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RESEARCH ON THE DESIGN AND SIMULATION OF FRONTAL COLLISION ASSESSMENT OF A TRUCK WITH EMERGENCY VEHICLE SUPPRESSION SYSTEM

Summary. In response to the growing threat of vehicle-ramming attacks targeting critical infrastructure such as airports, government facilities, and public gathering spaces, this study focuses on the design and simulation of a direct frontal collision between a heavy truck and an emergency vehicle barrier using the Finite Element Method (FEM). The simulation model is developed to replicate realistic impact conditions, allowing detailed analysis of the barrier's structural behavior under extreme loads, including deformation patterns, stress distribution, and energy absorption capacity. Material properties, contact interactions, and boundary constraints are carefully defined to enhance simulation accuracy. The results reveal

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that an optimally designed barrier with reinforced structures and effective energy-dissipating features can significantly reduce damage and vehicle intrusion, thereby improving overall protective performance. This confirms the crucial role of FEM-based simulation in the early design phase of physical security systems, offering a cost-effective and predictive approach to evaluating and optimizing barrier effectiveness before real-world deployment.

Keywords: crash simulation, emergency vehicle barrier, chevrolet silverado, energy absorption, front-end collision, hyper radios

1. INTRODUCTION

The growing population, rapid urbanization, and increasing global security instability have significantly elevated the risk of vehicle-ramming attacks – particularly those involving trucks, which are heavy, easily accessible, and difficult to stop. According to the Global Terrorism Database, vehicle-based attacks accounted for over 50% of terrorism-related deaths in Western countries in 2016 alone [1]. Additional studies, such as "Democratization of terrorism: an analysis of vehicle-based terrorist events" [2], recorded 257 vehicle-related terrorist incidents worldwide between 1970 and 2019, resulting in 808 deaths and 1,715 injuries – 71% of which occurred in just the last six years of the study period. Crowded public spaces, including festivals, sporting events, and outdoor dining areas, continue to be vulnerable targets.

In this context, emergency vehicle barriers play a critical role in safeguarding vital locations such as airports, government buildings, and high-profile events. Analyzing the direct impact of collisions between trucks and such barriers is essential for optimizing structural design, minimizing potential damage, and enhancing the overall effectiveness of protective systems. Advanced simulation tools, particularly those based on Computer-Aided Engineering (CAE), offer valuable insights into the performance of barrier systems under realistic crash conditions.

In Vietnam, ensuring the security of critical infrastructure has become increasingly urgent, especially amid deeper international integration and mounting regional instability. The protection of administrative centers, military zones, and airports is not only a national priority but also a reflection of the country's international credibility. High-profile visits by world leaders in 2023-2024 – including the Presidents of the United States, Germany, and Russia – further underscore the importance of maintaining robust and reliable security systems.

Given the rising threat of terrorism and illegal intrusions across Southeast Asia, research into high-performance barrier systems is both timely and essential. Such efforts significantly contribute to national security by enabling the design of practical, efficient, and modern defense solutions aimed at protecting both people and critical infrastructure.

2. THEORETICAL FOUNDATIONS OF AUTOMOTIVE COLLISIONS

2.1. Finite element method

The Finite Element Method (FEM) is a numerical technique used to obtain approximate solutions for physical fields within a problem domain by discretizing the space into simple elements connected by nodes. FEM is widely applied in various fields such as structural mechanics, heat transfer, fluid mechanics, acoustics, and many other engineering problems.

In nonlinear dynamic analysis, the equation of motion is derived based on the principle of virtual work and is expressed in matrix form as follows [3]:

$$[\boldsymbol{M}].(\ddot{\boldsymbol{X}}) + [\boldsymbol{K}](\boldsymbol{X}) = \boldsymbol{F_{ext}} \quad (1)$$

Where:
$\boldsymbol{X}$ is the nodal position vector;
$\ddot{\boldsymbol{X}}$ is the acceleration vector;
[M] is the mass matrix;
[K] is the stiffness matrix;
$\boldsymbol{F_{ext}}$ represents external forces.
Nonlinearity arises from contacts, material behavior, and geometric effects, necessitating an advanced time integration scheme to handle strong nonlinearities.

2.2. Calculating the energy of the collision problem

When a collision occurs between a vehicle and an emergency barrier, the initial velocity of the vehicle is denoted as $\boldsymbol{v_o}$ (the velocity at the onset of impact), and v is the velocity after the collision with the obstacle. In this case, $\boldsymbol{v} = 0$ and $\boldsymbol{v_0} \neq 0$ (the vehicle comes to a complete stop) [4, 5]. The kinetic energy at the moment of impact is determined by the following equation:

$$\boldsymbol{E_k = \frac{1}{2} m {v_o}^2} \quad (2)$$

In the case of a perfectly plastic (inelastic) collision [6], the entire kinetic energy is converted into deformation energy, which is calculated as:

$$\boldsymbol{E_k = \frac{1}{2} m v_0^2 . \int_0^{\Delta X_{max}} F_{(\Delta X, \Delta V) dx}} \quad (3)$$

In there:
$\boldsymbol{F}$ – is the instantaneous deformation force (N);
$\boldsymbol{\Delta X}$ – is the instantaneous deformation when the vehicle collides (m);
$\boldsymbol{\Delta V}$ – is the vehicle's deceleration (m/s);
$\boldsymbol{\Delta X_{max}}$ – is the maximum deformation of the front of the car when stopping (m);
$\boldsymbol{m}$ – is the mass of the vehicle (kg).

The equation of motion of the vehicle during the collision process is expressed as:

$$\boldsymbol{m}.\ddot{x} + \boldsymbol{F} = \boldsymbol{0} \quad (4)$$

3. MODEL BUILDING

3.1. Application of numerical simulation in collision problem analysis

This study employs HyperWorks 2020 with the Radioss solver for standardized model analysis, ensuring consistency and accuracy. Design parameters are adjusted across configurations to assess performance. The analysis follows a structured workflow to ensure result reliability.

