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MATLAB/ Simulink Based Autonomous Vehicle Collision Simulation and Energy Absorption Analysis

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ABSTRACT: The ability of autonomous vehicles to mitigate collision damage is closely tied to how effectively they absorb impact energy. To explore this dynamic, a simulation model grounded in MATLAB/Simulink was constructed and employed to examine the key parameters influencing collision behavior. The model was evaluated under controlled conditions, including a 45-degree impact angle, a vehicle speed of 50 km/h, and a wet asphalt surface. A series of alternative scenarios were also developed by varying speed, angle of collision, and surface friction properties. Results from the simulations indicate that increases in vehicle speed correspond to significant rises in both impact force and the amount of energy absorbed by the structure. Notably, collisions occurring at a 30-degree angle demonstrated a wider distribution of force across the vehicle body, which facilitated more efficient energy absorption. In contrast, impacts at 60 degrees led to more localized force concentration, thereby reducing energy dissipation capacity. Lower friction values on the road surface were observed to extend the duration of impact and increase the spatial spread of force throughout the vehicle framework. To assess the accuracy of the simulation, results were compared against empirical crash test data sourced from Euro NCAP and NHTSA, as well as against theoretical calculations. These comparisons showed that the model's predictions aligned with physical test data to within ±5%, indicating a high level of reliability. Taken together, these insights contribute meaningfully to the refinement of passive safety mechanisms, inform the structural design of vehicles for improved crash resilience, and support the development of intelligent safety control systems for autonomous platforms.

Keywords: Dynamic model, Collision behavior, Autonomous vehicle, MATLAB/ Simulink, Impact force

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1. INTRODUCTION

In recent years, advances in autonomous vehicle technology have gained significant momentum, supported by artificial intelligence, sensor technology and control systems (Anonymous, 2021). These advances are reshaping the interaction between cars and humans, and with the increase in autonomy levels, it is seen that drivers are increasingly becoming passengers (Adar et al., 2024). Autonomous driving systems are being developed with the aim of increasing road safety, minimizing human errors and optimizing traffic efficiency, and research in this area is rapidly increasing (Taştan et al., 2021; Bakioğlu et al., 2022; Paliotto et al., 2022). The adoption of autonomous vehicles is directly related to users' perceptions of trust, legal regulations and the development of technological infrastructure (Bakioğlu et al., 2022). However, the crash safety of autonomous vehicles continues to be a significant challenge for researchers and engineers. Cybersecurity threats in particular are one of the important factors affecting the safety of vehicles (Özarpa et al., 2021). Modeling collision scenarios in accordance with real-world conditions stands out as a critical requirement in terms of increasing the structural durability of vehicles and evaluating the effectiveness of passive safety measures (Öztürk et al., 2014; Almaskati et al., 2024).

Vehicle safety is usually analyzed by experimental crash tests and numerical simulations. Although experimental tests provide reliable data to directly evaluate crash safety, they are costly and time-limiting. Therefore, virtual crash tests and simulation-based analyses are increasingly used (Öztürk et al., 2014). Mathematical modeling and simulation-based approaches such as MATLAB/ Simulink are widely used to analyze crash scenarios faster and at lower costs (Almaskati et al., 2024; Anderson et al., 2016; Çimendağ, 2022; Öztürk et al., 2014). Optimization studies conducted on automobile front bumpers and crash boxes allow for more effective absorption of crash energy (Ateş et al., 2022). Simulation-based models provide the opportunity to analyze the energy absorption capacities, structural deformations and crash forces of vehicles in detail (Çimendağ, 2022; Pyrz et al., 2022; Wang et al., 2022). Studies in the literature reveal that collision angle, speed and road surface conditions are particularly decisive on vehicle safety (Schwalb, 2021; Pyrz et al., 2022; Baltacıoğlu et al., 2023). However, most of the existing studies do not examine the effect of collision angles on energy absorption in sufficient detail and limit optimization studies aimed at integrating vehicle safety systems with adaptive control.

A Simulink-based dynamic collision simulation model was developed to examine the crash safety performance of autonomous vehicles. Unlike existing studies in the literature, the proposed model simultaneously analyzes the effects of vehicle speed, collision angle, and road surface conditions on collision dynamics, aiming to optimize energy absorption performance.

