J. Eng. Technol. Sci., Vol. 54, No. 5, 2022, 220511

A Study on Small Vehicle Structure in Rear Under-Ride Impact by Using A CAE Based Methodology

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Highlights:

- Simple model for truck with Vietnamese current rear protection device was built.
- Hatchback to truck full rear impact modeling with different overlap percentages (25%, 50% and 100%) and different speeds.
- Evaluation of the crash for vehicle structure base on IIHS rating.
- Optimizing the design of the rear bumper of the truck to improve the safety of small cars.
- Optimizing the design of the hatchback body structure to improve the safety in rear-end collisions with large trucks.

Abstract. This study simulated and evaluated the safety of a small car structure in a collision with the rear of a truck. The parameters of bumpers currently used in Vietnam were employed to build a model of the rear truck bumper. The setting of simulation conditions was based on the NCAP (New Car Assessment Program) crash test. According to actual crash conditions, a collision simulation was performed with different vehicle speeds from 40 to 60 km/h, corresponding to the case of a passenger vehicle moving in a city colliding with a truck standing still. In addition, the percentage of rear-end collision was also taken into account, just like in real-world collisions, at 25%, 50%, and full rear impact. The simulation results were analyzed and evaluated according to the IIHS rating (Institute Insurance for Highway Safety). The results from different case studies showed that the rear bumper typically used on trucks is only safe for passenger cars in a collision at a low speed of 40 km/h and that in a collision at a higher speed will affect the passenger's safe space and cause high injuries and casualties. Therefore, it is necessary to improve safety by optimizing the rear bumper design and the frontal structure of the small car chassis.

Keywords: *CAE; hatchback; under-ride; rear impact; vehicle structure.*

Received January 4th, 2022, Revised May 29th, 2022, Accepted for publication June 29th, 2022.
 ISSN: 2337-5779,
DOI : 10.5614/j.eng.technol.sci.2022.54.5.11

1 Introduction

Today, due to the increasing demand for travel and freight transportation, road traffic accidents occur more frequently, and the level of danger is increasing as well. Collisions are common and can be classified into three types: frontal collisions, side collisions, and rear collisions, where the latter are the most common. Many studies and publications, for example [1,2], have studied the bus frame structure in frontal collisions in order to improve passenger safety when a collision occurs. For passenger cars, many articles have been published on the study of a collision model with a fixed barrier, partially to analyze and evaluate the damage to the car as well as the safety of the passengers inside the vehicle. Based on the research results in [3-5], a small frontal collision is a very dangerous type of collision that has a great impact on the passenger's safe space. As a result, many studies have been conducted to improve the small car chassis in order to improve passenger safety in the event of a collision, such as Ref. [6], which optimized the design of the bearing frame head section by changing the bearing tube shape. Ref. [7] showed that an optimal design of the chassis structure by varying the thickness of the parts can improve occupant safety. Passengers are also at risk when frontal collisions from the rear occur, in particular, in collisions between a passenger car and a large truck. A collision simulation between a car and a truck from the rear with and without bumpers was performed in [8]. The results showed that the rear bumper design needs to be improved to enhance the safety of small cars when a frontal rear-end collision occurs.

In order to reduce rear-end collision accidents, Ref. [9] developed a system to assist drivers to avoid chain collisions, because rear-end collisions between a small car and a large truck are extremely serious, threatening the lives of passengers in the passenger car. Therefore, many studies have been done to improve the truck rear bumper. For example, [10] optimally designed the bars in the rear bumper.

Simulation is a widely used method to shorten experimental time as well as costs. Therefore, it has been used by many authors for research, for example [11,12], who used a finite element model to analyze the rear bumper structure during a collision. A synthesized survey and evaluation to come up with a plan to improve the rear bumper of large trucks was carried out in [13] and [14].

The research content of this article focuses on a truck rear bumper design that is popular in the market in Vietnam. Based on the surveyed parameters, the truck rear bumper was modeled in the CATIA software. Then the Hypermesh software was used to mesh the parts and assign the material properties. Next, a collision simulation was performed with a passenger car model using the LS-DYNA software [15].

The research method used in this study was an actual survey on the current situation of truck rear bumpers in Vietnam to build a rear bumper finite element model of the truck rear bumper for the crash test simulation. The results were analyzed specifically for a number of cases. Finally, the conclusion of this paper suggests that this research can be further extended to improve rear crash safety by improving the truck rear bumper design.

