considerable disturbances and vibrations, which, if not effectively managed, can cause discomfort to passengers. Therefore, a well-engineered suspension system is essential not only to maintain stability and control, but also to enhance the overall driving experience and passenger comfort.

The development of vehicle suspension systems has seen extensive exploration of passive, semi-active, and active systems, as documented in various studies [1]. Although active suspension systems have received significant attention in academic circles [2], passive suspension systems remain the predominant choice in the automotive industry due to their reliability and cost-effectiveness. The inherent simplicity, durability, and lower cost of passive systems make them particularly suitable for mass-market vehicles, ensuring a balance between performance and affordability for a wide range of consumers.

Traditional passive suspension systems typically consist of a spring element for static load support and a damping element for energy dissipation, together forming the mass-spring-damper system. However, recent technological advances have introduced the inerter as a supplementary component to futo enhance suspension performance furtherinerter is a compact, two-terminal device that translates the rotational inertia of a flywheel into the translational inertia between its terminals[3].

Incorporating the inerter into suspension systems presents a significant advance in optimizing vehicle dynamics, addressing both ride quality and handling performance. Traditional suspension systems rely heavily on passive components like springs and dampers; however, the inerter introduces a novel element that significantly alters the suspension's dynamic response, offering enhanced control over the system's reaction to various road disturbances. This device provides engineers with the ability to fine-tune suspension behavior in a way that adapts to varying road conditions, offering greater flexibility in performance optimization and allowing for more precise control over comfort and stability.

The challenge of mechanical vibrations in various technical systems has driven extensive research into the applications of inerters. These studies highlight the need to investigate vibrations that can affect performance, accelerate wear and tear, and potentially cause equipment failure. Known for their ability to manage kinetic energy, inerters have proven to be a viable solution to reduce vibration and stabilize the system in multiple engineering disciplines, including automotive engineering [4–8].

Previous research on the integration of inerters into vehicle suspension systems has often been limited to simplified, reduced-order models, such as the quarter-car model, which capture only a fraction of the complex dynamics of real-world systems. These studies, while informative, do not account for the full range of interactions present in higher-order models. The current literature lacks comprehensive simulation frameworks that integrate inerters into full-scale, multi-degree-of-freedom (DOF) vehicle models, missing critical insights into their behavior under realistic driving conditions.

This study addresses this limitation by employing a 14-degree-of-freedom (DOF) vehicle model, providing a more detailed and realistic representation of the suspension system. By utilizing a co-simulation approach between VI-CarRealTime and MATLAB/SIMULINK, we investigate the dynamic behavior of a vehicle equipped with an inerter across varying road conditions, focusing on two distinct scenarios: a transient road input and a frequency response evaluation across multiple bumps. Rather than varying inertance values as in previous studies, this research uses an optimization approach through VI-CarRealTime to determine the ideal inertance values for the front and rear axles, focusing specifically on enhancing ride quality. The key contribution of this work is its comprehensive analysis of inerter optimization to improve both ride comfort and handling under various road conditions, offering a detailed and comparative evaluation against traditional passive suspension systems.

In summary, this research offers a significant advancement over previous studies by integrating an inerter into a highly detailed 14-DOF vehicle model and utilizing a co-simulation framework to explore its effects. The findings provide new insights into how the inerter improves suspension performance, particularly in terms of vibration reduction and vehicle stability, under diverse road profiles. By expanding the scope beyond simplified models, this study contributes to the design of more advanced suspension systems, offering engineers a powerful tool to optimize both ride comfort and handling in diverse driving scenarios, with practical implications for the design of real-world vehicles.

2 Vehicle Model

The quarter-car model, often referred to as the 1/4 vehicle suspension model, is a fundamental concept in vehicle dynamics. It is primarily used to analyze and simulate the behavior of a single wheel and its corresponding suspension system. This model focuses on a simplified representation of the vehicle's suspension dynamics, isolating the interaction between the wheel, the suspension components, and the vehicle's body (sprung mass). Despite its simplicity, it is highly efficient and its equations are used to incorporate the inerter into the suspension system.