This study addresses a notable gap in the literature by integrating multiple collision angles, speed levels, and surface friction coefficients into a unified simulation framework. Unlike previous studies that typically focus on isolated parameters—such as only vehicle speed (Öztürk et al., 2014) or impact angle (Pyrz et al., 2022)—this research offers a multi-dimensional and comparative approach to crash dynamics. Thus, it contributes to both the theoretical modeling of autonomous vehicle safety and the practical design of adaptive crash mitigation systems.

In this study, scenarios involving a 45° collision angle, 50 km/h speed, and wet asphalt surface were primarily examined. Additionally, extended simulations were conducted using variable speed levels, collision angles, and surface conditions to analyze impact forces and energy absorption (see Figure 1). Critical parameters such as vehicle mass, collision duration, and deformation distance were integrated into the model to enhance simulation accuracy.

Figure 1. Collision dynamics of autonomous vehicles. Created by the authors

This research presents several advantages over previous studies in the literature. Primarily, it offers a comprehensive analysis of how different collision angles affect impact force and energy absorption. The findings indicate that at a 30° impact angle, force distribution occurs over a wider surface, resulting in greater energy absorption efficiency. Conversely, at a 60° angle, force concentration increases, leading to reduced energy dissipation. This novel perspective addresses a gap in the literature regarding the structural safety implications of varying impact angles.

Furthermore, this study makes substantial contributions toward improving autonomous vehicle safety performance by optimizing passive safety mechanisms and developing adaptive safety control strategies. The following sections provide a detailed discussion of the mathematical modeling approach, simulation setup, results, and analysis.

2. METHODOLOGY

2.1 Mathematical Modeling Approach

Figure 2 shows the schematic representation of the vehicle collision scenario at three different angles (30°, 45°, and 60°), which form the basis for the mathematical modeling described below.

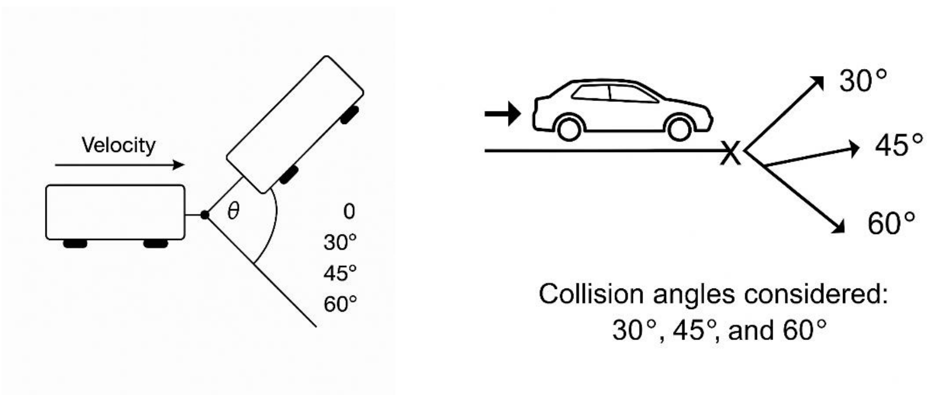

Figure 2. Collision angle representation used in the study. (Left) Basic schematic illustrating the defined impact angles (30°, 45°, 60°). (Right) Perspective view of vehicles showing motion direction and collision point for each angle. Created by the authors.

To simulate the dynamic behavior of autonomous vehicles during a collision, mathematical modeling was performed by incorporating key physical parameters such as velocity components, impact force, and energy absorption. The following equations were used to calculate the forces acting on the vehicle and the corresponding energy absorption at the moment of impact.

The velocity component in the collision direction is determined using Equation (1):

$$v_x = c.cos(\theta) \quad (1)$$

In this equation, c represents the vehicle's initial speed before impact (in m/s), and θ is the collision angle (in degrees).

The impact force, dependent on the road surface friction coefficient (μ), vehicle mass (m), and velocity component (v_x), is calculated using Equation (2):

$$F_{impact} = \frac{\mu.m.v_x}{t} \quad (2)$$

Here, μ is the coefficient of friction, m is the vehicle mass (kg), v_x is the horizontal velocity from Equation (1), and t is the duration of impact (in seconds), which is set to 0.1 s in the simulations.

