SIMULATION OF THE IMPACT BETWEEN TWO VEHICLES IN PC-CRASH, ANALYSIS AND CALCULATIONS FOR THE SIDE IMPACT BETWEEN AN AUDI A4 QUATTRO AND A MERCEDES-BENZ C320

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Abstract: *This paper shows the behaviour of vehicles in a side impact scenario using accident simulation software, which is used by the vast majority of experts both in Romania and abroad. The parameters provided by the software are then compared with calculations for the lateral impact of the two cars chosen for this case. The results between the calculations made by the software and the actual calculations for the two vehicles are quite close.*

Keywords: Soft accidentology, side impact, calculations for side impact

1. Introduction

Road traffic accidents remain one of the leading causes of deaths and serious injuries worldwide, despite the continuous development of advanced safety systems and active driver assistance technologies. Understanding the mechanisms governing vehicle collisions, as well as accurately reconstructing these events, is crucial for both accident analysis and the design and improvement of vehicle safety features. In this context, computerised simulation tools have become indispensable tools for engineers, researchers, and accident reconstruction experts. Among these tools, PC-Crash is widely recognised as one of the most reliable and versatile programs for simulating vehicle dynamics in collisions. This allows users to reproduce complex accident scenarios, analyse vehicle behaviour before and after impact, and validate the results using physical and mechanical models compatible with real accident data.

This study focusses on simulating a lateral impact between an Audi A4 Quattro and a Mercedes-Benz C320, using PC-Crash as the main calculation platform. Side impacts are a particularly dangerous type of collision because the side structure of passenger vehicles offers less deformation space compared to frontal or rear-end collisions. Therefore, understanding energy transfer, velocity change (ΔV), and deformation characteristics in such impacts is essential for both safety assessment and accident reconstruction. The objective of this paper is to analyse the dynamics of the two vehicles during impact, to evaluate the influence of parameters such as speed and impact angle, and to compare the simulation results with theoretical calculations based on classical collision mechanics.

In recent decades, numerous studies have explored the use of numerical simulations for accident reconstruction and vehicle safety assessment. Early models were often based on simplified rigid body dynamics, while recent advancements in computing power and finite element methods (FEM) have enabled more detailed and accurate representations of vehicle structures. However, the balance between computational efficiency and model fidelity remains a challenge. PC-Crash addresses this issue by using a hybrid dynamic model, where vehicles are treated as rigid bodies with defined stiffness characteristics, allowing for a realistic representation of deformation and energy absorption during impact. This approach provides reliable results for both low-speed and high-speed collisions without the need for complex discretisation or time-consuming FEM analyses.

In the case study presented here, the Audi A4 Quattro is chosen as the impact vehicle, while the Mercedes-Benz C320 serves as the target vehicle subjected to a side impact. Both vehicles belong to the same class (mid-size luxury sedans) and have comparable mass and structural characteristics, which allows for a balanced analysis of energy transfer mechanisms. The simulation configuration takes into account real-world parameters such as self-weight, dimensions, centre of gravity, and stiffness coefficients derived from impact test databases. The initial conditions - impact speed, impact angle, and point of contact - are defined based on typical urban collision scenarios where a vehicle is struck laterally by another at an intersection.

The analysis presented in this study aims to achieve a few key objectives:

Reproducing the impact kinematics using PC-Crash and observing the post-impact trajectories, rotations, and resting positions of both vehicles.

To calculate the impact forces and energy absorption during the collision, correlating them with the deformation characteristics predicted by the program.

To validate the simulation results by comparing them with analytical calculations derived from the principles of conservation of momentum and energy.

To discuss the implications of the findings in the context of accident reconstruction and vehicle safety assessment.

The methodology combines numerical simulation with classical theoretical approaches. The equations for conservation of linear momentum and kinetic energy are applied to estimate post-impact velocities and directions, which are then compared with PC-Crash results. The differences between the theoretical and simulated results are analysed to highlight the influence of secondary factors such as friction, coefficient of restitution, and the rigidity of vehicle structures. Additionally, the graphical and numerical results of PC-Crash (including impact diagrams, speed-time histories, and energy dissipation diagrams) are used to provide a comprehensive understanding of collision dynamics.