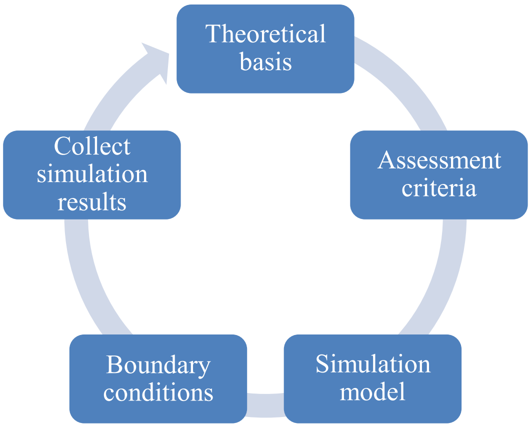
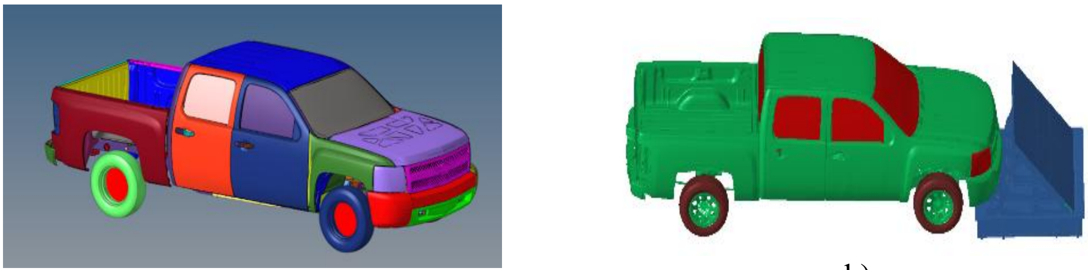


Fig. 1. Procedure for analyzing collision problems

3.2. Model setup

The researched vehicle, the Chevrolet Silverado, is constructed using a body-on-frame design, similar to that of heavy-duty vehicles like trucks and SUVs, rather than the unibody construction commonly found in passenger cars. This type of construction is typical in trucks, off-road vehicles, and heavy-duty applications due to its high strength, durability, and ability to withstand rough terrain and heavy loads.

Based on the 3D model of the Chevrolet Silverado vehicle from the CCSA open database sponsored by NHTSA, using Hypermesh software with Radioss solver for meshing, the number of elements divided is 730068 elements with mesh sizes from 6 mm to 10 mm [7].



a) b)

Fig. 2. Simulation model: a) Chevrolet Silverado; b) setting up material for the model

Tab. 1

Chevrolet Silverado vehicle specifications [7]

Type	Chevrolet Silverado version 3E
Body type	4-door short cab pickup truck
Weight	2,337 kg (5,152 lb)
Engine type	4.8L V8
Gear	M30 4 Speed Automatic
Tire size	P245/70R17

Then create connections between the parts in the model, and create a rigid body to create connections between the non-welded parts, and replace the missing parts. Create materials and material properties for each part of the car.

Tab. 2

Material specifications [8]

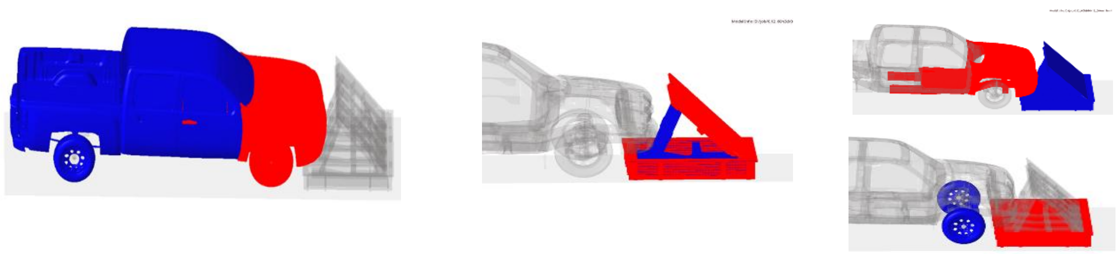
Material / Parameter	M36_PLAS_TAB (Case and chassis)	M1_ELAST (Tire)	M44_COWPER (Glasses)	Unit
Volumetric mass	7.85e-09	7.86e-09	2.5e-09	Kg / m^3
Young's modulus	210000	200000	70000	MPa
Poisson's ratio	0.3	0.28	0.22	
Yield stress			30	MPa
Plastic stiffness coefficient			1000	MPa

3.3. Set up interactions between components

The collision problem is a complex nonlinear problem, with contact being one of the most important factors. Physically, contact refers to the transfer of stress between two rigid bodies when they are in contact. Numerically, contact is a nonlinear form due to its severe discontinuity.

Modeling the contact between the parts is very important to ensure accurate and realistic simulation results. We use the TYPE7 option to set up the interaction between the parts. The main advantage of the TYPE7 interface is that the stiffness is constant and increases as the node passes through the middle surface of the shell. This solves many problems with poor contact (common when using TYPE3 or TYPE5 interfaces) [10].

There are three types of interactions that need to be implemented. The first is the interaction among the finite elements of the vehicle (Figure 3a), followed by the interaction among the finite elements of the barrier (Figure 3b), and finally, the finite element interaction between the vehicle and the barrier.



a) b) c)

Fig. 3. Connection setup: a) vehicle finite element connection; b) barrier finite element connection; c) vehicle–barrier finite element connection

3.4. Set up road surface, wall and impact velocity

The purpose of establishing interactions between the vehicle, and the road and the wall is to avoid the occurrence of element penetration into the road or wall during a collision. Then, the speed is assigned to all vehicle components; the speed is selected as 40km/h based on the actual test speed when testing vehicle collisions with walls, besides we will consider another case where the vehicle hits the barrier at a speed of 60km/h (According to NHTSA).

