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Ride Test on Vehicles Travelling Over Speed Bumps: Simulation with CarSim Software

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Abstract

This study explores the effects of different speed bump geometries—flat-topped, sinusoidal, and parabolic—on vehicle dynamics and ride comfort using CarSim simulations. The analysis focuses on key parameters such as vertical forces on the suspension, vertical acceleration, and the wheel surface adhesion index. The results show that flat-topped bumps generate the highest vertical forces, reaching peaks of up to 6,000 N on the front suspension, leading to increased discomfort. Sinusoidal bumps, in contrast, generate smoother transitions, with vertical forces peaking at approximately 3,500 N, improving ride comfort. At vehicle speeds of 30 km/h, the vertical forces on the suspension increase significantly, with flat-topped bumps reducing the wheel surface adhesion index to as low as 0.6, indicating a higher risk of wheel slip and compromised vehicle stability. In contrast, sinusoidal bumps maintain a more favorable adhesion index of 0.85 at similar speeds. These reductions in adhesion elevate the risk of loss of control, especially at higher speeds. The findings suggest that adaptive suspension systems, capable of adjusting damping and stiffness based on the bump geometry and vehicle speed, would enhance ride quality and stability. Additionally, smoother bump designs, such as sinusoidal profiles, are recommended to reduce the impact on vehicle dynamics, particularly in urban environments. These insights contribute to improving both vehicle design and road safety, ensuring safer and more comfortable driving experiences.

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1. Introduction

Simulation of vehicle dynamics over speed bumps is a critical area of research in automotive engineering, particularly for enhancing ride comfort and safety. Although speed bumps are effective in controlling vehicle speed in residential areas, they introduce challenges related to vehicle vibrations and passenger discomfort [1]. These vibrations can be particularly problematic for vehicles with less sophisticated suspension systems [2]. Numerous studies have used simulation tools such as CarSim to analyze these dynamics and optimize vehicle parameters for better performance over such road irregularities.

One of the key aspects in simulating vehicle behavior over speed bumps is understanding the influence of different suspension configurations. Research has shown that the stiffness of suspension springs and damping characteristics play a significant role in ride comfort when traversing speed bumps [2], [3]. For example, simulations using CarSim have demonstrated that optimizing suspension parameters, particularly in electric vehicles, can lead to improved ride comfort [3]. Additionally, modeling the interaction between speed bumps and vehicle dynamics allows the prediction of vertical dynamics, which is essential for assessing passenger comfort [4].

In addition to riding comfort, the impact of speed bumps on vehicle noise levels has been investigated. Studies suggest that the noise generated by vehicle crossing speed bumps varies based on factors such as vehicle type and driving style [5], [6]. For instance, aggressive driving tends to exacerbate noise emissions, and this effect can be quantitatively assessed through simulations that replicate real-world conditions [6]. The relationship between vehicle speed, bump geometry, and resultant noise levels is complex and requires detailed modeling to accurately predict the outcomes [7]. Moreover, advancements in technologies such as deep learning and machine learning have been explored to enhance vehicle navigation and control systems when approaching speed bumps [8], [9].

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By integrating accelerometer sensors and machine learning algorithms, it is possible to detect road irregularities, make real-time adjustments to vehicle dynamics, and optimize comfort and safety [8].

In this study, the CarSim software was used to simulate vehicle performance over speed bumps [10]. The simulation allows for a detailed analysis of the vehicle's response to these obstacles, enabling adjustments to key parameters, as required. The results of these simulations provide insights into optimizing vehicle suspensions to enhance comfort and safety [11]. The objective of this study is to investigate a vehicle's response to speed bumps using CarSim simulations [12]. Various parameters, including the vehicle height change, vertical acceleration, and forces acting on the vehicle, were analyzed during the ride test [13]. The findings of this research are expected to offer valuable guidance to the automotive industry in designing vehicles that offer greater comfort and safety for road users [14]. This study focused on the critical aspects of ride testing and explored the potential of using CarSim simulation technology to develop better-performing vehicles [15]. By gaining a deeper understanding of vehicle responses when crossing speed bumps, this research aims to improve ride quality and optimize passenger comfort [16].

2. Methods

The current simulation utilized CarSim, a software tool developed by the Mechanical Simulation Corporation, which is widely used to simulate the dynamic behavior of passenger vehicles and light trucks. CarSim offers an accurate, detailed, and efficient method for simulating various aspects of vehicle performance, including ride comfort, handling, and stability. It is considered an industry-standard software for vehicle dynamics simulations because of its comprehensive modeling capabilities and ability to predict real-world vehicle behavior under a wide range of conditions [10].