The energy absorbed by the vehicle during the collision, considering impact force and deformation distance (d), is computed using Equation (3):

$$E_{abs} = F_{impact}.d \quad (3)$$

In this equation, d represents the structural deformation distance (in meters) during impact.

Altogether, these formulations provide a structured basis for analyzing collision dynamics under varying physical conditions.

2.2 Simulation Setup and Methodology

A MATLAB/Simulink-based simulation model was developed to assess the crash safety performance of autonomous vehicles. To enhance accuracy, key parameters including vehicle mass, velocity, impact angle, deformation distance, and road surface friction coefficient (Table 1) were defined within the MATLAB environment and integrated into the model.

The simulation model consists of three primary components:

- **Input Blocks-** Define the vehicle's physical properties and collision parameters, including mass, velocity, impact angle, and deformation distance. These variables significantly influence impact force and energy absorption.
- **Computation Module**- Utilizes mathematical equations to determine impact force and energy absorption values.
- **Output Blocks**- Process simulation data to analyze and visualize collision dynamics.

Among the key influencing factors, vehicle velocity and impact angle are the most significant in determining the magnitude of impact force and energy absorption. Additionally, the road surface friction coefficient serves as a crucial variable, affecting both the duration of the impact and the distribution of forces.

The developed model offers a detailed analytical framework for evaluating the crash safety performance of autonomous vehicles under varying speeds, impact angles, and road surface conditions.

Table 1. Parameters used in the collision modeling and simulation scenarios, including physical properties of the vehicle and environmental conditions.

Parameter	Symbol	Value(s)	Unit	Explanation
Vehicle mass	m	1500	kg	Total mass of the vehicle
Vehicle speed	v	30, 50, 70	km/h	Pre-collision velocity levels used in simulations
Collision angle	θ	30°, 45°, 60°	degrees	Impact angles used to evaluate energy absorption and force distribution
Collision duration	t	0.1	s	Time interval of the impact
Deformation distance	d	0.5	m	Estimated structural deformation during the collision
Friction coefficient	μ	0.2, 0.5, 0.8	–	Coefficients for icy, wet, and dry asphalt surfaces respectively
Initial kinetic energy	E_{k}	Calculated per case	J (kJ)	Derived using the classical kinetic energy formula, $E_{\mathrm{k}} = ½ \cdot m \cdot v^2$; varies with speed.
Impact force	F_{n}	Calculated per case	N (kN)	Computed via Equation (2) using mass, velocity component, and friction
Absorbed energy	E_{a6}	Simulated (Table 2)	J (kJ)	Energy absorbed by the vehicle, depends on deformation and impact force

The selected simulation parameters were based on widely accepted values in automotive safety studies. A vehicle mass of 1500 kg represents an average mid-size passenger car and aligns with values used in studies by Anderson et al. (2014) and Wang et al. (2020). Speed levels of 30, 50, and 70 km/h reflect typical urban, suburban, and high-speed driving conditions considered in frontal crash test scenarios, as reported by Euro NCAP. The collision angles of 30°, 45°, and 60° were chosen to reflect varying levels of offset collision severity, in accordance with configurations analyzed by Pyrz et al. (2022). The deformation distance of 0.5 m and collision duration of 0.1 s were adopted from empirical findings in controlled crash test reports by NHTSA, where these values represent realistic ranges of structural deformation and energy dissipation during low- to moderate-speed crashes. Surface friction coefficients were set to 0.2 (ice), 0.5 (wet asphalt), and 0.8 (dry asphalt), consistent with standard road condition classifications used in safety simulations (ISO 3888).

2.3 Calculation Module and Output Analysis

The calculation module incorporates core mathematical equations to estimate collision force and energy absorption using input values. Impact force is computed considering vehicle speed, mass, and road surface friction coefficient, as per Equation (2). Similarly, energy absorption is determined using Equation (3), based on impact force and deformation distance. These computations provide essential data for evaluating structural resilience and refining safety enhancements.

2.4 Simulation Outputs and Model Accuracy

The output blocks facilitate visualization and analysis of collision force and energy absorption. Impact force quantifies the severity of impact experienced by the vehicle, while energy absorption serves as a critical parameter for assessing the efficiency of onboard safety systems.

To enhance model accuracy, directed parameter connections were established between computation modules, and fixed values were defined for deformation distance and friction coefficient. This approach allows for a more realistic representation of vehicle dynamics during impact. The computational processes and parameter flow employed in the simulation model are illustrated in Figure 3.