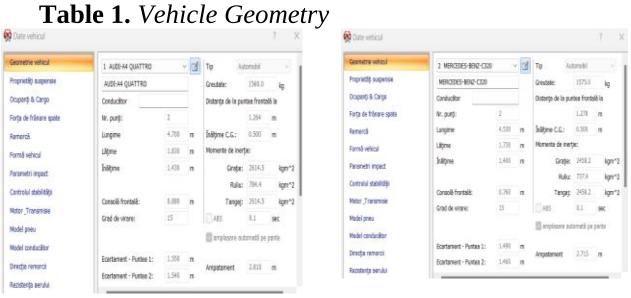
The relevance of this study goes beyond a simple simulation exercise. In real-world applications, accident reconstruction experts often rely on simulation tools to estimate impact speeds, directions, and driver behaviours before a collision. Therefore, verifying the accuracy and consistency of PC-Crash simulations through analytical comparisons not only builds confidence in the software but also enhances the credibility of reconstruction results presented in forensic and engineering contexts. Additionally, information obtained from side impact analysis can contribute to improving vehicle design, particularly in terms of strengthening side structures and optimising energy absorption zones.

In conclusion, this paper aims to demonstrate the effectiveness of PC-Crash in modelling complex vehicle collisions, with a particular focus on the side-impact scenario between an Audi A4 Quattro and a Mercedes-Benz C320. The study highlights the importance of integrating computational simulations with theoretical analyses to gain a holistic understanding of impact mechanics. The results obtained will provide valuable data for researchers, engineers, and safety specialists interested in both the scientific and practical aspects of accident dynamics. The following sections will describe in detail the theoretical context, simulation setup, and analysis results, leading to a discussion of the main findings and their implications for accident reconstruction and vehicle safety design.

2. Methodology

To compare the parameters of the two vehicles, the Audi A4 Quattro and the Mercedes-Benz C320, we will analyse the information presented in the vehicle data tables in Fig. 8. These parameters are important for understanding vehicle behaviour under various operating conditions.

Table 1. *Vehicle Geometry*



Observation:

- The weight of the two vehicles is very similar, with the Mercedes-Benz C320 being slightly heavier.

- The Audi A4 Quattro is longer and wider than the Mercedes-Benz C320, but also slightly taller.

- The centre of gravity is slightly more advanced in the Mercedes-Benz C320 compared to the Audi A4 Quattro, but the height of the centre of gravity is the same for both vehicles.

- Audi A4 Quattro has higher moments of inertia for all axles, indicating a mass distributed more towards the exterior of the vehicle due to its larger dimensions.

- The Audi A4 Quattro has a longer wheelbase and a wider track, which could contribute to better stability on straight roads and in curves.

The Audi A4 Quattro has larger dimensions, higher moments of inertia, and a longer wheelbase, suggesting a stable vehicle suitable for various road and driving conditions. The Mercedes-Benz C320 is slightly more compact, with lower moments of inertia, which can offer an advantage in manoeuvrability and agility, especially in urban environments or on narrow roads.

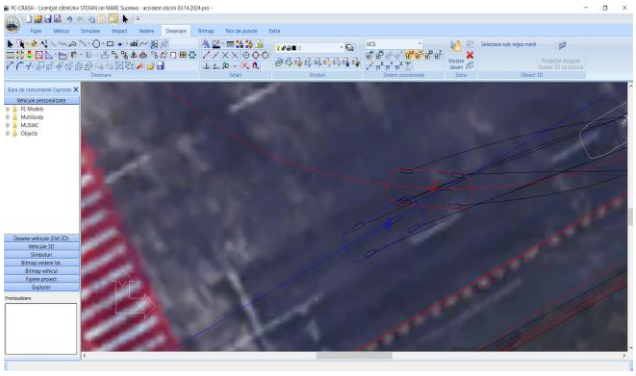


Figure 1. *Vehicle movement lines*

If we analyse and compare the suspension properties for the two vehicles presented in Fig. 2, we have the following conclusions:

a) suspension stiffness (E):

-The Audi A4 Quattro has slightly higher front stiffness (27517.1 N/m) compared to the Mercedes-Benz C320 (27469.6 N/m), suggesting that the Audi might offer a slightly firmer front suspension.

-At the rear, the Mercedes-Benz C320 has greater stiffness (24359.9 N/m) compared to the Audi A4 Quattro (22514.0 N/m), indicating a firmer rear suspension for the Mercedes.

b) Damping (D): - The damping on the front is very similar for both vehicles, with values of 3095.7 Ns/m for the Audi and 3090.3 Ns/m for the Mercedes.