2.3. Vehicle mechanical model

The method used in this research is a simulation conducted using the CarSim software, aiming to replicate real-world conditions when vehicles cross speed bumps. The data obtained from these simulations provided valuable insights into how vehicles respond to such obstacles, including changes in comfort levels, stability, and other key performance parameters. This approach allows for a better understanding of the dynamic behavior of vehicles in these scenarios.

Figure 1 shows the vehicle setup for the CarSim simulation, where a B-class hatchback is simulated with specific configurations for its body, powertrain, suspension, and other systems. Table 1 provides a detailed description of the setup, based on this figure.

Figure 1. B-class hatchback car model

Table 1. B-class hatchback vehicle modeling parameters

Suspension Parameters	Value (Unit)
Front spring stiffness, k_s	32,000 N/m
Rear spring stiffness, k_s	28,000 N/m
Damping coefficient, C_s (front and rear)	2,500 Ns/m
Wheelbase	2.6 m
Track width	1.5 m
Vehicle mass	1,200 kg
Tire stiffness, k_t	200,000 N/m
Wheel size	185/65 R15

The performance metrics selected for the evaluation of the CarSim simulation are described as follows. These following metrics are focused on measuring the suspension system behavior and how the vehicle responds dynamically when traversing obstacles, such as speed bumps.

1. Jounce – front tracks the vertical displacement of the front wheels as the suspension compresses and rebounds while encountering bumps or road irregularities.
2. Jounce – rear, similar to the front jounce, measures the vertical displacement of the rear wheels.
3. Spring: Force vs. compression: This metric measures the relationship between the spring force and spring compression in the vehicle's suspension system.
4. Springs compression: This parameter measures the overall compression of the suspension springs in both the front and rear axles during bump traversal.
5. Vertical Forces: This metric tracks the vertical forces acting on the vehicle, particularly at the wheels.
6. Jounce stop compression is a suspension component that limits the upward travel of the wheel.
7. The rebound stop compression and rebound stop compression track the opposite movement to the jounce, where the suspension extends as the vehicle moves away from the road surface (after the vehicle passes over a bump or road dip).

Vehicle ride testing is an important aspect of motor vehicle development and improvement. When vehicles traverse different types of road obstacles, such as speed bumps, ride quality becomes a crucial factor in the driver's experience and passenger comfort. This quality can also affect the overall safety and performance of vehicles. The suspension model can be represented by the following basic equation that defines the total force acting on the suspension system [17]:

$$F_{total} = k_s.\Delta s + C_s\frac{d\Delta s}{dt} + m_s.\frac{d^2\Delta s}{dt^2} \tag{1}$$

Where F_{total} is the total force acting on the suspension, k_s is the spring constant, C_s is the damping coefficient, and Δs is the suspension displacement.

Vehicle geometry is a crucial factor that affects performance. Key dimensions such as the wheelbase, wheel width, wheel diameter, and distance from the wheel center to the road surface all play important roles. Wheelbase and wheel width significantly influence stability, while wheel diameter and wheel center height affect both stability and ground clearance.

The following equation describes the rate of vehicle rolling, $\dot{r}$ at constant speed [18]:

$$\dot{r} = \frac{a \cdot u - b \cdot \dot{\delta}_f}{I_z} \tag{2}$$

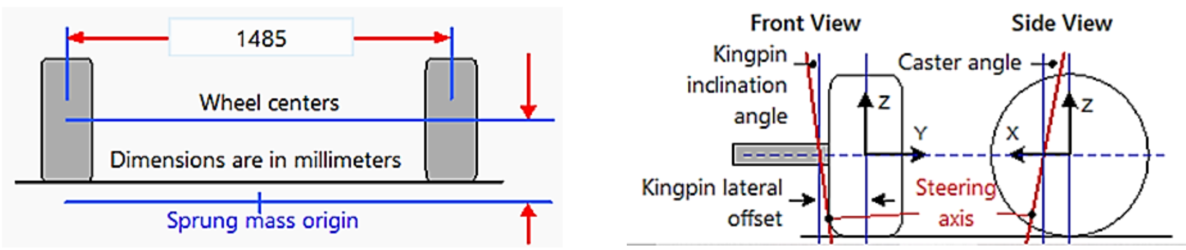
where a and b represent the distances from the vehicle's center of mass to the front and rear axles, respectively. $\dot{\delta}_f$ is the rate of change of the front steering angle, and I_z is the vehicle's moment of inertia about the vertical axis.