2 Methodology

2.1 Vietnamese Current Rear Under-Ride Guard Analysis

Currently, most vehicles in Vietnam are not required to have rear bumpers. For this reason, most car owners equip their cars with rear bumpers themselves. However, these bumpers do not follow any standards except that the length and width of the rear bumper installed must not exceed the length and width of the rear bumper according to the original design of the vehicle. In this article, a survey on rear bumpers of different trucks was conducted at a registration center in Ho Chi Minh City.

The survey results showed that there are many different styles of bumpers on trucks, but the durability and safety of these bumpers in the event of a collision have not been tested and evaluated for safety. In the actual survey of 100 trucks registered at this center, there were bumpers with the structure as shown in Figure 1.

The Vietnam registry does not check the quality of the rear bumpers and some cars without a rear bumper are still on the road. Or they have a rear bumper but it is not of good quality or it has been damaged during use. It is not safe when a small car collides from the rear, as shown in Figure 2.

It is for this reason that this study surveyed popular bumpers used on existing trucks in Vietnam, as depicted in Figure 3. Then we took the parameters to model a truck rear bumper for use in the simulation of a collision from the back with a passenger car.

There are several reasons why large trucks fitted with a rear bumper are still not safe: because the rear bumper was not designed to ensure the quality of use over a longer period, because it has been damaged, or because the rear of big trucks is long, so attaching a low rear bumper affects the exit angle after the vehicle passes over a high slope, making it prone to collision with the road surface.

Isuzu with roof. Weight 11 tons; 6750 mm x 2350 mm x 2060 mm; Hc = 735 height from ground to crate 1.1 m; rear port 1 m to 80 cm long; body: iron box 90 x 30 mm.

Isuzu QKR L1. Truck body width 1700 mm; rear bar length L2: 1000 mm; chassis L3 800 cm; H1: 750 cm; H2: 600 cm; H3 150 cm, D 7 mm.

KIA K165. Weight 4765 kg with body 3500 mm x 1670 mm x 1700 mm; distance between the body and the ground 95 cm; rear port: 1 m long, 35 cm high, 60 cm from the ground using V60 2 mm iron.

Isuzu with roof. Weight 11 tons with body 6750 mm x 2350 mm x 2060 mm; Hc = 735 mm; height from ground to crate 1.1 m; rear port 1 m long to 80 cm; body: iron box 90 x 30 mm.

Figure 1 Actual registration station survey on types of truck rear bumper designs used in Vietnam.

Figure 2 Field survey of trucks with and without rear bumper on the Trung Luong Expressway.

2.2 Design Rear Under-Ride Guard Model

This paper is based on an actual survey at an automobile registration station, as shown in Figure 1, to select the type of rear bumper most commonly used on existing trucks in Vietnam. Then we proceeded to build a 3D model of the rear bumper of the truck based on the actual parameters of the vehicle depicted in Figure 3.

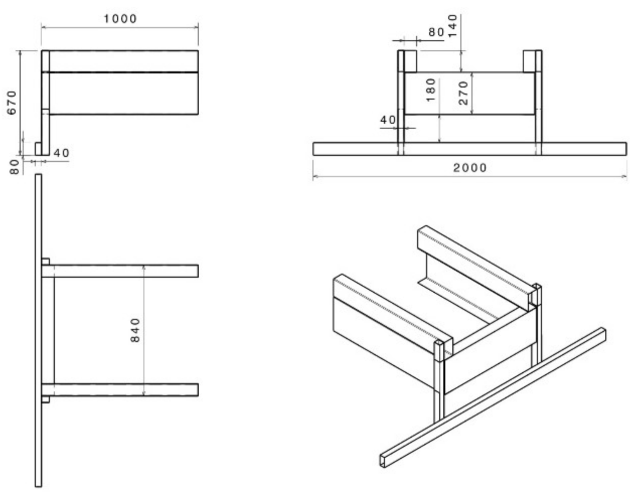


Figure 3 3D drawing and truck rear bumper parameters (mm).

The rear bumper structure consists of many parts assembled together, where the chassis of the truck is kept the same, as shown in Figure 4. The chassis includes a part (no. 1) to support the upper frame and is mounted on the longitudinal chassis (no. 2) and the horizontal chassis (no. 7). The rear bumper part (no. 4) is linked to the chassis through a connecting rod (no. 3). To further reinforce the bumper mounting, bearing bowls are used (no. 5 and 6). After completing the rear bumper model with the CATIA software, the Hypermesh software was used to mesh and assign materials and attributes to the details. The completed truck rear bumper finite element model is shown in Figure 5. The parameters of each detail, such as materials and element dimensions, are shown in Table 1.