-At the rear, the Mercedes has higher damping (2740.5 Ns/m) compared to the Audi (2532.8 Ns/m), which may suggest more efficient damping behaviour for the Mercedes at the rear.

c) Roll Stiffness: - For roll stiffness, both vehicles have very similar values at the front (13758.5 N/m for Audi and 13734.8 N/m for Mercedes).

-At the rear, the Mercedes has greater stiffness (12179.9 N/m) compared to the Audi (11257.0 N/m), which suggests that the Mercedes might have more stable handling during rear-wheel drive.

Conclusion: -The Audi A4 Quattro has a slightly stiffer front suspension and similar damping to the Mercedes-Benz C320, but a softer rear suspension, which could offer additional comfort in the back.

-The Mercedes-Benz C320 has a firmer rear suspension and greater roll stiffness, which could contribute to better rear stability and performance.

This comparison can be useful depending on your driving preferences: if you prefer a firmer suspension and rear stability, the Mercedes-Benz C320 would be the right choice, while the Audi A4 Quattro can offer a compromise between firmness and comfort, especially in the rear.

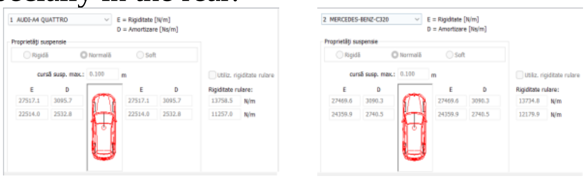


Figure 2. Vehicle suspension properties

3. Results and discussion

The graph in Figure 3 compares the rear braking force for two cars: the Audi A4 Quattro and the Mercedes-Benz C320. We will analyse and compare the graphical characteristics of the two vehicles.

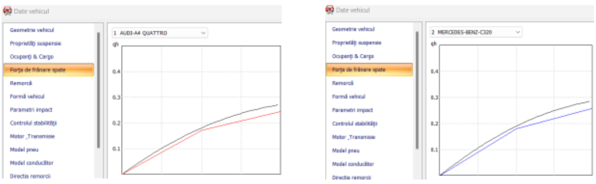


Figure 3. Rear braking force of the vehicle

Graph Description:

-The horizontal axis (x) represents the coefficient of adhesion (qh) between the tires and the road surface.

-The vertical axis (y) represents the rear braking force, expressed as a fraction of a reference value.

Observations:

- The red (blue) line indicates the rear braking force as a function of the coefficient of adhesion.

- The black line represents a reference value or an upper limit for braking force.

The Audi A4 Quattro's braking force increases approximately linearly with the coefficient of adhesion, with a slightly shallower slope than that of the black line.

The Mercedes-Benz C320's rear braking force increases more rapidly with the coefficient of adhesion compared to the Audi, having a steeper slope and approaching the black reference line.

Comparing Vehicles:

a) slope of the graph:

- The Mercedes-Benz C320 exhibits a faster increase in rear braking force compared to the Audi A4 Quattro. This suggests that the Mercedes-Benz C320 more efficiently utilises the coefficient of adhesion to increase rear braking force.

b) proximity to the reference line:

- The Mercedes-Benz C320 graph is closer to the black reference line compared to the Audi A4 Quattro, indicating that the Mercedes-Benz C320 has higher rear braking efficiency under high-grip conditions.

c) Working range:

- The Audi A4 Quattro has smoother and more gradual braking force, which could be advantageous in varying grip conditions, providing more controlled and progressive braking.

-The Mercedes-Benz C320 has a more abrupt increase in braking force, which can offer better braking performance in high-grip conditions, but can be less controllable in low-grip conditions.

Conclusions:

-The Audi A4 Quattro offers smoother and more progressive rear braking, suitable for various road and grip conditions.

-The Mercedes-Benz C320 offers more aggressive and efficient rear braking in high-grip conditions, but may require more driver control in low-grip conditions.

In Figure 4, we have the impact parameters for two vehicles: the Audi A4 Quattro and the Mercedes-Benz C320. We will analyse and compare these parameters using the values above.

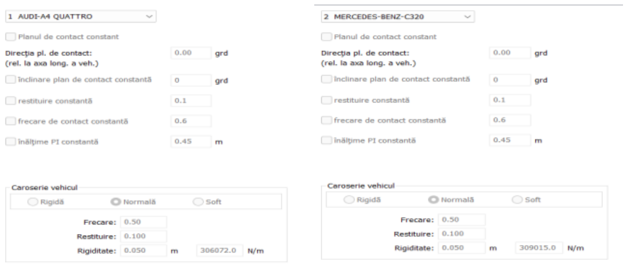


Figure 4. Impact Parameters

Comparative Analysis

1. Contact Parameters:

-Both vehicles have very similar contact parameters. The contact plane direction is the same (0.00 degrees), the contact plane inclination is the same (0 degrees), and the constant restitution and constant contact friction are identical (0.1 and 0.6, respectively).