In contrast, the 14-degree-of-freedom (DOF) model, also known as the Twin Track model, is adopted in vehicle dynamics simulations, particularly for dynamic driving simulators. The 14 DOF model can be subdivided into a ride model, which relates to the vehicle's response to road imperfections, and a handling model, which describes acceleration, braking, and turning behavior, like pitch, roll and yaw. This model intricately integrates the complex interactions of vehicle forces into an advanced analytical framework. It includes both the vehicle's body (sprung mass) and the wheels along with their supports (unsprung masses), providing an authentic representation of driving scenarios.

The 14 DOF model elaborates on five essential components: one sprung mass and four unsprung masses at each vehicle corner, capturing both the rotational and vertical dynamics of the wheels. This comprehensive configuration, which incorporates 14 DOF, is instrumental in providing a detailed representation of vehicle dynamics, essential to accurately simulate real driving conditions [9].

While the quarter-car model provides a simplified framework for understanding the vertical dynamics of the suspension and the integration of the inerter, it serves primarily as the theoretical basis for modeling the inerter's behavior in SIMULINK. However, the full-scale simulations utilize a more detailed 14-degree-of-freedom (DOF) model in co-simulation with VI-CarRealTime to capture the comprehensive vehicle dynamics.

3 Inerter Mechanism

The inerter is a passive mechanical component with two terminals that generate a resistance force proportional to the relative acceleration between these terminals. This proportionality constant, termed inertance, is measured in kilograms (kg). According to Smith [3], the dynamic behavior of an ideal inerter can be described by the following equation:

$$F_{inerter} = b(a_2 - a_1), \tag{1}$$

In eq. (1), $F_{inerter}$ represents the force exerted by the inerter, b denotes the inertance in kilograms, and a_1 and a_2 are the accelerations at the terminals of the inerter. Essentially, the inerter's force is directly related to the difference in acceleration between its two connection points.

Inerters can be integrated into vehicle suspension systems through several configurations, as detailed by Smith and Wang [10]. In this study, however, emphasis is placed on the parallel configuration, which is widely regarded as one of the most commonly utilized arrangements. In the parallel configuration (Figure 1), the inerter is placed alongside the traditional spring and damper components. The equations governing the parallel inerter integrated into a quarter-car model are expressed as follows:

$$m_s\ddot{z_s} = k(z_u - z_s) + c(\dot{z_u} - \dot{z_s}) + b(\ddot{z_u} - \ddot{z_s}), \tag{2}$$

$$m_u\ddot{z_u} = k_t(z_g - z_u) - k(z_u - z_s) - c(\dot{z_u} - \dot{z_s}) - b(\ddot{z_u} - \ddot{z_s}) \tag{3}$$

In eq. (2) and eq. (3), m_s and m_u are the sprung and unsprung masses, k is the stiffness of the spring, c is the damping coefficient, b is the inertance, k_t is the stiffness of the tire, and z_s, z_u, and z_g are the vertical displacements of the sprung mass, the unsprung mass, and the input of the road, respectively. These equations capture the dynamics of the suspension system in the parallel configuration.

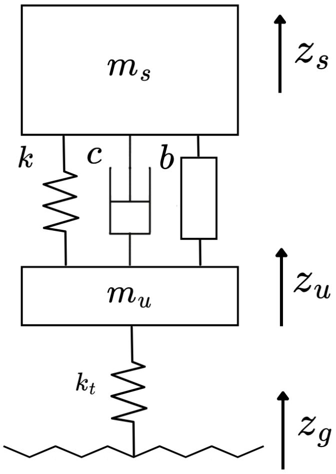

Figure 1. Quarter vehicle model with inerter in parallel configuration

4 Simulation Process

This section outlines the simulation process used to assess the impact of the inerter on vehicle ride comfort and handling performance. The co-simulation is carried out using the 14-degree-of-freedom (DOF) vehicle model in VI-CarRealTime, which interacts with a SIMULINK model of the inerter to simulate the system's dynamic behavior under different road conditions. The subsections below detail the simulation platform, the setup, and the metrics used to evaluate the vehicle's performance.

4.1 VI-CarRealTime

To evaluate the dynamic behavior and performance implications of integrating inerters into passive suspension systems using a 14-degree-of-freedom (DOF) vehicle model, we employed VI-CarRealTime (VI-CRT), a state-of-the-art simulation tool widely used in the automotive industry. VI-CarRealTime allows for accurate, real-time simulation of vehicle dynamics under various driving conditions, helping to reduce the need for costly physical testing. This tool is widely recognized for its reliability and precision in assessing vehicle modifications, making it popular among racing teams and automotive engineers.