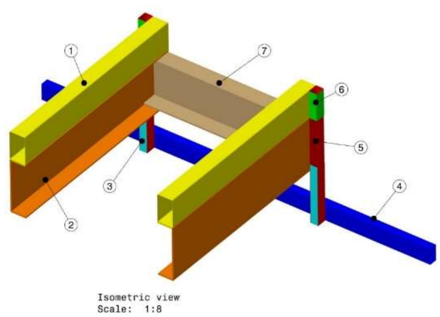


Figure 4 Structure of the rear truck bumper.

When designing a truck rear bumper, one should keep in mind the following dimensions: the length of the connecting rod (no. 3) and the width of the rear bumper bar (no. 4) in Figure 4, designed according to the aforementioned Asian standards R 58 referred to in [8]. Based on this standard, there are boundary conditions when designing a truck rear bumper. Specifically, the distance from the ground to the rear bumper must be at least 550 mm. The width of the rear bumper is not allowed to be wider than the rear axle of the vehicle. The protrusion of the rear bumper should not be more than 2.5 mm above the rear of the truck.

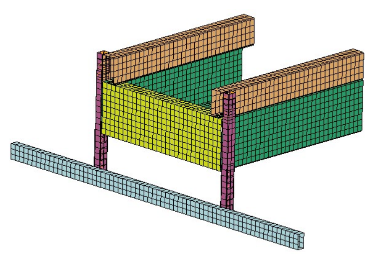


Figure 5 FEM model of the rear of the truck.

Table 1 List of components of the rear truck model.

ID	Components	Thickness (mm)	Material	Element size (mm)
1	Body support bar	3	Mat 24	20
2	Vertical chassis	7	Mat 24	30
3	Connecting bar	3	Mat 24	10
4	Cross bar	1.4	Mat 24	10
5	Lower reinforcement	3	Mat 24	10
6	Upper reinforcement	3	Mat 24	10
7	Horizontal chassis	7	Mat 24	30

In this paper, the simulation method was mainly based on computer models. Therefore, the materials used in the model were mainly based on existing materials in Vietnam to make truck rear bumpers, as surveyed in Section 2.1. The properties of these materials are referred to in [6] with the following properties: mass density RO = 7.85E-09 (kg/mm^3), E = 2.05E+05 (GPa) Young's modulus, PR = 0.3 Poisson's ratio, SIGY = 155 (MPa) Yield stress and in LS-DYNA software, these parameters correspond to materials with MAT 24.

2.3 Hatchback to Truck Rear End Impact Modeling

In this research, in order to reduce the calculation time of the computer, the truck rear bumper model shown in Figure 5 was used instead of a full truck model. The small vehicle hatchback models has been tested and evaluated by [12]. The complete model for rear-end collision studies between a hatchback and a truck is shown in Figure 6.

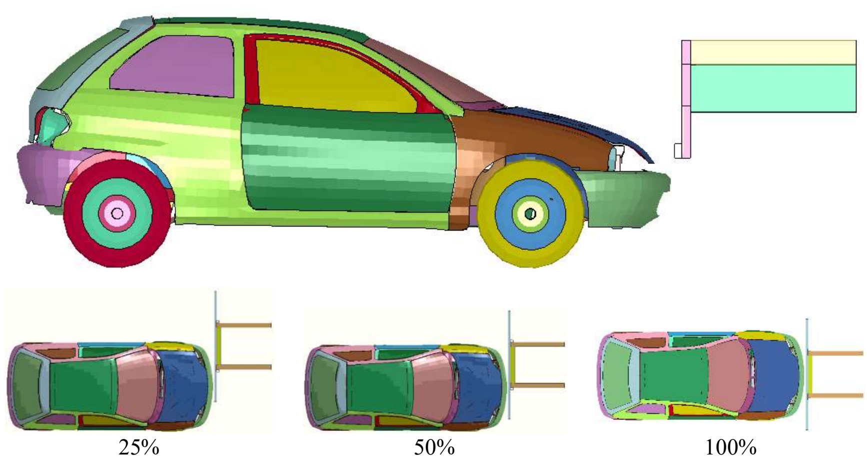


Figure 6 Hatchback to truck full rear impact modeling in left and top view with different overlap percentages (25%, 50% and 100%).