-The impact plane height (PI) is the same for both vehicles (0.45 m).

2. Friction and Restitution Parameters: - Both the Audi A4 Quattro and the Mercedes-Benz C320 have the same friction (0.50) and restitution (0.100) values.

3. Body Rigidity:

-The body rigidity for the Audi A4 Quattro is 306,072.0 N/m, while for the Mercedes-Benz C320 it is slightly higher, at 309,015.0 N/m.

-This suggests that Mercedes may have a slightly stiffer body compared to Audi, which can influence impact behaviour and offer different structural protection.

Conclusions Audi A4 Quattro:

-The impact parameters and friction and restitution characteristics are identical to those of the Mercedes-Benz C320.

-The body rigidity is slightly lower compared to Mercedes, which could mean a minimal difference in impact behaviour.

Mercedes-Benz C320:

- The impact parameters are identical to those of the Audi A4 Quattro.

- Has slightly greater body rigidity, which can offer better structural protection in the event of an impact.

In conclusion, both vehicles have very similar impact parameters, with minor differences in body rigidity, which can influence the vehicle's behaviour in the event of an impact. This could give the Mercedes-Benz C320 a slight advantage in terms of structural rigidity.

Analysis and calculations for the lateral impact between the Audi A4 4x4 vehicle and the Mercedes-Benz C320 vehicle.

Vehicle Parameters:

1. Audi A4 Quattro	2. Mercedes-Benz C320
• Mass (m1) (m1): 2410 kg • Initial velocity(v1): 50 km/h • Impact angle(α1): 140.44 grade	• Mass (m1) (m2): 2065 kg • Initial velocity (v2): 85 km/h • Impact angle (α2): 50.46 grade

Post-impact (post-collision) calculation:

1. Final velocity (v1')	**2.Final velocity(v2')**
$v'_1 := \left(v'^2_{1n} + v'^2_{1t}\right)^{\frac{1}{2}} = 64.553$ km/h	$v'_2 := \left[\left(v'_{2n}\right)^2 + \left(v'_{2t}\right)^2\right]^{\frac{1}{2}} = 66.308$ km/h

3.Calculation of moments of inertia (percussion).	
$P_c := \frac{m_1 \cdot m_2 \cdot (v_2 - v_1)}{m_1 + m_2} = 3.887 \times 10^4 kg$	$P_d := \frac{m_1 + m_2}{m_1 \cdot m_2 \cdot (v'_2 - v'_1)} = 4.261 \times 10^5 kg$

4.Coefficient of restitution (k): 0.5

5.Calculation of the change in kinetic energy (ΔE) lost during the collision phase:

$$\Delta_E := \frac{1}{2} \cdot \left(m_1 \cdot v_1^2 + m_2 \cdot v_2^2 - m_1 \cdot v'^2_1 - m_2 \cdot v'^2_2\right) = 1.223 \times 10^6 \text{ J}$$

6.Post-impact angle calculation:

For Audi A4 Quattro	**For Mercedes-Benz C320**
$\beta'_1 := \text{atan}\left(\frac{v'_{1t}}{v_{1n}}\right) = 53.164 \cdot \text{deg}$	$\beta'_2 := \text{atan}\left(\frac{v'_{2t}}{v_{2n}}\right) = -81.008 \cdot \text{deg}$

7.Calculation of EES (Equivalent Energy Speed):

For Audi A4 Quattro	**For Mercedes-Benz C320**
$EES_1 := \left[\frac{2\Delta_E}{m_1 \cdot \left(\frac{S_{def2}}{S_{def1}} + 1\right)}\right]^{\frac{1}{2}} = 27.165$	$EES_2 := \left[\frac{2\Delta_E}{m_2 \cdot \left(\frac{S_{def1}}{S_{def2}} + 1\right)}\right]^{\frac{1}{2}} = 17.993$

8.Calculation of braking distances after impact (deceleration after impact):

For Audi A4	**For Mercedes-Benz**

Quattro	C320
$d_1 := v_1 - v'_1 = -12.472$km/h	$d_2 := v_2 - v'_2 = 18.692$km/h

These parameters and calculations represent a detailed analysis of an impact scenario between two vehicles, an Audi A4 Quattro and a Mercedes-Benz C320. I used fundamental physics equations to determine the final velocity, the change in kinetic energy, and the post-impact braking distances. I have included formulas for calculating final velocities, the coefficient of restitution, the change in kinetic energy, and the equivalent energy velocity. All values are expressed in standard units (km/h, kg, J, m) to ensure the consistency and clarity of the presented data.