Both the wheelbase and wheel width are fundamental to vehicle stability and ride comfort. A longer wheelbase provides better stability but can make the vehicle more difficult to maneuver, while a wider wheel width also improves stability but may reduce handling responsiveness, as shown in detail in Figure 2(a). The lateral motion equation describes the lateral acceleration of a vehicle [19].

$$m\,.\,a_y = -C_f\,.\,\delta_f - C_r\,.\,\delta_r - m\,.\,u\,.\,r \tag{3}$$

where C_f and C_r are the front and rear cornering stiffnesses, δ_f and δ_r are the front and rear steering angles, m is the vehicle mass, u is the vehicle speed, and r is the roll rate.

This model allows for six degrees of freedom, including vertical displacement, pitch, and roll, as shown in Figure 2(b).



(a) (b)

Figure 2. Wheel geometry (a) and axis of the model (b)

Geometric factors, such as wheelbase, wheel width, wheel diameter, and wheel center-to-road distance, have a significant impact on the overall vehicle performance. A longer wheelbase and wider wheel width generally improve stability, but increase the moment of inertia, making the vehicle more difficult to control. Conversely, a larger wheel diameter enhances stability but may contribute to instability under certain conditions. Increased ground clearance, due to a higher distance from the wheel center to the road surface, can improve off-road capability but may increase the likelihood of rollover [20].

Consequently, vehicle designers must carefully balance these factors to achieve optimal performance. In the automotive industry, ride tests are critical for evaluating vehicle performance, and are typically conducted based on the ISO 2631 standard, which defines human sensitivity to vibration [21]. The ride test in CarSim uses the following equation to calculate the Ride Comfort Index (RCI) [22]:

$$\mathrm{RCI} = \frac{1}{T}\int_0^T \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2 dt} \quad (4)$$

Where T denotes the test duration, n denotes the number of vibration measurements, and ai denotes the acceleration in the i^{th} direction. This index quantifies ride comfort based on the vertical, lateral, and longitudinal accelerations experienced by passengers.

2.2. Speed bump geometry

Speed bumps are common road obstacles, particularly in urban areas, and are designed to reduce vehicle speed and enhance road safety. However, they also affect riding comfort and require vehicles to have appropriately designed suspension systems to handle bumps effectively [23].

In this simulation, a small, smooth speed bump was selected with its geometry based on the Indonesian local standard for speed bumps [24]. This geometry represents the typical speed bumps found in urban environments. The key specifications for the speed bump used in the simulation are as follows: height, 5–9 cm; total width, 35–39 cm; clearance, where the bump's highest point reaches 50% of its width, as shown in Figure 3.

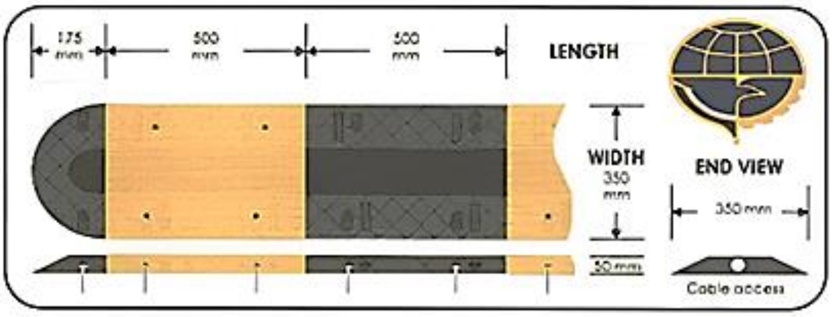


Figure 3. Speed bump obstacles based on Indonesian local standard

2.3. Simulation scenarios

The simulation was conducted with the vehicle passing over each speed bump at four different speeds: 10, 20, 30, and 40 km/h. These speeds were selected to reflect a range of driving conditions from slow residential speeds to higher speeds encountered on the streets. During the simulations, no additional driving inputs, such as braking or acceleration, were applied, allowing the simulation to focus on the vehicle's natural response to speed bumps.

3. Results and Discussion

3.1. Jounce – back

"Jounce – back" refers to the vertical movement of the vehicle's rear wheels, specifically the compression and rebound of the rear suspension as it responds to road conditions. Jounce measures the extent to which the rear wheel suspension moves up or down when the vehicle encounters an obstacle, such as a speed bump, and provides valuable insights into ride comfort and suspension performance at the back of the vehicle.