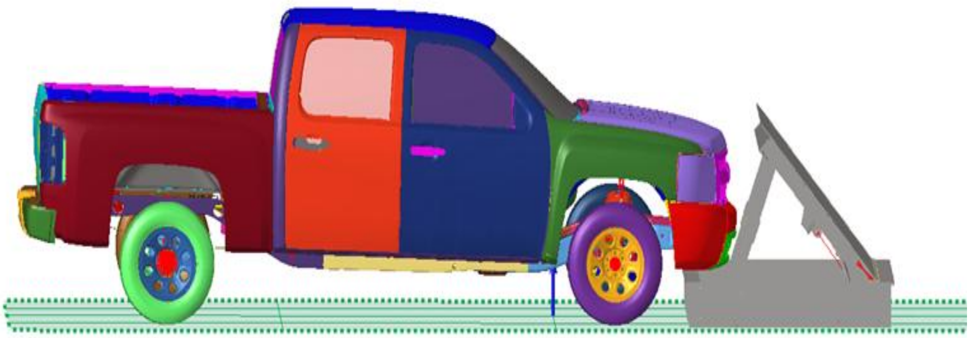


Fig. 4. Infinitely flat rigid walls after creation

4. RESULTS AND DISCUSSION

4.1. Impact energy

After analyzing the conditions for collision and running the problem, we have energy lines such as Internal Energy, Kinetic Energy, and Total Energy as shown in Figures 5 and 6. Here we will have an energy balance to be able to evaluate the correctness of the problem.

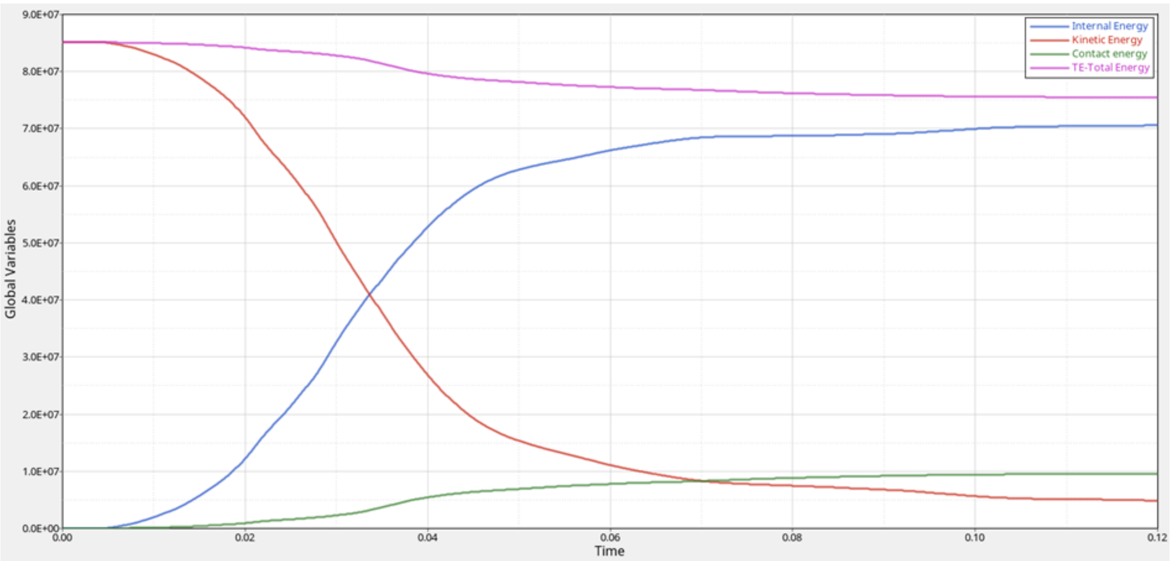


Fig. 5. Energy graph of the problem when the collision occurs at a speed of 40km/h

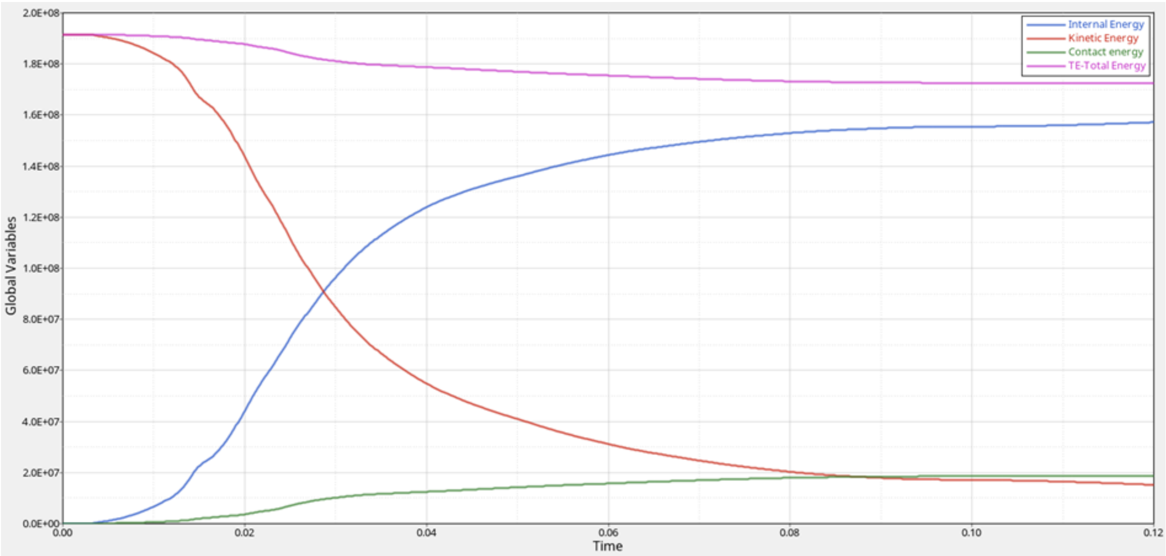


Fig. 6. Energy graph of the problem when the collision occurs at a speed of 60km/h

With a vehicle mass of 1.378 tons and an initial speed of 40 km/h, the total theoretical energy in this case is calculated as:

$$\boldsymbol{E} = \frac{1}{2} \times \boldsymbol{m} \times \boldsymbol{v}^2 = \frac{1}{2} \times \mathbf{1378} \times (\frac{\mathbf{11111}}{\mathbf{1000}})^2 = \mathbf{85060,02}\ \text{J} = \mathbf{8.506} \times \mathbf{10^7}\ \text{mJ} \quad (5)$$

The total energy from the simulation energy plot is $8{,}512.10^7$ mJ. The result shows that the theoretical energy and the simulation result are nearly identical, indicating that the simulation model can be considered reliable.