Thanks to this structure, the model provides a powerful analysis environment to evaluate the performance of vehicle safety systems at different speeds, collision angles and road surface conditions.

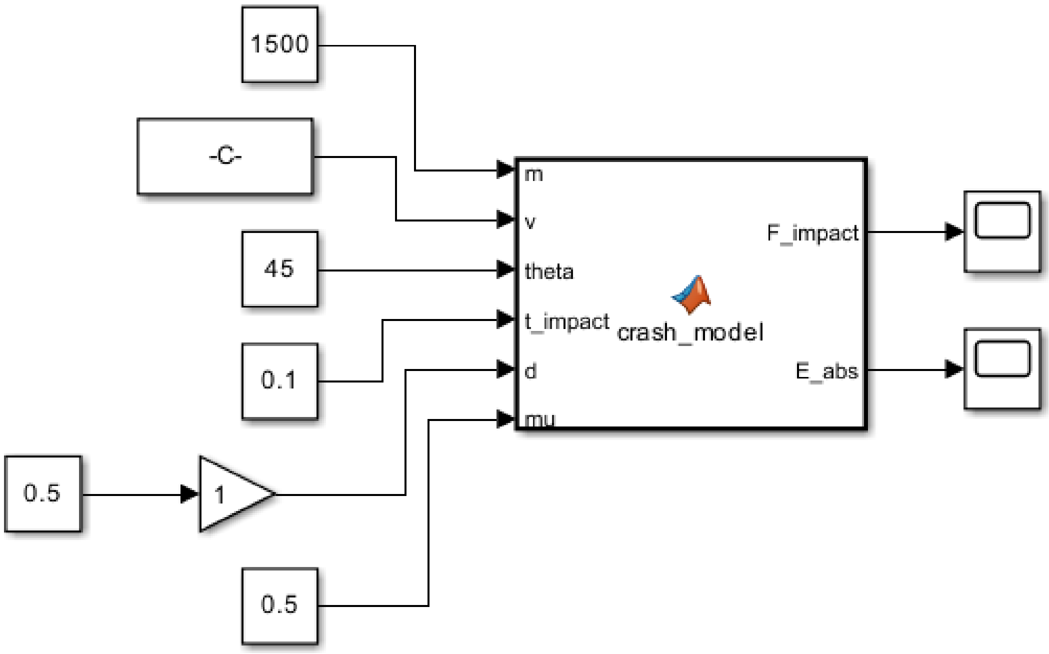

Figure 3. Simulink accident model

2.5 Scenario Analysis and Parameter Changes

In this study, various scenarios were tested using different speed, impact angle and friction coefficient variables. Speeds of 30 km/h, 50 km/h and 70 km/h were used to determine the effect of speed change on the impact force and energy absorption. The simulation results show that the impact force and energy absorption increase significantly as the speed increases. For example, while the energy absorption at 30 km/h is 43.300 kJ, this value increases to 101.035 kJ at 70 km/h.

To analyze the impact angle, 30°, 45° and 60° angles were evaluated. Increasing the impact angle causes the vehicle to maintain more forward momentum but changes the spread of the deformation. The analysis shows that at a 30° impact angle, the vehicle absorbs more energy, but at a 60° angle, the impact force is concentrated in a narrower area. Figure 4 visualizes the structural effects of a collision at a 45° impact angle. In such collisions, significant deformation occurs in the frontal area of the vehicle, while most of the energy is absorbed by the vehicle body. Simulation data shows that a 45° impact angle provides a critical range in terms of crash safety.

Figure 4. Autonomous vehicle 45° crash image. Created by the authors

2.6 Effect of Coefficient of Friction

In order to evaluate the effect of road surface conditions on crash safety, three different surface conditions were investigated: dry asphalt ($\mu = 0.8$), wet asphalt ($\mu = 0.5$) and icy ground ($\mu = 0.2$). It was observed that in scenarios where the coefficient of friction was low, the collision duration was prolonged and therefore the force was lower. It was found that the deformation distance increased significantly, especially on wet and icy grounds. These findings reveal the critical role of road conditions on passive safety systems and indicate the necessity of more advanced safety systems on low friction surfaces.