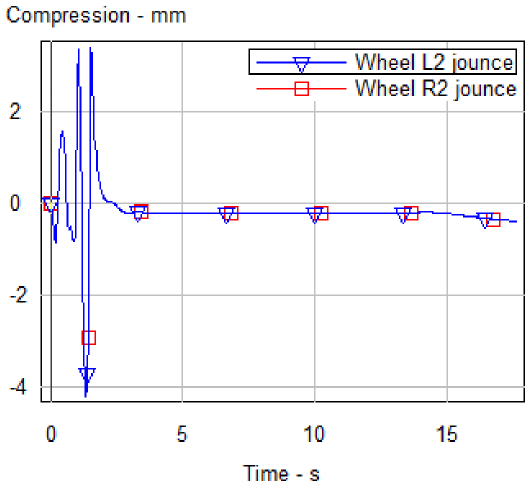


Figure 4. Jounce – back plot

Figure 5 shows the rear wheel force (compression) over time, with the X-axis representing time (in seconds) and the Y-axis representing the suspension compression of the left rear wheel (L2) and the right rear wheel (R2) in millimeters. The tests were conducted at a vehicle speed of 10 km/h.

The graph reveals that both the left and right rear wheels experienced minimal vertical displacement, with compression values within the -4 mm to 2 mm range. This indicated a relatively smooth ride. Interestingly, the graph shows two distinct points of double compression at approximately 0.5 seconds and 1.5 seconds. This suggests that the rear wheels underwent two stages of compression when passing over the speed bump. The double compression observed could lead to a decreased level of comfort for passengers seated at the rear of the vehicle. Adjustments to the rear suspension system, such as stiffer springs or enhanced shock absorbers, could help improve the overall stability and passenger comfort, particularly when the crossing speed bumps at lower speeds, such as 10 km/h.

3.2. Spring: Force vs. compression

The Spring: Force versus compression plot in CarSim visualizes the relationship between the force exerted by the suspension springs and the corresponding level of compression. This plot provides valuable insight into the elastic characteristics of the vehicle suspension system, helping to evaluate how the springs respond to varying levels of compression under loads.

In Figure 9, the graphical analysis of "Spring: Force vs. Compression" in the driving comfort test at a speed of 10 km/h using the CarSim software shows the relationship between the spring force and spring compression level. The X-axis of the graph reflects the compression rate of the spring in millimeters, whereas the Y-axis shows the spring force in Newtons.

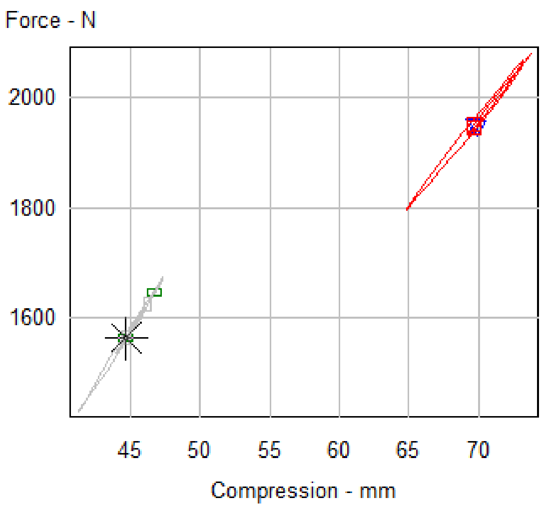


Figure 9. Spring: force vs. pressure compression plot

The analysis results revealed that the spring force increased as the compression increased, indicating that the spring became stiffer when compressed. The peak spring force occurred at approximately 70 mm, indicating the maximum compression limit of the spring. The level of driving comfort at the rear is considered to be lower than that at the front because of the high spring force. In conclusion, the test results suggest modifications to the springs to improve ride comfort, with the suggestion of replacing the springs with softer springs as a potential solution.

The results revealed a clear linear relationship between the spring force and compression; as the compression increased, the spring force also increased proportionally. This trend indicates that the suspension springs became stiffer as they compressed. The rear suspension is subjected to greater loads and experiences more vertical displacement, which can result in a rougher ride for passengers seated in the rear of the vehicle, thereby reducing ride comfort at the rear of the vehicle.

3.3. Spring compression

Spring compression refers to the degree to which springs in a vehicle's suspension system compress under different driving conditions. Understanding the extent of spring compression helps evaluate how well the suspension absorbs vertical forces, which in turn affects ride comfort and vehicle stability.