Based on the CMVSS No. 223 [16,17], the full hatchback vehicle model during rear impact was set. In this case, the velocity of the vehicle model was $V_1 = 40$ to 60 km/h and the velocity of the truck was $V_2 = 0$, which is the same situation as standstill, where the rear of the truck becomes a rigid barrier.

The finite element method is commonly used in solving structural problems. However, this calculation takes a long time for design optimization. In this study, it was assumed that the truck rear bumper structure model was rigid and did not absorb energy at impact, making the collision very severe depending on different conditions. When a vehicle collides with a truck from the rear, the equation for conservation of energy is written as follows:

$$\frac{1}{2}\mathrm{m}v_0^2 = E_{vint} + E_{vke} + E_{truck} \tag{1}$$

where v_0 is the vehicle's initial velocity,

m is vehicle mass,
E_{vint} is the absorbed energy,
E_{vke} is the final kinetic energy,
E_{truck} is the energy absorbed by the rear bumper or truck chassis.

Assume that the $E_{truck} = 0$ in this research is a rigid barrier.
In this case, we can rewrite the energy equation as:

$$\frac{1}{2}m'v_0^2 = E_{vint} + E'_{vke} \tag{2}$$

here, m_0 is the equivalent vehicle mass and E'_{vke} is the kinetic energy of the vehicle post-crash. It now follows from Eqs. (1) and (2) that

$$m' = \mathrm{m} - \frac{2}{v_0^2}\left(E_{truck} + E_{vke} - E'_{vke}\right) \tag{3}$$

Assuming $E_{vke} = E'_{vke}$, the above relation becomes

$$m' \approx m - \frac{2}{v_o^2}\left(E_{truck}\right) \tag{4}$$

According to [9-11], the energy absorbed by the barrier in the case of vehicles with different masses makes no difference.

Energy absorption, E_a, is a main criterion for structure design in crashworthiness. To find the particular value, E_a is computed by integration of the load-displacement curve as follows:

$$E_a = \int_0^{\delta_{max}} P(\delta)d\delta \tag{5}$$

where $P(\delta)$ is a prompt impact load, δ and δ_{max} are the compressing displacement and the maximum compressing displacement, respectively. The mean impact load can be found from Eq. (5):

$$P_{mean} = \frac{1}{\delta}\int_0^{\delta} P(\delta)d\delta \tag{6}$$

In crashworthiness, the mean crushing load is used as a measurement of the energy absorbing ability of a structure in relation to a specific axial displacement. The top peak load is also a sign that the load initiates crumpling and the energy absorption process begins. In practical situations, the mean crushing and initial peak load are the essential parameters in evaluating the energy absorption.

The hatchback model used in this paper is similar in size to small cars in common use in Vietnam. The specific vehicle model information is as follows: overall vehicle dimensions (length, width, and height) are 3750 x 1590 x 1430 mm; the model has a wheelbase of 2730 mm; the ground clearance is 160 mm; the wheel diameter is 310 mm; and the weight is 865 kg.

2.4 Rear Impact Simulation Results and Discussions

In this study, various cases of rear-end collision between a passenger car and a truck are presented, as depicted in Table 2. The car's speed was varied between 40 and 60 km/h, corresponding to the case when a vehicle moves in a city in a densely populated area or in a suburban area without a median line. The percentage of rear-end collision was also changed to match real-life crash situations, such as 100% full collision, 50% half collision, and 25% partial collision.

Table 2 The results of different cases of hatchback to truck rear impact.