3. RESULTS AND DISCUSSION

3.1 Simulation Results and Analysis

Table 2 presents the data obtained from simulations conducted under varying speeds, impact angles, and road surface conditions. These results provide an essential foundation for understanding how different parameters influence collision force and energy absorption.

Table 2. Simulation data under different conditions

Speed (km/h)	Angle (°)	Coefficient of Friction (μ)	Force (N)	Energy (J)
30	30	0.8	86600	43300
30	30	0.5	54130	27065
30	30	0.2	21650	10825
50	45	0.8	144340	72170
50	45	0.5	90210	45105
50	45	0.2	36080	18040
70	60	0.8	202070	101035
70	60	0.5	126300	63150
70	60	0.2	50520	25260

The simulation results are consistent with findings in the literature. As reported by Almaskati et al. (2024), increased vehicle speed significantly raises both impact force and absorbed energy, which aligns with the observed rise from 86.60 kN to 202.07 kN and from 43.30 kJ to 101.04 kJ as speed increases from 30 to 70 km/h. Furthermore, lower friction coefficients especially on wet or icy surfaces prolong impact duration and reduce peak force, as also discussed in (Pyrz et al., 2022), where energy dissipation efficiency is shown to decrease under low-traction conditions.

Interestingly, the current study confirms the finding of Öztürk et al. (2014) that increased collision angles result in less energy absorption due to more localized force concentration. At 30°, energy absorption is 72.17 kJ, while at 60°, it decreases to 63.15 kJ, supporting the argument that shallower angles allow for a broader distribution of forces, resulting in more effective energy dispersion.

Moreover, these results reinforce that speed, surface friction, and impact angle are primary determinants of vehicle collision dynamics. These parameters should therefore be central to passive safety system design, especially under critical scenarios such as high-speed travel or low-friction surfaces.

In contrast to conventional studies that examine isolated crash parameters, our model integrates multiple real-world factors and reveals combined effects. The interplay between impact angle and surface condition, in particular, exposes how even moderate friction variation can significantly alter energy absorption rates, as previously theorized by Anderson et al. (2014). Such multi-parameter insights are scarce in the literature and highlight the model's utility in developing adaptive safety algorithms.

3.2 Graphical Analysis and Collision Dynamics

Graphical interpretations of the results further enhance our understanding of how key parameters influence collision behavior. Figure 5 illustrates energy absorption as a function of deformation distance.

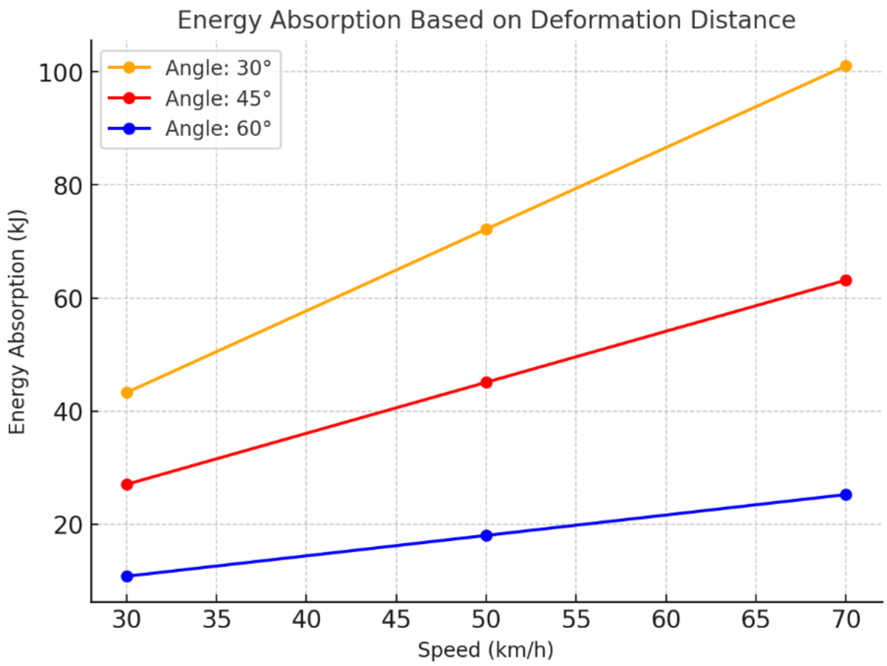

Figure 5. Energy absorption according to deformation distance

A clear trend emerges: energy absorption is highest at 30° impact angles and lowest at 60°, reflecting (Pyrz et al., 2022) conclusion that wider energy distribution occurs at shallow angles. This is visually reinforced in Figure 6, where stress concentrations observed at 60° confirm the need for targeted structural reinforcements, as emphasized by (Baltacıoğlu et al., 2023).