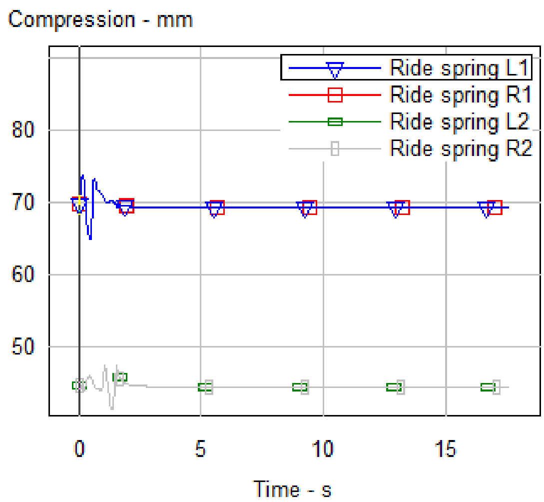


Figure 5. Spring compression plot

In Figure 6, the graph illustrates the spring compression for all four wheels during the simulation, conducted at a speed of 10 km/h using the CarSim software. The X-axis represents the time in seconds, while the Y-axis shows the compression level in millimeters for the springs. The graph compares the compression levels of the front-left (L1), front-right (R1), rear-left (L2), and rear-right (R2) springs. The front springs experienced significantly more compression than the rear springs did. Both front springs show compression levels hovering at approximately 70 mm, with slight variations as the vehicle crosses the bump. The rear springs, however, show much lower compression, with values of approximately 50 mm for both the left and right rear wheels.

This difference in compression between the front and rear suspensions indicates that the front of the vehicle bore the majority of the vertical load when crossing the speed bump. This could be owing to the natural weight distribution of the vehicle, which typically places more weight on the front axle. In addition, the rear springs seem to encounter less compression overall, which may indicate that they are stiffer than the front springs.

The plot shows that the front spring compression peaks occur at multiple points, particularly around 0.5 seconds and 1.5 seconds, suggesting that the front suspension experiences two distinct compression events as the vehicle crosses the speed bump. This could be attributed to the front wheels hitting the bump first and experiencing the initial compression, followed by a second compression as the rear wheels traverse the bump, which affects the vehicle's overall suspension response. The rear spring compression, while lower, follows a similar double compression pattern, with smaller peaks also occurring around 0.5 seconds and 1.5 seconds. The lower compression in the rear springs may suggest that the rear suspension is stiffer than the front suspension, potentially leading to a reduced ride comfort for passengers seated at the back. The lower levels of compression may also indicate that the rear suspension does not absorb vertical forces effectively, which could result in a bouncier or less comfortable ride.

3.4. Vertical strength

The vertical force plot shows the forces acting on the vehicle wheels in the vertical direction during the simulation. These forces are a result of the suspension's response, the interaction between the tires and the road surface, and the overall vehicle dynamics when encountering obstacles, such as speed bumps. Understanding vertical forces helps assess a vehicle's ride comfort and stability, as well as the effectiveness of the suspension system in absorbing road impacts.

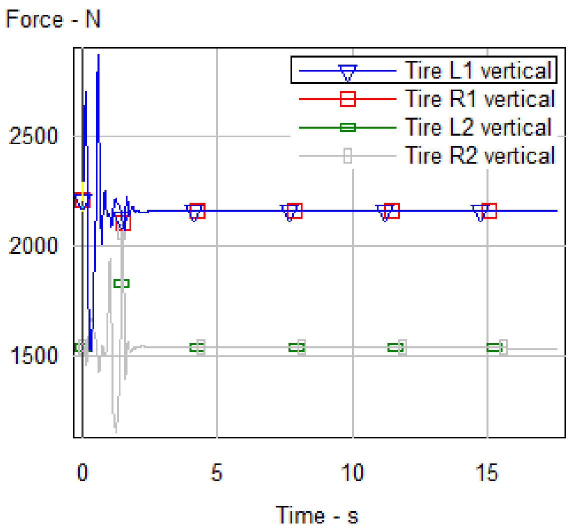


Figure 6. Vertical force plot

In Figure 7, the x-axis represents time in seconds, while the y-axis shows the vertical force in Newtons (N). The graph shows that the front tires experience higher vertical forces than the rear tires, with peak forces reaching approximately 2500 N on the front left tire and around 2000 N on the front right tire. In contrast, the rear tires exhibited significantly lower forces, with both the left rear and right rear tires peaking at approximately 1500 N. This disparity suggests that the front suspension bore the brunt of the load when crossing the speed bump.

Peaks in the vertical force occur at specific points as the vehicle crosses the speed bump. The highest forces on the front tires are observed at around 0.5 seconds and 1.5 seconds, which correspond to the front tires initially hitting the speed bump and then experiencing a secondary compression as the rear tires follow over the bump. The peaks for the rear tires are delayed, occurring at around 0.75 seconds and 1.75 seconds, slightly after the front tires, reflecting the rear suspension's response to the bump. This pattern of two peaks for both the front and rear wheels suggests that the vehicle undergoes two distinct impacts: one when the front tires hit the bump, and the other when the rear tires passed over it. The front suspension experiences greater vertical forces owing to these repeated impacts, leading to a higher level of discomfort for the front-seat passengers.