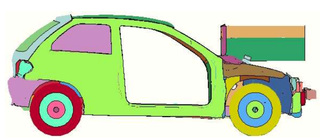
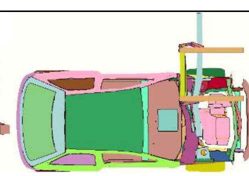
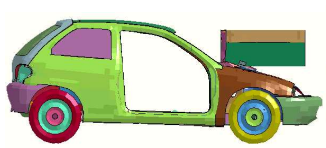
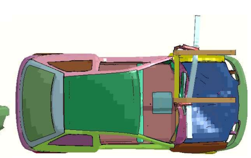
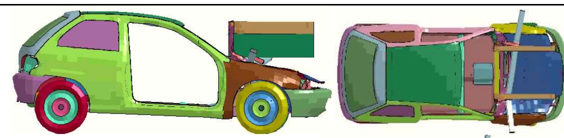
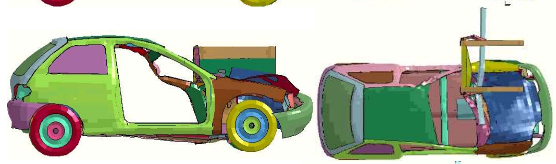
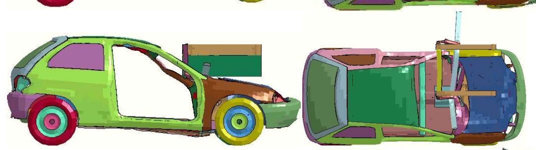
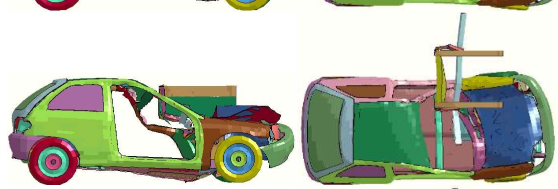
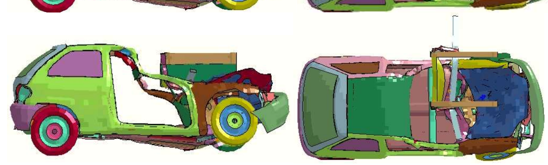
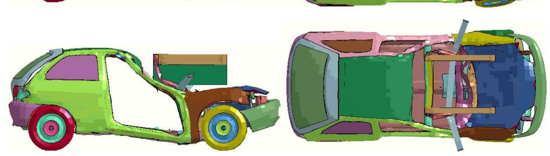
Case	% Rear impact	Vehicle speed (Km/h)	Post-crash results	
1	25	40		
2	50	40		

Table 2 Continued. The results of different cases of hatchback to truck rear impact.

Case	% Rear impact	Vehicle speed (Km/h)	POST-CRASH results
3	100	40	
4	25	50	
5	50	50	
6	100	50	
7	25	60	
8	50	60	
9	100	60	

In the cases mentioned above, the truck bumper model is presented as a full-truck model and is stationary. To evaluate the safety of the hatchback sub-frame, the present study referred to the IIHS assessment standards with measurement points as described in Table 3, including the main sub-frame positions, such as footrest and brake pedal, points on the control panel, the seats and the door frame.

The post-collision simulation results are shown in Table 2. In the 9 proposed research cases, the post-collision results show that the percentage of rear-end collision has a great influence on the chassis structure and safety space of the occupants. Specifically, in the case of a collision with a small overlap (25%) from the rear is the most serious, affecting the passenger's safety space, especially in the speed range of 50 and 60 km/h. In the case of a 50% overlap in rear-end collision, the impact on the passenger's safe space is slightly reduced compared to the 25% collision, but the passenger's safe space is still not guaranteed at the speed range 50 and 60 km/h. The structure of the car frame in the two cases mentioned above is heavily deformed, especially the A pillar and the body frame. In the case of a 100% overlap full collision at a low speed of less than 50 km/h, the safe space is guaranteed, but at a speed of 60 km/h, the chassis is deformed and intrudes into the occupant safety space.

In Figure 7 shows a comparison of the energy absorbed in different cases of rear-end collisions between the car and the truck. Based on this energy graph, we can observe that in cases 1, 2 and 3, a vehicle moving at a speed of 40 km/h when colliding with a truck from behind, the absorbed energy level in the 25% case is higher than in the other two cases. This is similar to the cases of 50% and 100% overlap collisions. We infer that the amount of absorbed energy increases as the vehicle speed increases.

Table 3 List of measure points on the hatchback model.

Measure point	Components	Nodes ID
1	Reference N1	39072
2	Reference N2	39086
3	Reference N3	39079
4	Footrest	39323
5	Left toe pan	39055
6	Center toe pan	39075
7	Right toe pan	39118
8	Brake pedal	39054
9	Left instrument panel	38036
10	Right instrument panel	39140
11	Door	47249
12	Seat mount N1	40483
13	Seat mount N2	40477
14	Seat mount N3	40351
15	Seat mount N4	40354