With a vehicle mass of 1.378 tons and an initial speed of 60 km/h, the total theoretical energy in this case is:

$$\boldsymbol{E} = \frac{1}{2} \times \boldsymbol{m} \times \boldsymbol{v}^2 = \frac{1}{2} \times \mathbf{1378} \times (\frac{\mathbf{16667}}{\mathbf{1000}})^2 = \mathbf{191396,54}\ \text{J} = \mathbf{1,914.10^8}\ \text{mJ} \quad (6)$$

The total energy from the energy plot is $1{,}915.10^8$ mJ. The close match between the theoretical calculation and simulation result again demonstrates the reliability of the simulation model.

From the energy plots in Figure 5 and 6, it can be seen that after the moment of impact (0.12 seconds), the total energy in the system drops to $7{,}546.\ 10^7$mJ (for 40 km/h) and $1{,}723.\ 10^8$ mJ (for 60 km/h), corresponding to an energy loss of approximately 11.3% and 10%, respectively. This lost energy is not actually lost but is transformed into other forms such as internal energy-reflecting structural deformation and interaction energy, which represents hard-to-quantify forms like sound, heat due to friction, or mechanical vibrations.

Notably, the interaction energy in the two cases reached $9{,}58.\ 10^6$ mJ (at 40 km/h) and $1{,}878.\ 10^7$ mJ (at 60 km/h), accounting for 99.17% and 97.8% of the total energy dissipation, respectively. This indicates that most of the energy absorption occurs in the contact and deformation zones, demonstrating the efficiency of the emergency barrier in dissipating kinetic energy.

A portion of the energy loss may also be attributed to numerical characteristics of the model, such as uneven mesh quality or non-optimal boundary conditions. However, the close agreement between theoretical values and simulation results confirms that the model accurately reflects the energy transformation mechanism and can be used to predict the safety performance of real-world damping solutions.

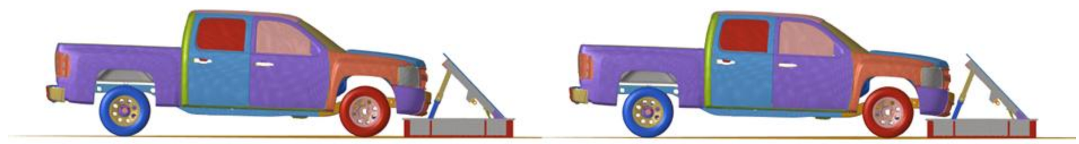
The energy analysis from the simulation clearly demonstrates the system’s energy absorption and dissipation mechanisms during collision, with the majority of the kinetic energy being converted into internal and interaction energy-characteristic of plastic impact behavior. This forms an important foundation for assessing the reliability of the model as well as its capability to protect passengers and vehicles in real-world crash scenarios.

4.2. Vehicle safety assessment during collision

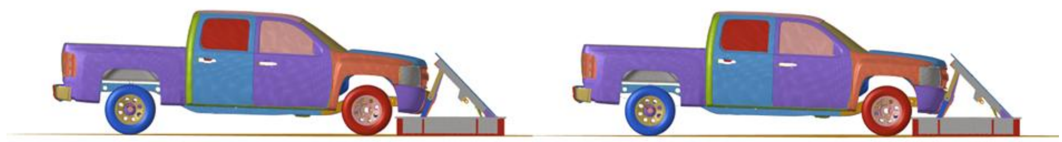
Vehicle timeline in process – Table 3.