The higher vertical forces observed on the front wheels indicate that riding comfort at the front of the vehicle is lower than that at the rear. The stiffer suspension response required to handle these forces can result in a harsher ride, particularly for passengers seated in front of a vehicle. The rear suspension, which experiences lower forces, may offer a smoother ride for rear-seat passengers, but the overall balance between front and rear comfort appears to be uneven. Given that the front suspension bears most of the vertical load, modifications may be required to improve comfort.

3.5. Jounce stop compression

The Jounce Stop Compression plot illustrates the compression experienced by the vehicle’s suspension when it reaches the upper travel limit, also known as the Jounce Stop. The jounce stop is a critical suspension component designed to prevent excessive movement and limit compression when the suspension is fully compressed, such as when a vehicle crosses obstacles such as speed bumps.

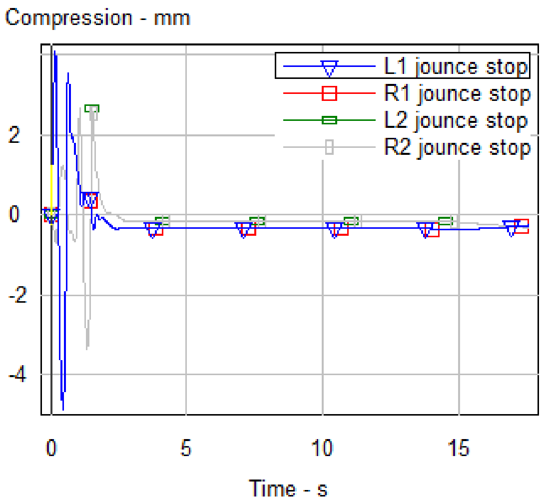


Figure 7. Jounce stop compression plot

In Figure 8, the x-axis represents time in seconds, while the y-axis represents the compression of the jounce stops in millimeters. The plot compares the jounce stops during the driving comfort test at a speed of 10 km/h. The graph reveals that all four wheels experience jounce-stop compression as the vehicle crosses the speed bump, with the front wheels showing higher compression than the rear wheels. The front jounce stops experiencing peak compression values close to 3 mm, whereas the rear jounce stops remain below 1 mm. This suggests that the front suspension was compressed more heavily than the rear suspension when the vehicle encountered the bump.

Compression peaks occur at different times for the front and rear wheels. The first peaks are observed at approximately 0.25 seconds and 1.25 seconds, which corresponds to the front wheels encountering the speed bump. The rear wheels show compression peaks slightly later, at around 0.5 seconds and 1.5 seconds, reflecting the rear suspension's response as the back of the vehicle passes over the bump.

This pattern aligns with the natural sequence in which the vehicle's front wheels hit the obstacle first, followed by the rear wheels. The higher compression levels in the front suspension suggest that the front jounce stops were more engaged, possibly because of the greater load carried by the front axle and the vehicle's forward weight distribution. To improve the overall driving comfort, especially for front-seat passengers, adjustments to the front suspension system, such as stiffer springs or improved shock absorbers, are recommended.

3.6. Compression stops rebound

"Rebound Stop Compression" in CarSim software refers to the suspension's behavior when the wheels return to the ground after crossing an obstacle, such as a speed bump. This parameter is crucial for assessing both driving comfort and vehicle stability, as excessive compression or rebound can negatively affect a vehicle's overall handling and passenger experience.

In Figure 9, the X-axis represents time in seconds, whereas the Y-axis shows the compression of the rebound stops in millimeters. The graph compares the rebound stop compression of the wheels during a driving comfort test conducted at a speed of 10 km/h. The figure indicates that all four wheels experienced some level of rebound stop compression as the vehicle passed over the speed bump. Notably, the front wheels exhibited higher levels of rebound stop compression than the rear wheels. The front suspension compresses significantly more, with values reaching approximately 3 mm during the rebound phase, whereas the rear suspension shows minimal rebound, with compression remaining below 1 mm.

The graph reveals that rebound compression peaks occur at distinct intervals. Peak compression occurs at approximately 0.25 seconds and 1.25 seconds, indicating the points at which the front wheels rebound after encountering the bump. The rear wheels exhibit peak rebound compression slightly later, at around 0.5 seconds and 1.5 seconds, following the same pattern as the front wheels but with significantly lower compression values. This rebound behavior shows that the front suspension is more actively involved in managing the dynamics of the vehicle as it crosses the bump, whereas the rear suspension experiences much less vertical movement.