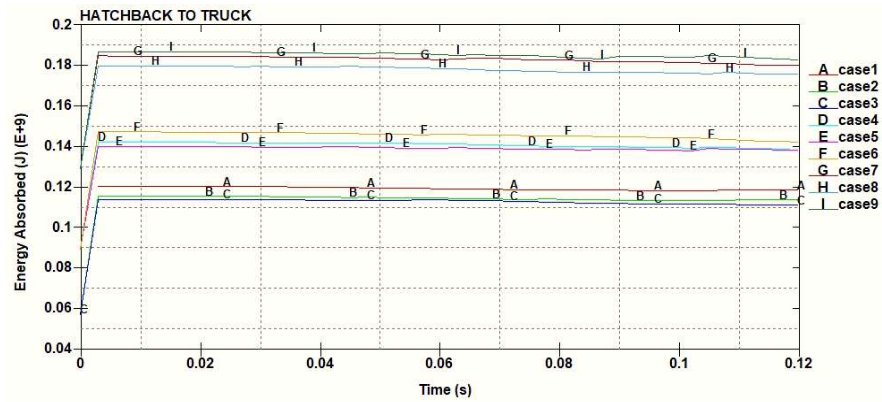


Figure 7 Comparison results of energy absorbed for the different cases.

Figure 8 shows a comparison of the displacement of the passenger car model in different collisions in terms of speed as well as collision percentage. The results in the graph show that the faster the car moves during the collision, the larger the displacement will be. Specifically, within the same speed range there is not a large difference between collisions at different percentages. During the first 0.03 s due to a collision with the rear bumper of the truck, the displacement increases gradually when the rear bumper is deformed and is no longer in contact with the front of the car. During the remaining time, the displacement increases linearly due to not contacting any vehicle components.

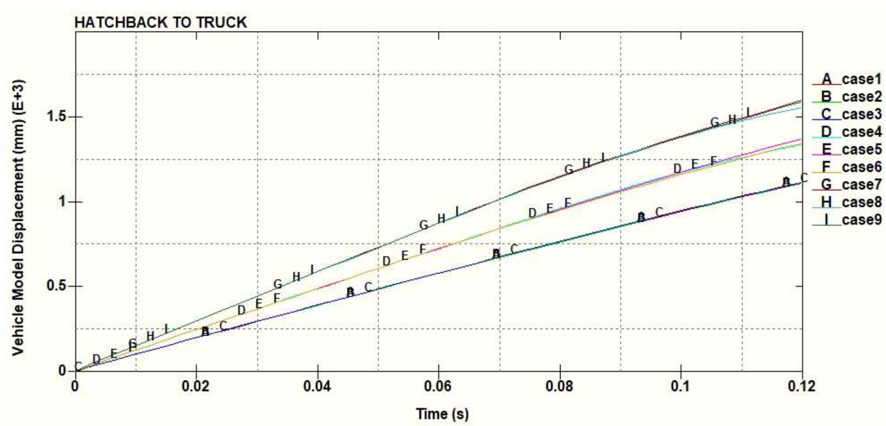


Figure 8 Comparison results of displacement for the different cases.

Figures 9 and 10 are divided into 3 separate zones, A, B and C. Zone A is the area where the car collides with the rear bumper of the truck; the rear bumper is completely deformed. Then we switch to zone B, which is the area where there is almost no contact between the passenger car and the rear bumper of the truck because the engine compartment is lower than the truck frame. When the passenger car moves to the end of the engine drill part, it starts to collide with the truck frame at the A pillar and the passenger car frame. At this time, we move to zone C, where most of the impact on the car's chassis structure and the passenger's safe space occurs.

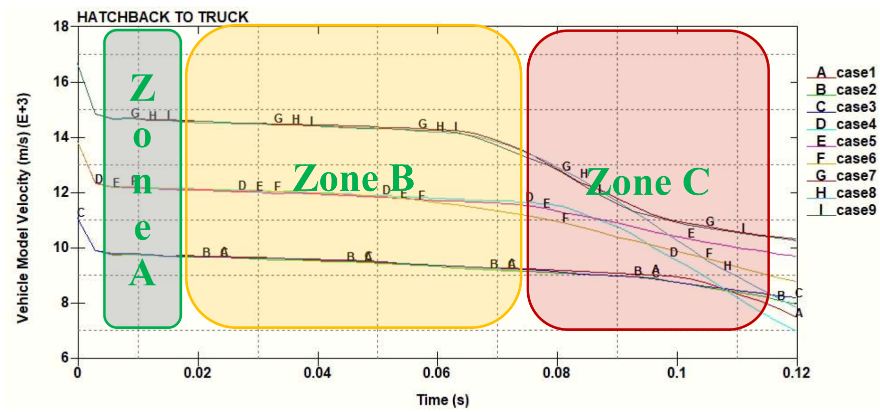


Figure 9 Comparison results of velocity for different cases.