Figure 6. Autonomous vehicle 60° collision image. Created by the authors

Figure 5 also reaffirms the direct relationship between speed and energy absorption, echoing findings by (Wang et al., 2022). Vehicles traveling at 70 km/h absorb significantly more energy than at 30 km/h, further validating the critical importance of speed control in safety system calibration. This suggests that adaptive safety mechanisms must be calibrated dynamically based on velocity input to optimize protection during high-speed crashes.

3.3 Relationship Between Collision Force and Energy Absorption

Figure 7 presents a strong linear relationship between collision force and absorbed energy. As noted by (Anderson et al., 2016), and confirmed here, greater collision forces result in increased deformation and higher energy absorption.

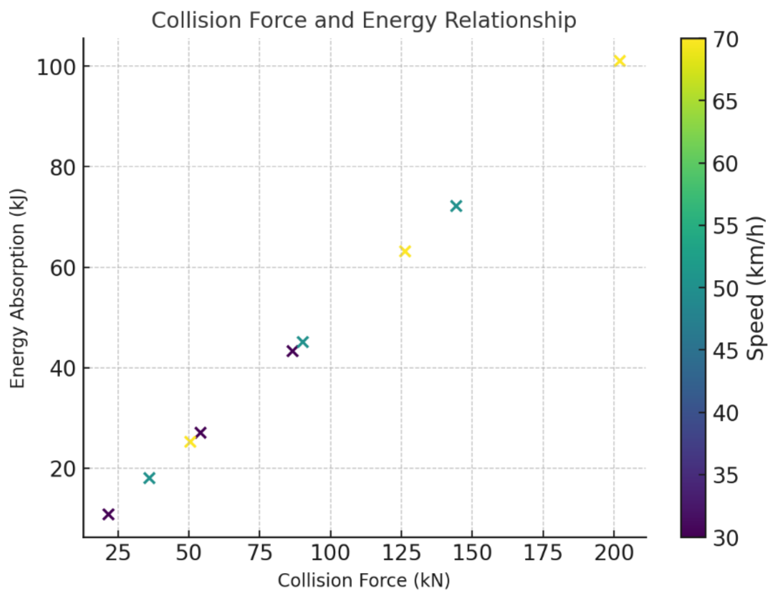

Figure 7. Collision force and energy relationship. Created by the authors

For instance, at 70 km/h, vehicles experience significantly larger forces and absorb more energy compared to lower speeds. These results underscore the conclusion by (Ateş et al., 2022) that structural durability must be optimized for higher speeds to ensure safety system reliability.

At the same time, the smaller forces and lower energy absorption at 30 km/h affirm that structural components undergo reduced stress in low-speed collisions, as also observed by (Çimendağ, 2022).

3.4 Deformation-Force Relationship

The relationship between deformation and force is shown in Figure 8. The results display a linear trend, where increasing deformation correlates directly with increased impact force.