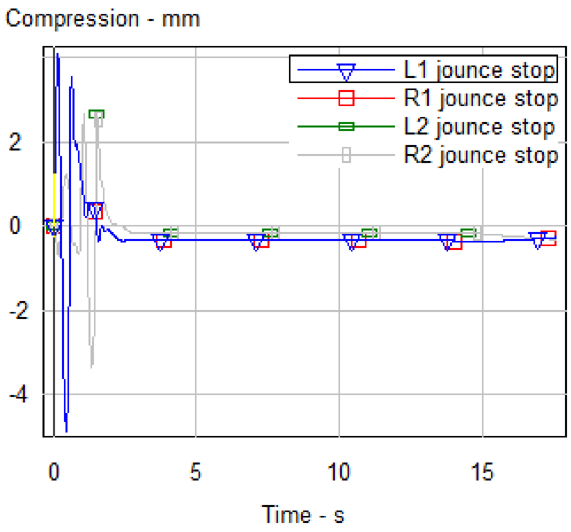


Figure 8. Rebound stop compression plot

The higher rebound compression at the front suggests that the front suspension experiences more significant forces, which may lead to a rougher ride for the front-seat passengers. Excessive rebound compression can result in uncomfortable bouncing or oscillations as the vehicle's suspension returns to its normal position after fully compressing the bump. The rear suspension, with its lower rebound compression values, likely provides a smoother ride for rear passengers. To improve the overall ride quality and stability, modifications to the front suspension, such as stiffer springs or enhanced shock absorbers, are recommended to manage rebound forces better and reduce passenger discomfort.

3.7. Jounce – front

"Jounce – front" refers to the vertical movement of the vehicle's front wheels, specifically the compression and rebound of the front suspension as the vehicle responds to road conditions. Jounce is a critical measure of ride comfort, as it quantifies the extent to which the suspension absorbs impacts from road obstacles, such as speed bumps. In this context, CarSim measures the up-and-down movement (compression) of the front suspension during a test, thereby providing insight into the suspension's ability to handle bumps.

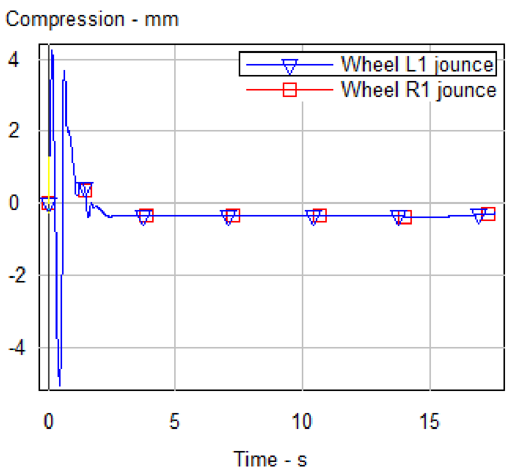


Figure 9. Jounce – Front plot

Figure 4 illustrates the front wheel jounce (compression) over time, with the X-axis representing time (in seconds) and the Y-axis showing the compression of the front wheels (in millimeters). The simulation was conducted at a vehicle speed of 10 km/h to measure the compression of both the left and right front wheels.

From the graph, it is evident that the compression levels remain relatively low, within a range of 4 mm or less. This indicates that the vehicle maintains good ride comfort during the test, as minimal suspension travel suggests the effective absorption of vertical forces without excessive body movement. Small fluctuations in the compression values suggest that the vehicle is relatively stable with no significant deviations or excessive oscillations.

The low compression values observed in this test, with both wheels remaining well under a vertical displacement of 4 mm, indicate that the vehicle suspension system performs effectively at a test speed of 10 km/h. The smooth ride and minor compression differences between the left and right wheels suggest that ride comfort is well maintained, with no significant disruptions to passenger comfort.