VI-CarRealTime provides a comprehensive suite of features that model key aspects of vehicle dynamics, including Kinematics & Compliance (K&C), which encompasses tire characteristics, suspension geometry, chassis dynamics, braking systems, engine performance, and transmission behavior. These elements are crucial for understanding how modifications—such as the integration of an inerter into a suspension system—affect a vehicle's overall dynamics under both steady-state and transient driving conditions [9].

In this study, we co-simulated VI-CarRealTime with SIMULINK to integrate the inerter into the suspension system. VI-CarRealTime manages the overall vehicle dynamics, including the 14-DOF model, while SIMULINK models the inerter in its parallel configuration within the suspension, by adding an Inerter force into de Damper Force. The two platforms communicate in real time, allowing VI-CarRealTime to simulate how the vehicle responds to road conditions, while SIMULINK computes the inerter's influence on suspension performance. This co-simulation framework provides detailed feedback on how the inerter affects both ride quality and handling performance.

The virtual car model in VI-CarRealTime was configured using predefined subsystems, including the body, driveline, brakes, and the suspension system. These suspension parameters were then customized through co-simulation with SIMULINK. By integrating the inerter into the passive suspension system, the setup enabled a comprehensive analysis of the system's behavior during dynamic events, such as bumps, cornering, and road imperfections.

4.2 Simulation Setup

The simulations were conducted using fixed inertance values of 10 kg in the front and 30 kg in the rear axle, focusing on evaluating the system's response to two distinct road profiles: a multiple bump profile and a step maneuver. The vehicle model is a 14-degree-of-freedom (DOF) model, co-simulated with SIMULINK and VI-CarRealTime to integrate the inerter into the suspension. The vehicle speed was set at a constant 80 km/h. The multiple bump road profile consisted of spaced, repeated bumps with a height of 0.05 m, analyzed at a frequency of 10 Hz. In contrast, the step maneuver simulates a sudden road elevation of 0.1 m, providing a more abrupt input to test the suspension's response to sharp, isolated disturbances.

The fixed vehicle speed of 80 km/h was chosen for its relevance to real-world driving conditions where vibration absorption and ride quality are most critical. At this speed, the suspension system must effectively absorb vibrations caused by uneven road surfaces to maintain passenger comfort and vehicle stability. Additionally, 80 km/h represents a high speed commonly encountered on freeways , where road imperfections such as bumps and potholes are frequent. This speed offers a balanced evaluation of how the inerter affects both ride quality, in terms of chassis vertical acceleration, and handling, particularly in terms of vibration isolation and dynamic tire load management.

Remark 1: Step Road Profile: A road step of 0.1 m was used to simulate a sharp vertical input, such as encountering a bump or curb. This scenario helps evaluate the suspension system's performance during abrupt changes in road height, focusing on how the inerter contributes to reducing the vehicle's vertical acceleration and controlling dynamic tire load.

Remark 2: Multiple bumps: A spaced, repeated pattern of bumps was designed to progressively decrease the spacing between bumps as the vehicle moves forward, allowing the system to reach higher frequencies. This setup simulates real-world driving conditions, gradually increasing the frequency of road disturbances to challenge the suspension system's ability to manage both low- and high-frequency vibrations. By starting with larger spacing and moving to smaller spacings, this test provides valuable insights into the suspension's vibration isolation capabilities at varying frequencies.

During the simulations, data was recorded in SIMULINK and VI-CarRealTime, with key metrics such as sprung mass acceleration and dynamic tire load being tracked in real-time. The data was then exported to MATLAB for detailed analysis and plotting. This approach allows for a comprehensive evaluation of how the suspension system with the integrated inerter performs under different road inputs and driving conditions.

4.3 Ride and Handling metrics

The evaluation of the suspension system with the integrated inerter focuses on two primary metrics: chassis vertical acceleration for ride quality and front and rear dynamic tire load for handling. These metrics were selected due to their direct impact on passenger comfort and vehicle stability during the dynamic events simulated in the study, such as multiple bumps and transient road inputs.