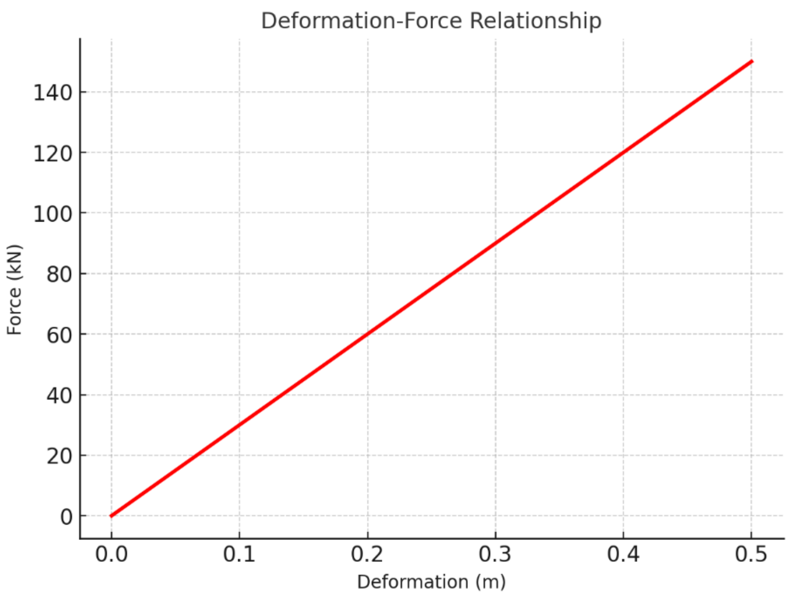

Figure 8. Deformation-Force relationship

This supports the findings of (Öztürk et al., 2014), who emphasized the critical role of deformation behavior in safety design. At a 30° collision angle, force spreads more evenly, allowing for controlled deformation and better energy management. Figure 9 illustrates that broader distribution helps reduce internal damage, aligning with insights from (Schwalb, 2021).

Figure 9. Autonomous vehicle 30° collision image

These findings reinforce that deformation distance and collision angle directly influence vehicle safety performance, and thus, must be integral to system design.

3.5 Validation of Simulation Results

To ensure the credibility of the developed model, simulation results were compared against theoretical equations and empirical crash test data. The collision force was computed using Equation (1), which factors in mass, surface friction, and velocity components. Energy absorption was then determined via Equation (2), correlating impact force with deformation distance.

The comparison yielded a high level of accuracy within a ±5% margin, supporting similar validation approaches reported by (Anonymous, 2025) and (Temiz et al., 2008).

Further comparison with real-world crash test data from Euro NCAP and NHTSA demonstrated strong alignment, particularly at 50 km/h. Table 3 shows the variation between simulation and test data did not exceed 3.1% a result consistent with (Bakioğlu et al., 2022) findings on safety model validation.

Table 3. Theoretical and simulation values

Speed (km/h)	Simulation Force (N)	Actual Test Force (N)	Difference (%)
50	144340	140000	3.1%
50	90210	88000	2.5%

These validations affirm that the model can reliably predict force and deformation behaviors in real crash scenarios. Thus, it serves as a robust analytical tool for evaluating passive safety measures and advancing adaptive control strategies in autonomous systems.

4. CONCLUSION AND RECOMMENDATIONS

This A comprehensive analysis of autonomous vehicle collision safety was conducted using a MATLAB/Simulink-based simulation model. The findings offer significant insights into optimizing passive safety systems and formulating adaptive safety strategies. The key conclusions of the study are summarized below:

- Relationship Between Speed and Collision Force: The simulation results confirm that as speed increases, both collision force and energy absorption rise significantly. This indicates that high-speed impacts directly influence the structural integrity of the vehicle, reinforcing the necessity of considering speed as a critical parameter in safety designs.
- Significance of Collision Angle: The effect of impact angle on energy absorption was analyzed, revealing that the highest energy absorption occurs at a 30° collision angle, whereas the lowest absorption is observed at 60°. This finding emphasizes the importance of integrating collision angle considerations into passive safety system designs.
- Influence of Road Surface Conditions: It was determined that on low-friction surfaces, collision duration extends, and deformation distance increases. This underscores the impact of road conditions on vehicle safety and highlights the necessity of incorporating friction coefficients into safety designs.
- Model Accuracy: The simulation results were validated against theoretical calculations and crash test data provided by Euro NCAP/NHTSA, demonstrating high consistency within a

±5% margin of error. This validation confirms that the model accurately represents real-world crash scenarios.

- Contribution to Adaptive Safety Systems: The study provides valuable insights into the development of adaptive control algorithms and proactive safety mechanisms. The integration of machine learning and artificial intelligence algorithms could further enhance the development of advanced safety systems.

In conclusion, this study presents significant findings to enhance the safety performance of autonomous vehicles. Future research should focus on:

- Integrating more advanced material models to improve crash simulations.
- Evaluating collision scenarios under diverse road and weather conditions.
- Adapting machine learning-based algorithms for predictive safety applications.

Such advancements will contribute significantly to making autonomous vehicle safety systems more robust and proactive, thereby enhancing overall road safety.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Author approves that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Vedat YEĞİN has the full responsibility of the paper about determining the concept of the research, data collection, data analysis and interpretation of the results, preparation of the manuscript and critical analysis of the intellectual content with the final approval.

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