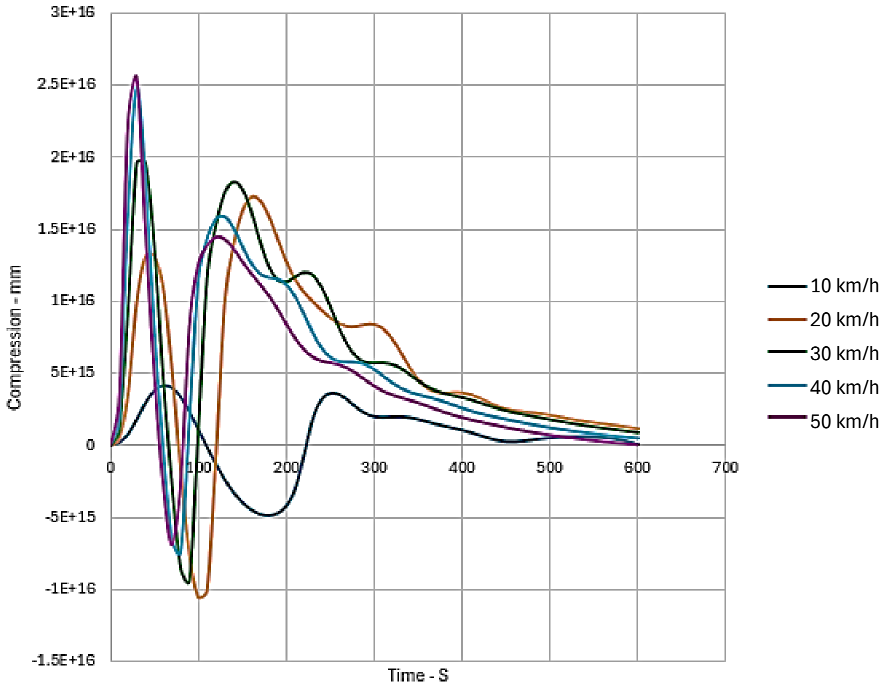


Figure 10. Combined jounce – front plot with speed variations

Figure 10 illustrates the front suspension jounce performance of the vehicle at various speeds: 10, 20, 30, 40, and 50 km/h. The X-axis represents time in seconds, while the y-axis shows suspension compression in millimeters. This graph allows for a comparative analysis of how the front suspension behaves under different speeds when traversing road obstacles, such as speed bumps.

The plot demonstrates that, as the vehicle speed increases, the amplitude of the suspension's compression and rebound also increases significantly. At lower speeds, such as 10 km/h, the suspension experiences a relatively moderate jounce with smaller peaks, indicating that the suspension system is able to absorb the vertical forces efficiently, providing a smoother ride for passengers. As the speed increases to 20 km/h and beyond, the jounce becomes more pronounced, with the amplitude of compression growing significantly. For instance, at 50 km/h, the suspension experienced the highest compression forces, as shown by the peaks reaching values exceeding 2.5E+16 mm. The sharp peaks and subsequent oscillations suggest that the suspension struggles more to stabilize the vehicle at higher speeds, leading to increased vertical movement and a potentially harsher ride for passengers.

Another observation was the time required for the suspension to stabilize after the vehicle crossed the speed bump. At lower speeds, the suspension returns to a neutral position more quickly with fewer oscillations. However, at higher speeds, the rebound oscillations were prolonged, indicating that the suspension required more time to stabilize the vehicle. For example, at 50 km/h, the suspension continued to oscillate for nearly 600 s, whereas at 10 km/h, the oscillations dampened much sooner, showing a more efficient return to equilibrium.

The data in Figure 10 highlight the inverse relationship between the vehicle speed and ride comfort. As the speed increased, the front suspension experienced greater jounce, leading to a rougher ride and less stability. The ability of a suspension to manage vertical forces diminishes at high speeds, which can result in passenger discomfort and compromised vehicle handling. At higher speeds, the suspension performance became less effective, as indicated by the larger compression and rebound cycles.

4. Conclusions

This study analyzed the impact of speed bumps on vehicle dynamics, focusing on the front suspension performance, ride comfort, and vehicle stability at various speeds using CarSim simulations. The results show that flat-topped bumps generate the highest vertical forces, reaching peaks of up to 6,000 N on the front suspension, leading to increased discomfort. Sinusoidal bumps, in contrast, generate smoother transitions, with vertical forces peaking at approximately 3,500 N, improving ride comfort. It demonstrated that higher vehicle speeds lead to increased jounce, vertical forces, and compression, particularly at the front suspension, resulting in a harsher ride and prolonged oscillations post-impact. At vehicle speeds of 30 km/h, the vertical forces on the suspension increase significantly, with flat-topped bumps reducing the wheel surface adhesion index to as low as 0.6, indicating a higher risk of wheel slip and compromised vehicle stability. These findings suggest that the current suspension system performs well at lower speeds, but may require modifications, such as stiffer springs or enhanced shock absorbers, to maintain comfort and stability at higher speeds.

In future work, it is recommended to conduct real-world experiments to validate the simulation results and further optimize the suspension system for a broader range of vehicles. Additionally, integrating adaptive suspension technologies that can dynamically adjust to road conditions and vehicle speeds could offer significant improvements in ride comfort and safety. Future studies may also explore rear suspension behavior in more detail and evaluate the influence of bump geometries at different speeds to develop more comprehensive vehicle suspension designs.

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