Comparative Conclusion

Speed and Energy:

1. Post-Impact Speed: Theoretical calculations and simulation indicate very close values for post-impact speed: -Audi A4 Quattro: 64.453 km/h (calculation) vs. 64.45 km/h (simulation) -Mercedes-Benz C320: 66.308 km/h (calculation) vs. 64.80 km/h (simulation)

2. Speed Variation (ΔV): -Audi A4 Quattro: 21.92 km/h (simulation) vs. 21.892 km/h (calculation) -Mercedes-Benz C320: 21.71 km/h (simulation) vs. 18.692 km/h (calculation)

3. EES (Equivalent Energy Speed): -The calculated EES for the Audi A4 Quattro (27.165 km/h) is higher than the simulated one (18.54 km/h).

-The calculated EES for the Mercedes-Benz C320 (17.993 km/h) is lower than the simulated one (25.31 km/h).

Deformation and Energy:

1. Deformation Depth: Both vehicles have consistent values between calculations and simulation: - Audi A4 Quattro: 0.14 m - Mercedes-Benz C320: 0.26 m

2. Deformation Energy: - Audi A4 Quattro: 20.69 kJ (simulation) - Mercedes-Benz C320: 38.91 kJ (simulation)

Stiffness and Coefficient of Restitution:

1. Stiffness: -Audi A4 Quattro: 2203.1 kN/m -Mercedes-Benz C320: 1171.4 kN/m

2. Coefficient of Restitution (e): -0.21 for both vehicles.

Impulse and Adhesion:

1. Impulse: -9499.71 Ns for both vehicles.

2. Adhesion Coefficient: - 0.44 for both vehicles.

Engineering Interpretation:

1. Audi A4 Quattro:

The post-impact velocity and velocity change (ΔV) are very close to the calculated values, indicating high accuracy of the theoretical model.

The deformation depth is consistent between the calculations and the simulation, confirming the rigidity of the vehicle structure.

A larger calculated EES compared to the simulated one can indicate less efficient impact energy dissipation in the theoretical model.

2. Mercedes-Benz C320:

Post-impact velocity and velocity change (ΔV) are slightly different between calculations and simulation, suggesting possible variations in the theoretical model compared to the simulated real conditions.

The depth of deformation is consistent, indicating a softer structure that absorbs more energy.

A smaller calculated EES compared to the simulated one can indicate an underestimation of the absorbed energy in the theoretical model.

3. Impulse and Adhesion: The impulse and coefficient of adhesion values are consistent across vehicles, indicating similar collision conditions.

4. Rigidity and Restitution: The Audi A4 Quattro exhibits greater rigidity, which can better protect the cabin but may transfer more energy to the passengers during an impact.

The Mercedes-Benz C320, with lower rigidity, absorbs more energy through deformation, reducing the energy transferred to passengers.

Overall Conclusion:

Audi A4 Quattro: A rigid structure with lower deformation values, which can better protect the passenger compartment but may transfer more energy to the passengers. A higher calculated EES compared to the simulated one suggests less efficient impact energy dissipation in the theoretical model.

Mercedes-Benz C320: A softer structure with higher deformation values and more efficient impact energy dissipation. The calculated EES being smaller than the simulated one indicates an underestimation of the absorbed energy in the theoretical model.