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Remark 3: Chassis Vertical Acceleration

Chassis vertical acceleration measures the vertical movement of the vehicle body in response to road disturbances. It directly affects ride comfort, as higher vertical accelerations can lead to discomfort for passengers. In this study, we use the RMS (Root Mean Square) value of vertical acceleration to evaluate the ride quality over time. Maintaining low RMS values ensures that the vertical accelerations remain within acceptable limits, contributing to a smoother and more comfortable experience for passengers, especially when encountering uneven road surfaces or sudden transitions.

The integration of the inerter is expected to decrease the amplitude of vertical accelerations by absorbing and dissipating energy more effectively than traditional suspension components. By keeping the RMS values of chassis vertical acceleration low, the inerter enhances the vehicle's ability to absorb shocks from the road, improving ride comfort and reducing the transmission of road vibrations to the occupants.

Remark 4: Front and Rear Dynamic Tire Load

Dynamic tire load refers to the normal forces acting on the tires during dynamic driving conditions, such as cornering, accelerating, or traveling over bumps. This metric is critical for handling performance because it determines how effectively the tires maintain contact with the road. The contact-patch, the area where the tire meets the road is essential for generating the forces required for steering, braking, and accelerating. Variations in tire load can cause uneven pressure on the contact patch, leading to a reduction in grip and increased instability, particularly during sharp maneuvers or at higher speeds.

In this study, we focus on the RMS (Root Mean Square) values of dynamic tire load to evaluate handling stability. These values provide a measure of the overall fluctuations in tire load over time. Consistent RMS values across the front and rear axles are crucial because large variations can lead to uneven tire contact with the road, compromising vehicle stability, especially during rapid changes in direction or while traversing uneven surfaces. Maintaining minimal variations in these RMS values helps ensure predictable handling and better control.

The suspension system equipped with the inerter is designed to manage these dynamic tire loads more effectively by minimizing fluctuations in the RMS values of the normal forces acting on the tires. By keeping these values consistent, the inerter helps maintain a stable contact patch, ensuring that the tires remain in optimal contact with the road during maneuvers such as cornering or when encountering road irregularities. This results in improved handling balance, enhanced stability during dynamic events, and a reduced risk of loss of traction. By keeping the variation in the RMS values low, the system also reduces uneven tire wear, contributing to long-term performance and safety.

5 Simulation Results

This section presents the results comparing the performance of the traditional passive suspension system and the Inerter-Spring-Damper (ISD) suspension system. The simulations were conducted using VI-CarRealTime and SIMULINK software, focusing on the vehicle's behavior when subjected to road disturbances at a speed of 80 km/h. The primary metrics analyzed include chassis vertical acceleration and dynamic tire load variations for both single bump and multiple bump scenarios.

5.1 Step Maneuver

Remark 5: Chassis Vertical Acceleration

The chassis vertical acceleration during the step input is presented in Figure 2. The use of the inerter results in a significant reduction in vertical acceleration, demonstrating an improvement in ride comfort when facing abrupt road disturbances such as a step. The numerical comparison in Table 1 shows a 3.41% reduction in chassis vertical acceleration when the inerter is activated.

Remark 6: Dynamic Tire Load

Figures 3 and 4 depict the dynamic tire load for the front and rear axles, respectively, during the step maneuver. The slight increase in dynamic tire load with the inerter, as seen in Table 1, is negligible, indicating that the inerter's impact on tire load distribution is minimal during abrupt disturbances. This ensures that handling and

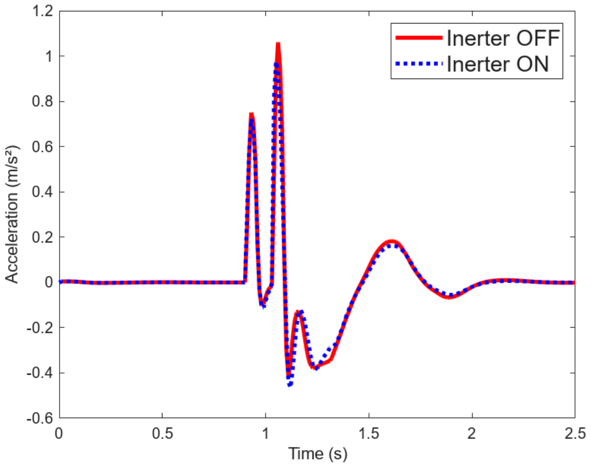

Figure 2. Chassis vertical acceleration for the step maneuver at 80 km/h.

traction are not compromised while improving ride comfort.