Tab. 3

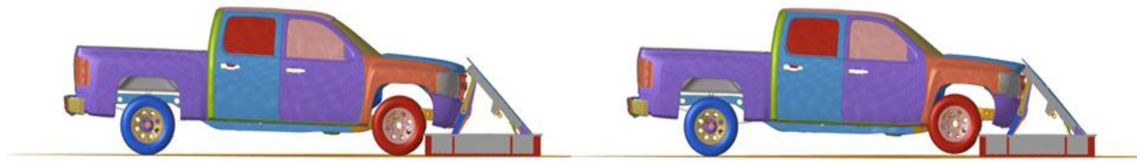
Timelines during the collision



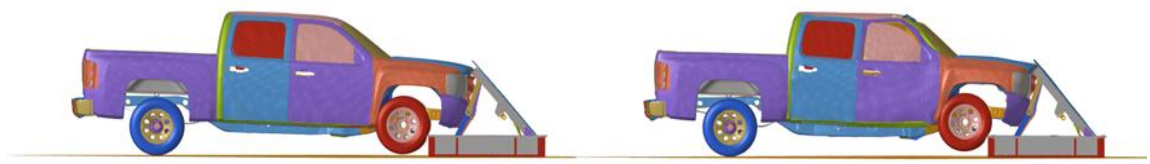
At time 0 s



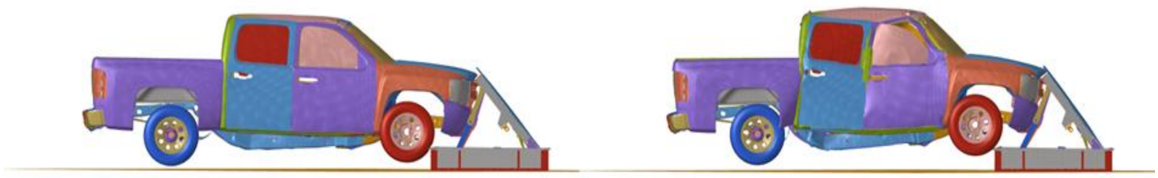
At time 0.012 s



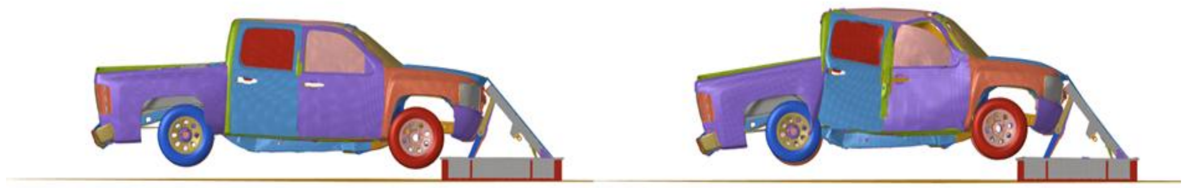
At time 0.024 s



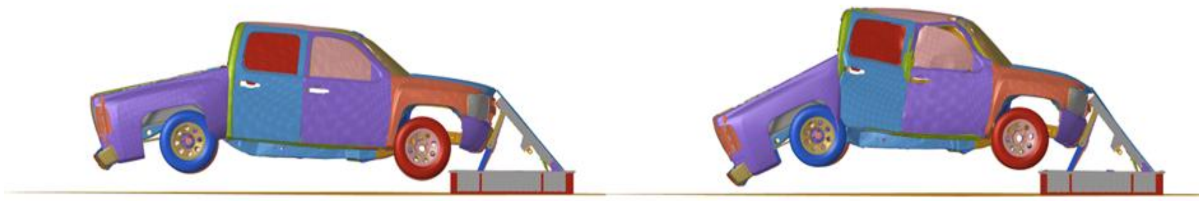
At time 0.036 s



At time 0.06 s



At time 0.09 s



At time 0.12 s

When a vehicle collides with a rigid object such as a barrier, the car's frame structure suffers severe deformation, especially in the front end and the area connecting the engine compartment and the passenger cabin. A deformed front bumper can damage the engine and threaten driver safety as the passenger compartment is intruded upon, reducing survival space.

To protect occupants, the cabin needs to be reinforced with load-bearing beams at the doors, roof, and floor to limit deformation during a collision. Analyzing the cabin floor, particularly at the driver's footrest area, helps assess intrusion levels and propose design improvements.

According to IIHS standards [9], safety performance is evaluated via crash simulations and the use of dummies to determine injury severity. In numerical simulations, nodes on the vehicle floor are monitored to measure displacement and intrusion into the passenger compartment. The results are then compared with IIHS criteria to evaluate occupant protection and suggest safer vehicle designs for the future.

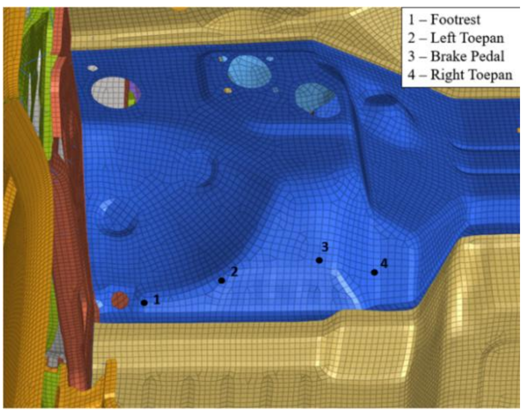


Fig. 7. Measurement point for driver intrusion

The research team measured the displacement of node 2039311 after the impact in two velocity scenarios.

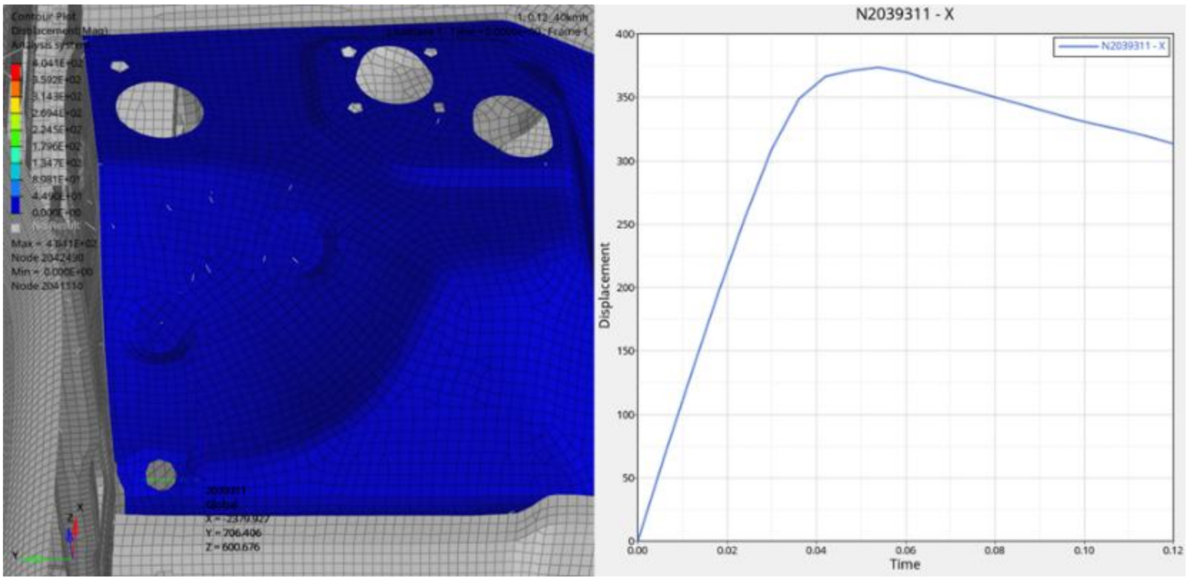


Fig. 8. Displacement graph of Node 2039311 along the X axis at 40 km/h

From the displacement graph of Node 2039453 – representing the driver's foot location – it can be observed that from the moment of impact until approximately 0.05 seconds, this point experienced significant continuous deformation. The maximum displacement amplitude reached 316 mm, indicating a strong direct impact that caused substantial movement in the vehicle floor. After this moment, the displacement gradually decreased and stabilized around 0.12 seconds. While there was a slight recovery due to the material's elasticity, the deformation remained high and relatively unchanged post-impact.