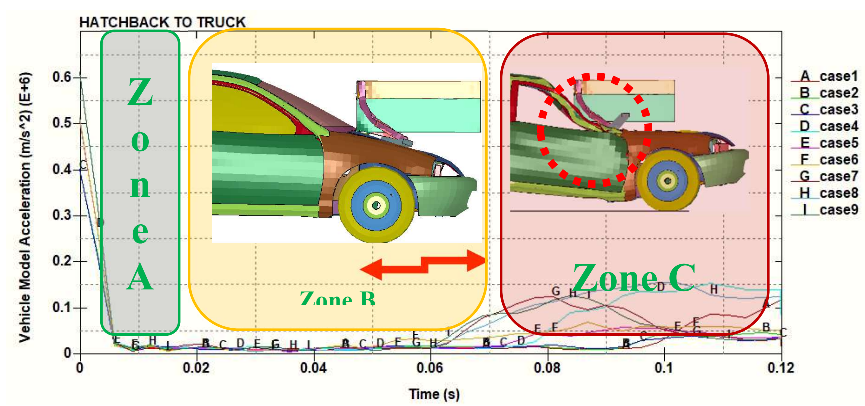


Figure 10 Comparison results of acceleration for different cases.

The results of comparing the speed of the passenger car are shown in the graph in Figure 9. We can see that in zone A, the car starts to collide with the rear bumper due to the reaction from the bumper, causing the vehicle speed to decrease suddenly. After that there is no resistance, so the speed decreases slowly and goes all the way to zone B. That is why we see in the graph of zone B that the speed decreases very slowly in all cases. At the end of zone B, the A pillar area of the car starts to collide with the truck's frame, leading to a rapid decrease in speed due to the drag from the truck's frame.

The comparison results of acceleration for different cases upon collision are shown in Figure 10. This graph shows when a change in velocity leads to a change in acceleration. Specifically in zone A and zone C, there is a large change in acceleration because in these two regions, the car and the truck collide. The acceleration in zone B shows almost no change.

Based on IIHS assessment of the safety of the chassis structure for passengers inside the vehicle and taking the values at the measurement points in Table 3, we can draw the sub-frame deformation graph and evaluate the safety according to the IIHS standards described in Figure 11. Based on this result, we can evaluate the degree of safety. The safety of the sub-frame is only guaranteed when the vehicle moves at a low speed of 40 km/h. When the vehicle moves faster than this speed, the rear bumper of the truck does not meet the stiffness requirements, leading to a direct impact on the chassis, causing the deformation to encroach on the passenger's safe space. Therefore, according to this assessment, passenger safety is not achieved in the speed range above 40 km/h.

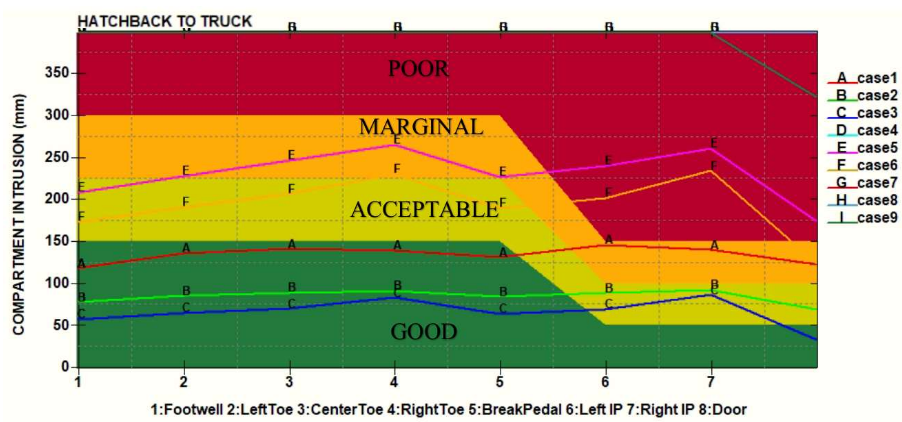


Figure 11 Comparison results of compartment intrusion and rating for different cases.

When the car moves at a speed greater than 40 km/h and collides with the rear of the truck, it causes the truck's rear bumper to deform, especially vertical connecting rod no. 3 and horizontal bar no. 4 as described in Figure 4. The rear bumper is deformed, resulting in a significant decrease in bumper stiffness. Also, the rear bumper of the truck is no longer able to stop the car, resulting in the car getting under the truck. The result can be seen in Table 2. The stiffness of the rear bumper has to be increased to improve the condition of the small car under-riding the truck. The rear truck bumper plays a very important role in reducing fatalities when a collision occurs between a car and a truck from behind.