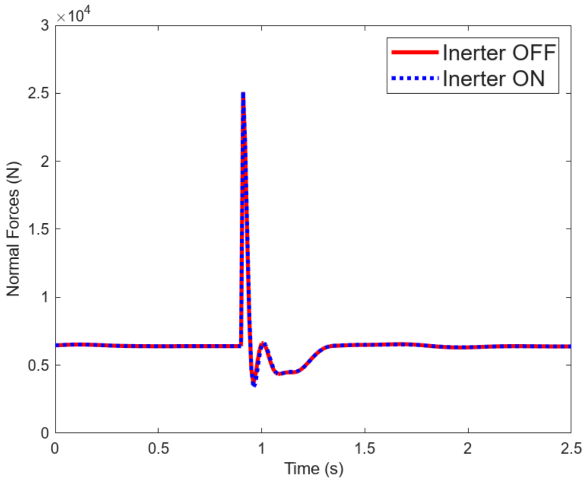

Figure 3. Front dynamic tire load for the step maneuver at 80 km/h.

Table 1. Comparison of Passive Suspension and ISD Suspension for Step

Variable	Inerter OFF	Inerter ON	Difference (%)
Chassis Acceleration Vertical (m/s²)	0.041452	0.040041	-3.41
Dynamic Tire Load Front (N)	6396.3	6396.6	+0.0052
Dynamic Tire Load Rear (N)	5299.6	5301.5	+0.036

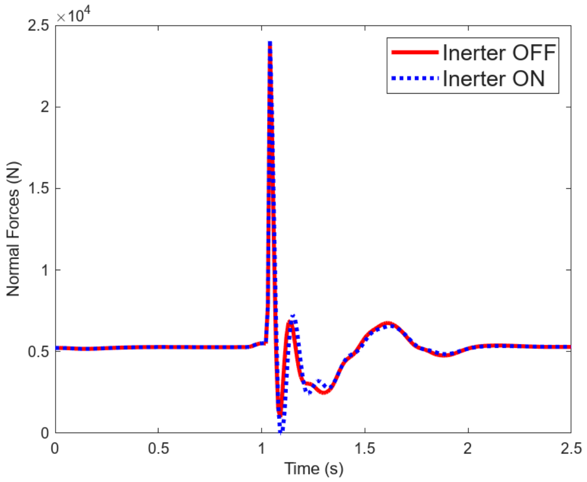

Figure 4. Rear dynamic tire load for the step maneuver at 80 km/h.

5.2 Multiple Bumps Maneuver

Remark 7: Chassis Vertical Acceleration

The vertical acceleration behavior over multiple bumps is shown in Figure 5. The results indicate a reduction in chassis acceleration when the inerter is activated, further confirming its effectiveness in improving comfort during continuous road disturbances. According to the data in Table 2, a 3.74% reduction in chassis vertical acceleration was observed, contributing to smoother vehicle dynamics over the bumps.

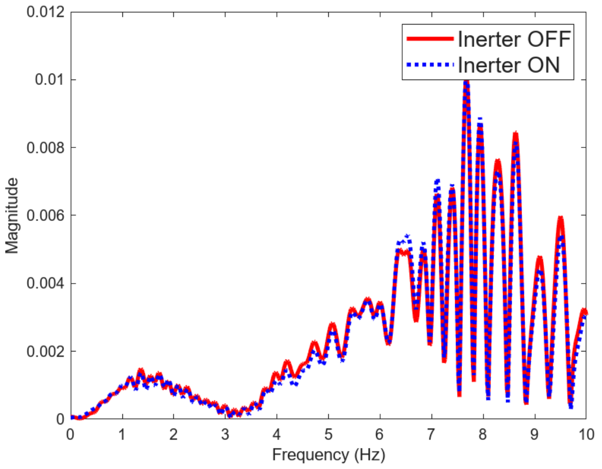

Figure 5. Chassis vertical acceleration for multiple bumps at 80 km/h.

Remark 8: Dynamic Tire Load

Figures 6 and 7 present the dynamic tire load for the front and rear axles over multiple bumps. The minor increase in tire load, particularly at the rear, as shown in Table 2, remains within acceptable limits. With only a 0.38% increase in rear tire load and a 0.056% increase in front tire load, the inerter's influence on tire load remains minimal, ensuring stability and control are maintained.