According to the Insurance Institute for Highway Safety (IIHS) [9], when floor displacement exceeds 300 mm, the affected area is rated "Poor" – a serious warning about the threat to the driver's survival space. The displacement exceeding this threshold at the footrest area indicates significant intrusion into the cabin, potentially causing severe injuries to occupants, especially to the legs and lower abdomen – vulnerable areas in frontal collisions.

From these results, it can be concluded that the simulated Chevrolet vehicle structure does not meet safety requirements for survival space in frontal collisions with rigid objects at 40 km/h. This highlights the urgent need to improve the design of load-bearing components at the front of the vehicle, reinforce the cabin floor system, and optimize both the material and structural geometry to better absorb and dissipate impact forces. Additionally, the introduction of controlled crumple zones and reinforcements in the floor area should be considered to reduce intrusion into the passenger cabin and enhance occupant protection in severe crashes.

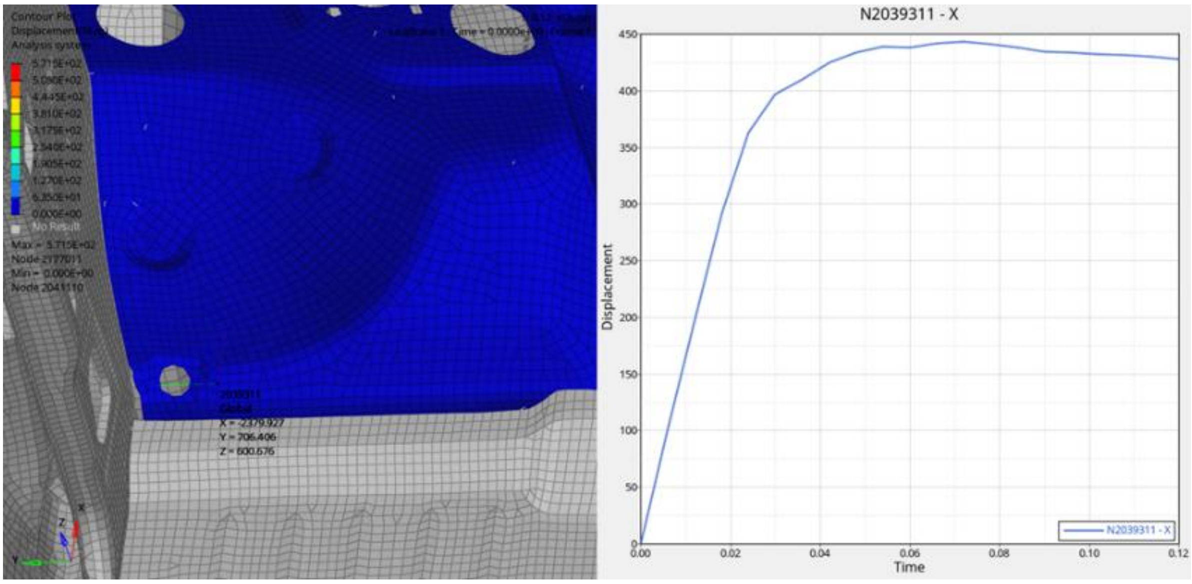


Fig. 9. Displacement graph of Node 2039311 along the X axis at 60 km/h

The displacement graph of Node 2039311 at 60 km/h shows a peak displacement of 443.05 mm at 0.072 seconds, slightly decreasing to 427.76 mm at 0.12 seconds. Compared to the 40 km/h impact, the deformation reduces more slowly due to the stronger force and insufficient material recovery time. The higher impact speed leads to greater and longer-lasting deformation, causing more severe structural damage to the vehicle.

According to IIHS standards [9, 10, 11], a displacement exceeding 300 mm at the driver's foot area falls into the "red zone," indicating a serious safety risk to the passenger compartment. The results confirm that the vehicle fails to ensure occupant survival space at both 40 km/h and 60 km/h, with a higher injury risk at increased speeds.

Comparing the two scenarios shows that increasing speed not only leads to greater deformation but also reduces the structure's recovery capability, emphasizing the need for improved design to enhance safety across various collision speeds.

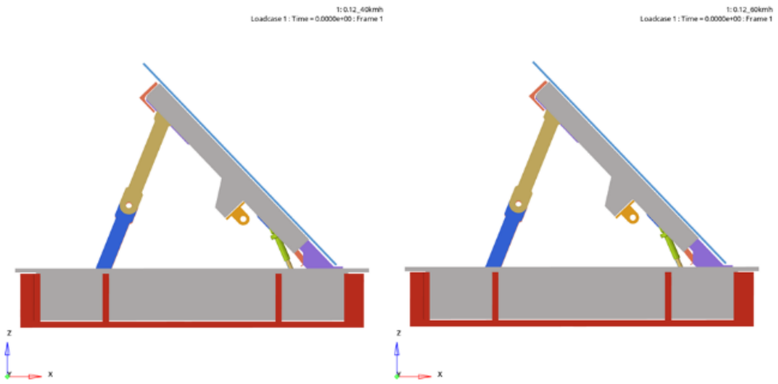
4.3. Barrier Assessment

In the crash simulation, the barrier is set in a fixed state, disallowing any movement, to ensure that the resisting force is entirely concentrated on the vehicle during the collision. This setup results in a sudden energy transfer from the vehicle to the barrier, causing significant deformation to the vehicle's frame structure and components such as the front bumper, engine compartment, and body. Since the barrier does not move or deform significantly, the collision energy is primarily absorbed by the vehicle.