2.5 Results Verification

The accuracy of the author's truck rear bumper model was validated against actual accident results in Vietnam. Figure 6 depicts two cases where the author had data to perform model checking: a 100% total collision and a 50% collision between a car and a truck from the rear. Both passenger cars had the same dimensions and specifications as the model car in these two cases, and the truck had the same rear bumper structure as the rear bumper model with the specifications described in Table 1.

The truck was stationary in both cases, and the car approached it from behind at a speed of 40 km/h based on the police accident report. In both cases, there were no injuries as a result of the collision. Only the front end of the small cars was damaged, while the truck's rear was unaffected. Figure 12 shows a comparison of the simulations and the actual results. According to the IIHS panel evaluation, the simulation and experimental results agree. As a result, the model's simulations yielded satisfactory results.

50% overlap real car-to-truck under-ride accident

Simulation result

Figure 12 Comparison of real accidents in Vietnam and simulations of 50% and 100% rear impact.

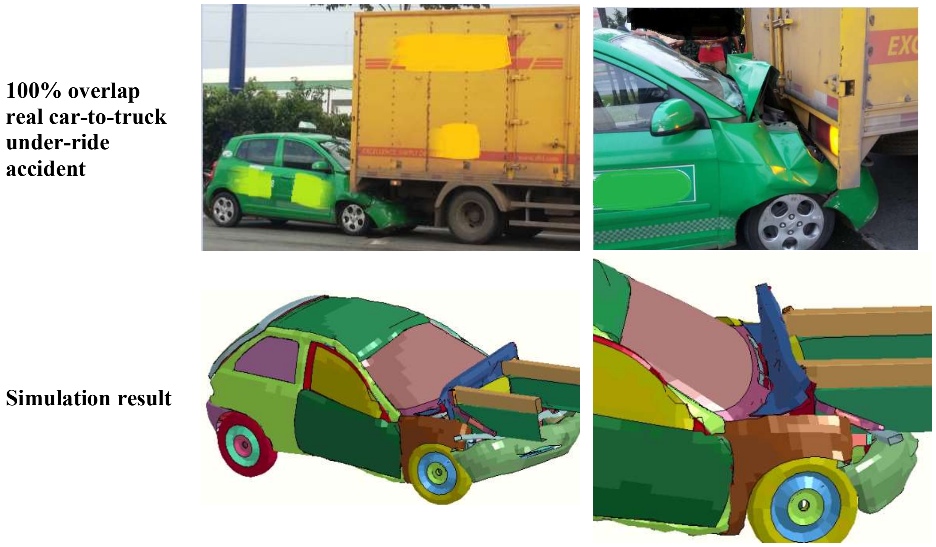


Figure 12 Continued. Comparison of real accidents in Vietnam and simulations of 50% and 100% rear impact.

3 Conclusions

In this study, a truck rear bumper was modeled that is commonly used on trucks in Vietnam. Also, this paper simulated the collision between a small hatchback car and this truck rear bumper. Based on the results of the crash simulation, the following conclusions can be drawn: with the current design, the rear bumpers only sufficiently protect hatchbacks in collisions at low speed (below 40 km/h). At this speed, the current truck rear bumpers meet crash safety at different collision percentages, such as 25%, 50%, and 100%. However, when the hatchback travels at a higher speed, from 50 km/h to 60 km/h, the rear bumper of the truck does not meet the safety requirements for cars in the event of a rear-end collision, leading to the car getting under the truck. The safety of the car after collision is assessed as poor.

In the current situation in Vietnam, most of the rear bumpers of trucks are self-designed and non-standard, which leads to the bumper structure not being durable enough for rear-end collisions, causing small vehicles to collide with the truck's frame. The current small vehicle structure can lead to critical accidental situations for passengers, particularly for the driver.

A development of this research in the future will be to optimize the design of the rear bumper of the truck to improve the safety of small cars. Secondly, optimizing the design of the hatchback body structure to improve the safety in rear-end collisions with large trucks.

A limitation of this paper was that only one numerical simulation method was used to simulate rear-end collisions of small cars and large trucks. The truck's rear bumper model was not tested in practice to evaluate the accuracy of the model. Due to time constraints, only one type of bumper in use on existing trucks on the market was modeled to perform the crash simulations with.

Acknowledgement

This work was supported in part by the research program of HUTECH University. We also acknowledge the support of time and facilities from Ho Chi Minh City University of Technology (HCMUT), and VNU-HCM for this study.

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