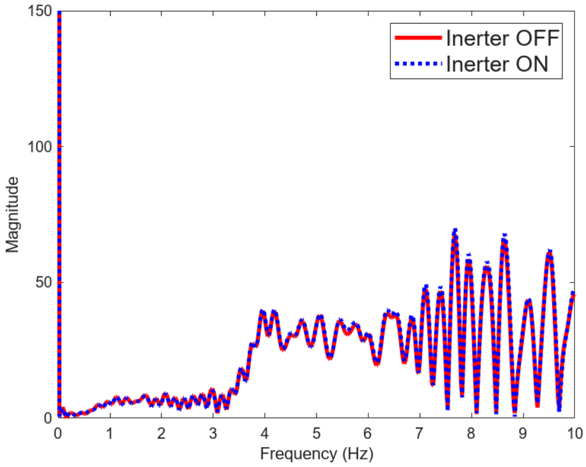

Figure 6. Front dynamic tire load for multiple bumps at 80 km/h.

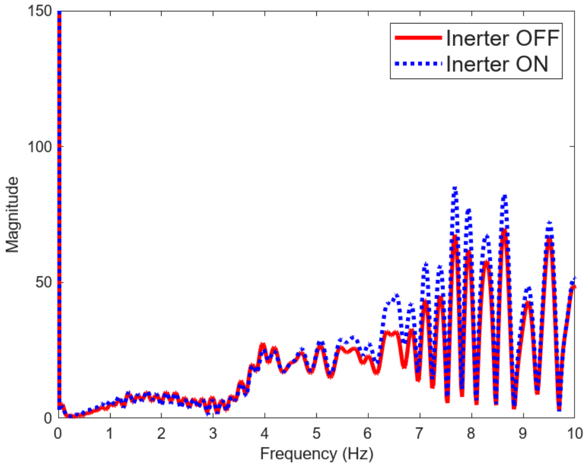

Figure 7. Rear dynamic tire load for multiple bumps at 80 km/h.

Table 2. Comparison of RMS Performance Metrics with INERTER_ON and INERTER_OFF Configurations

Variable	Inerter OFF	Inerter ON	Percentage Difference (%)
Chassis Acceleration Vertical (m/s²)	0.11763	0.11323	-3.74
Tire Normal Forces Front (N)	6535.9	6539.5	+0.056
Tire Normal Forces Rear (N)	5447.0	5467.9	+0.38

The results demonstrate that the use of the inerter significantly improves the ride comfort by reducing vertical acceleration in both step and multiple bump scenarios, without adversely affecting the handling. The data from Tables 1 and 2 show that while the inerter slightly increases dynamic tire load, the impact is negligible, making the suspension system more effective without sacrificing stability.

6 Conclusion

Through comprehensive analysis and simulations of various maneuvers, this research underscores the significant role of inertance in improving suspension performance, particularly regarding ride quality. By systematically comparing a standard suspension setup without an inerter to one equipped with an inerter, we consistently observed improvements in suspension response, most notably in the reduction of chassis vertical acceleration across all maneuvers. This reduction indicates a smoother ride and substantially enhances overall vehicle comfort.

Although the integration of the inerter did not lead to a significant reduction in dynamic tire load, it is crucial to emphasize that it did not adversely affect the vehicle's handling performance. This finding suggests that incorporating an inerter can optimize suspension systems by enhancing ride quality without compromising handling dynamics. The balance achieved between ride comfort and handling stability highlights the potential of inerters as a valuable addition to suspension design, contributing to superior vehicle performance.

In conclusion, the ISD suspension system consistently outperformed the conventional passive suspension system across all test scenarios. The significant reduction in vertical acceleration with the ISD suspension demonstrates improved ride comfort, while the minor increases in dynamic tire load show that handling remains stable. However, as inertance values increase, there is evidence of diminishing returns, with RMS values indicating the saturation of the inerter's kinetic and vibrational dampening capabilities. The insights provided by the 14-DOF model further emphasize the advantages of integrating advanced suspension technologies to enhance vehicle dynamics and passenger comfort under varied driving conditions.

This study contributes to the ongoing development of innovative suspension systems, highlighting the value of integrating components like the inerter. Future research should focus on further exploring these technologies, with an emphasis on achieving an optimal balance between ride comfort, handling performance, and overall vehicle dynamics.

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8 Authorship statement

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

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