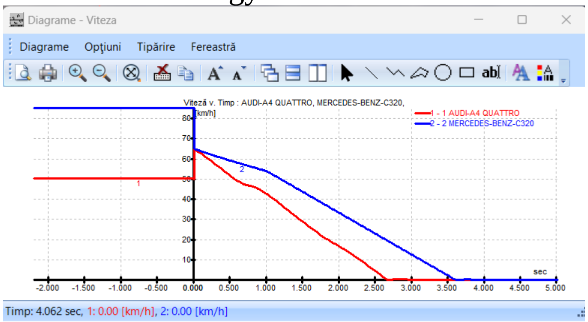


Figure 5. Speed vs. Time Diagram for Audi A4 Quattro, Mercedes-Benz C320

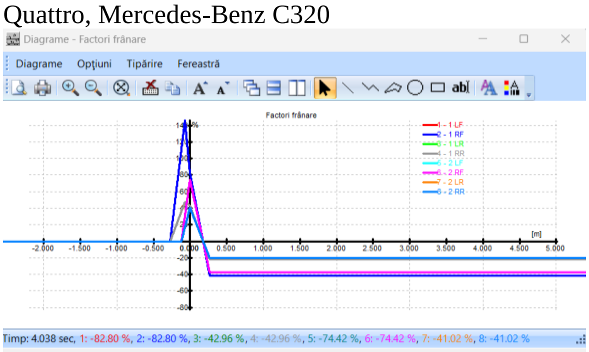


Figure 6. Braking factors, Axa x-distance

The diagram presented in the image illustrates the braking factors over time for various wheels of two vehicles during and after a collision. Braking factor curves are represented for each vehicle and are colour-coded for each wheel:

1-LF (red): The front left wheel of the first vehicle.

1-RF (blue): The front right wheel of the first vehicle.

1-LR (green): The left rear wheel of the first vehicle.

1-RR (magenta): The rear right wheel of the first vehicle.

2-LF (cyan): The second vehicle's left front wheel.

2-RF (yellow): The front right wheel of the second vehicle.

2-LR (orange): The left rear wheel of the second vehicle.

2-RR (violet): The right rear wheel of the second vehicle.

4. Conclusion

Comparative analysis and simulations performed using PC-Crash provided valuable insights into the dynamic behaviour of the two vehicles - the Audi A4 Quattro and the Mercedes-Benz C320 - during a side impact scenario. By correlating the simulation data with analytical calculations, it was possible to evaluate the program's accuracy and the physical realism of the reconstructed collision. The results obtained show a high degree of consistency between the theoretical and simulated values for post-impact velocity, energy dissipation, and deformation parameters, demonstrating the reliability of the hybrid dynamic model implemented in PC-Crash.

From the simulation results, it was observed that both vehicles experienced similar energy transfer mechanisms, but with notable structural differences that influence their deformation behaviour. The Audi A4 Quattro, characterised by greater stiffness and higher stiffness coefficients, exhibited lower deformation values and a slightly higher equivalent energy speed (EES). This indicates stronger structural resistance, but also a potentially greater transfer of energy to the passenger compartment. In contrast, the Mercedes-Benz C320, with a more flexible body structure, absorbed more energy through deformation, resulting in greater energy dissipation and reduced energy transmission to the occupants. This compromise highlights the balance between occupant safety and the vehicle's structural rigidity.

The comparison between the theoretical and simulated data confirms that PC-Crash provides accurate and realistic estimates of post-impact speeds and energy losses. The small discrepancies between the calculated and simulated EES values are mainly attributed to simplifications in the theoretical model, which does not fully account for secondary effects such as friction losses, angular momentum, and the non-linear deformation behaviour of the car body. However, these differences remain within acceptable engineering limits for accident reconstruction.

Analysis of braking characteristics and suspension properties revealed complementary performance trends between the two vehicles. The Audi A4 Quattro demonstrated smoother and more progressive braking, ensuring stability in varying grip conditions. In contrast, the Mercedes-Benz C320 demonstrated more aggressive braking efficiency in high-grip situations, although it might require more precise driver control in low-grip conditions. These observations are consistent with the differences in suspension stiffness and roll stiffness identified during the mechanical analysis.

Regarding engineering interpretation, the study confirms that:

The Audi A4 Quattro maintains higher structural integrity and stability in the event of a side impact, favouring cabin protection, but with a greater internal transfer of energy.

The Mercedes-Benz C320 offers better energy absorption through deformation, which can result in lower deceleration forces on the occupants but greater external damage to the body.

The consistency between the analytical and simulated post-impact velocities and ΔV values validates the robustness of the PC-Crash modelling approach for side-impact scenarios.

Overall, the investigation demonstrates that PC-Crash is a reliable and efficient tool for reproducing and analysing lateral impacts between vehicles of similar class and geometry. The strong correlation between simulated and theoretical results increases confidence in the use of the software for forensic accident reconstruction, safety validation, and educational applications. Additionally, comparative findings on vehicle stiffness, deformation behaviour, and energy absorption contribute to a deeper understanding of lateral collision dynamics, supporting future improvements in vehicle design and occupant protection systems.

Future work could extend this analysis by incorporating more advanced finite element models, exploring different impact angles and velocities, and validating the simulation results against experimental impact test data. Such studies would further enhance the predictive accuracy of PC-Crash and its applicability in complex real-world scenarios.

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