In reality, barriers have the capability to absorb collision energy through deformation and displacement, which helps reduce the impact force on the vehicle. Therefore, simulating a fixed barrier may limit the accuracy of evaluating the energy absorption effectiveness of both sides. However, this method simplifies the problem and provides a stable condition for collecting data on displacement, deformation, and stress on the vehicle, even though it does not fully reflect the actual interaction response between the vehicle and the barrier under real-world conditions.

Tab. 4

Barrier model in two velocity cases



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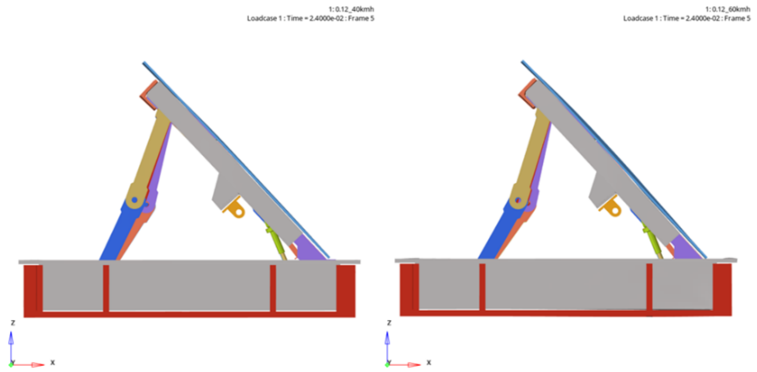
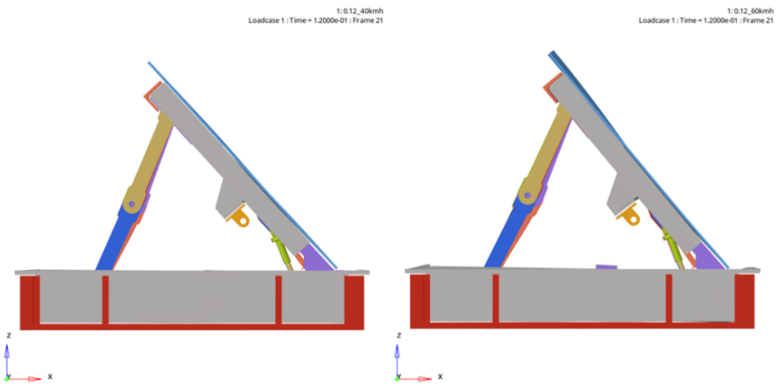


At time 0.024 s



At time 0.12 s

The crash simulation results show that the barrier post experiences direct impact and significant deformation when the vehicle crashes at a speed of 60 km/h. The strong impact force causes the post to bend and fold right at the initial contact point; despite being reinforced, it still undergoes considerable deformation. After the collision, the post's cap and base are pulled and displaced, leading to structural failure as the impact force exceeds the load-bearing capacity of the barrier.

The post serves as the primary energy-absorbing component of the barrier, thus undergoing the greatest deformation in the entire system, including bending, breaking, or cracking, depending on the force intensity and material properties. This deformation reflects the process of converting collision energy into internal energy and the barrier's ability to dissipate force throughout the crash event.

Therefore, the post is the main load-bearing part and the most severely damaged component of the barrier when the vehicle crashes at high speed. This results in significant structural changes and destabilization of the system's fixed points, reducing the overall protective effectiveness of the barrier.

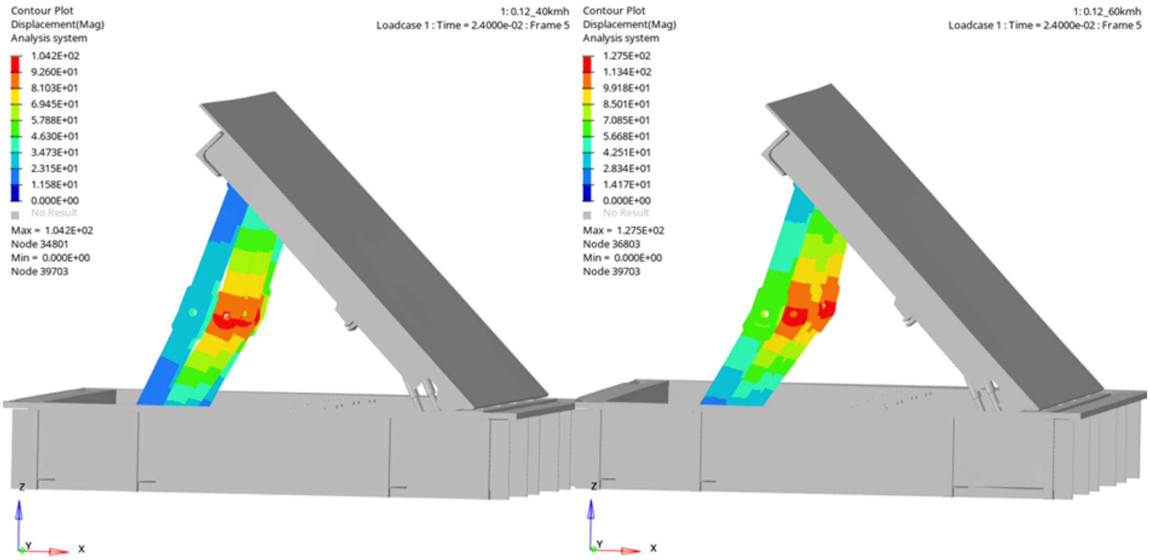


Fig. 10. Deformation of the strut at time 0.024 s in two cases

The greatest deformation during the collision occurred at the connection point between the two support beams of the barrier, where the vehicle's impact force was directly applied. This location concentrated the highest load, leading to significant structural deformation. At a speed of 40 km/h, the maximum deformation at this point reached 104.2 mm, indicating bending and shape change caused by the impact load.

When the speed increased to 60 km/h, deformation at the same point rose noticeably to 127.5 mm. The stronger force over a shorter period resulted in more kinetic energy being converted into internal energy, leading to greater structural deformation.

The difference in deformation levels between the 40 km/h and 60 km/h crash scenarios clearly reflects the effect of collision speed on the barrier's structure. This also underscores the importance of designing protective systems like barriers to withstand impact forces at various speed levels. Barriers need to be optimized to absorb energy effectively without sustaining severe damage in high-speed crash situations.

The stress distribution on the support beam is a crucial indicator for evaluating the barrier's load-bearing capacity during a collision. At a speed of 40 km/h, the maximum stress reaches 414.6 MPa, while at 60 km/h, this value increases to 432.6 MPa due to the stronger impact force and higher kinetic energy.

Although the stress remains within the material's load-bearing limit – ensuring that the support beam does not fail immediately and still performs its function of absorbing and dissipating energy – the increase in stress can lead to plastic deformation or material fatigue over time. This affects the support beam's ability to recover and its durability in subsequent collisions, especially at higher speeds.

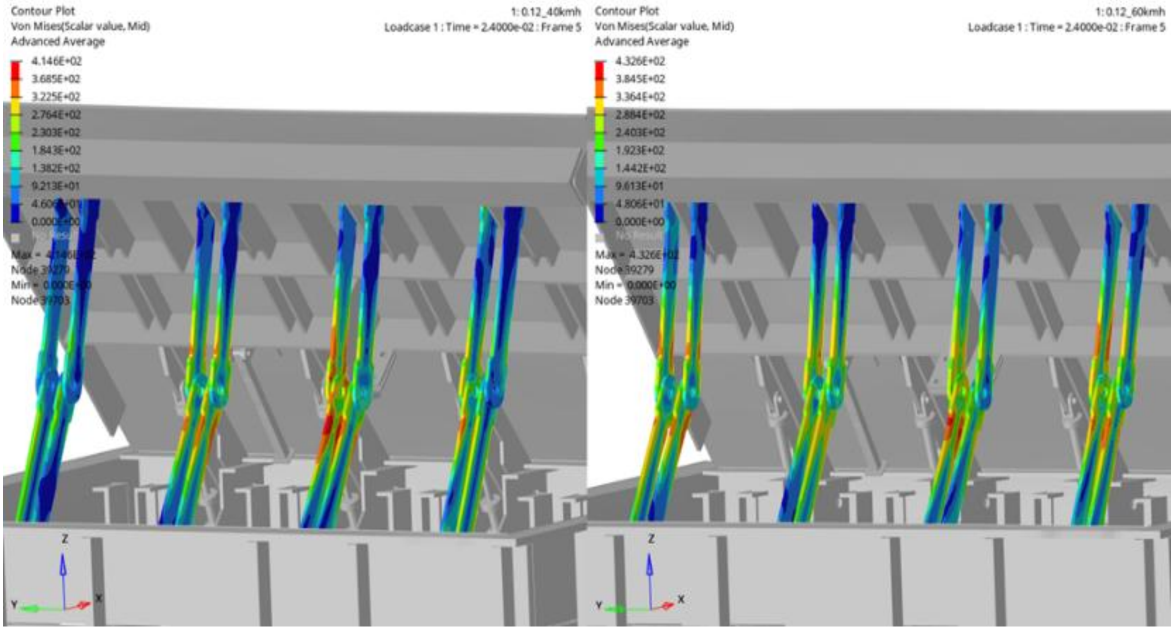


Fig. 11. Stress distribution of strut at time 0.024 s in two cases

Comparison between the two speed levels shows that increased collision speed not only raises the impact stress but also accelerates material degradation due to fatigue deformation. Therefore, optimizing the material and design of the support beam is essential to ensure both protective performance and long-term durability under various crash conditions.

5. CONCLUSION

Amid the growing threat of vehicle-based terrorist attacks targeting public areas and critical infrastructure, the development of barrier systems capable of effective interception and flexible deployment has become an urgent necessity. This study developed a finite element model to simulate a frontal collision between a heavy-duty truck and an emergency vehicle barrier system, thereby providing a comprehensive assessment of the proposed system’s energy absorption capacity and structural integrity.

Simulation results indicate that the proposed barrier structure is highly effective in limiting cabin intrusion, maintaining displacement within safety thresholds under both tested scenarios. To evaluate the level of intrusion into the driver compartment, the research team employed the IIHS (Insurance Institute for Highway Safety) standard. Energy analysis shows that most of the vehicle’s kinetic energy was converted into internal and interaction energy, confirming the system’s effective impact absorption capability and the reliability of the simulation model. Additionally, the stress and deformation distribution at major load-bearing areas provides a basis for structural optimization to enhance post-impact durability.

Compared to conventional automatic bollard-type barriers, which require fixed underground foundations and complex operating systems, the design presented in this study demonstrates clear advantages in mobility, rapid deployment, and adaptability to various terrain conditions. The system not only fulfills the function of stopping unauthorized vehicles but also improves occupant safety during impact scenarios.

In summary, this research has developed a reliable evaluation approach for emergency barrier systems through high-fidelity numerical modeling, integrating international safety standards and flexible structural design, thereby offering a technically feasible solution for real-world application. In the next phase, the authors will focus on fatigue analysis to assess the operational lifespan of the system under repeated impact conditions, aiming to ensure long-term performance and operational reliability.

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