

Performance of Rear Under-Ride Protection Device (RUPD) During Car to Heavy Truck Rear Impact

Hasan Muhamad Abid, Eida Nadirah Roslin, Rifqi Irzuan Bin Abdul Jalal



Abstract: Passenger vehicles crashes with Under-ride rear end of heavy vehicles result in fatal injuries due to sliding of passenger car beneath heavy trucks frames. This is related to an improper structure design of rear under-ride protection device (RUPD) that is mounted to the rear of the heavy vehicles. The design of effective RUPD must be taken into consideration during the design stage of truck chassis frame. There are two types of analyses used to investigate the performance of trucks RUPDs such as experimental tests and numerical analysis or simulation. This review aims to discuss the available research methods on the performance of RUPDs during car to heavy truck rear impact, and record their lack and potential areas. Moreover various crash velocities will be discussed for the car-to-heavy truck rear impact tests, as well as different scales of car frontal crash tests are included. Furthermore energy absorption capability of different truck RUPDs designs will be presented in this paper.

Keywords: Rear under Ride Protection Device (RUPD); Car to Heavy Truck Rear Impact; Energy Absorption.

I. INTRODUCTION

Since the beginning of the automotive history, people feared the consequences of accidents involving automotive which can cause severe injuries to passengers, other motorists, pedestrians and surrounding. These injuries, while some might heal over time, cause significant damage to self or properties. However most of these injuries cause fatality and permanent damage that rise people’s attention to the safety features of the vehicles.

When a small car crash the rear of a heavy truck, the car slides under the truck frame which cause intrusion into the car passenger zone and lead to fatal injuries of the occupants, see Fig. 1.

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Crashes fatality percentage was estimated 30% to 40% of deadly accidents involved cars crashed at the rear of heavy trucks [1].



Fig. 1 Car to truck rear impact with sever passenger compartment intrusion [1]

The poor design or, in many cases, absence of rear under ride protection device (RUPD) attached to the rear end of trailers, semi-trailers and heavy vehicle can cause fatal injuries or death of car occupants that crashes with their rear end [2]. Therefore there is a need for design improvement for the existing rear under ride protection device of heavy trucks to enhance the crashworthiness of the car-to-heavy truck rear impact.

Survey of Trucks Involved in Fatal Accidents (TFIA) was conducted by University of Michigan Transportation Research Institute (UMTRI) in collaboration with National Highway Traffic Safety Administration of U.S.A. (NHTSA) for years 2008 and 2009. The study focused on the amount of vehicles striking truck and slid under the rear frames of trucks as shown in Fig. 2.

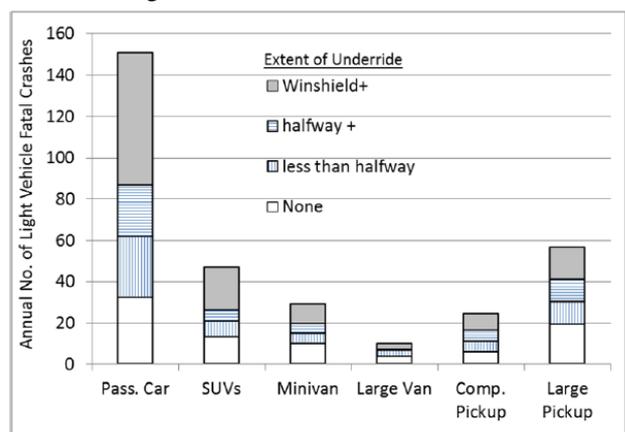


Fig. 2 Fatal accidents of light vehicles striking trucks and trailers rear ends [3]

The categorizations were beyond the windshield base, beyond half way, less than half way up to the hood and no under-ride. The most severe one was beyond the windshield base as it resulted in passenger compartment intrusion (PCI).

The survey showed about 319 fatal accidents of light vehicles to rear ends of trucks and trailers occurred annually and about 36% resulted in PCI. Large vans and pickups did not slide under trucks frames as compared to passenger cars but due to crash high speed and very short front end that resulted in PCI.

There are standard requirements for rear under-ride protection device such as the Canadian Motor Vehicle Safety Standard (CMVSS) No. 223 for light vehicles impacting rear end of trucks at speed of 56 km/h (35 mph). This regulation ensures RUPDs have strength and energy absorption capability to avoid PCI. The European standard, Economic Commission Europe ECE R.58 requires that during rear impact (35 mph) the distance between RUPD and rear extremity of trucks not more than 400mm, but there is no specific energy absorption requirement. NHTSA published Federal Motor Safety Standard (FMVSS) Nos. 223 and 224. FMVSS No. 223 specifies performance requirements of trucks RUPDs, and FMVSS No. 224 requires all new trailers and semitrailers weighing 4536 kg or more of gross vehicle weight rating (GVWR) must be equipped with a rear guard as specified in FMVSS No. 223 [4][3].

Table 1 presents a comparison of trucks RUPDs requirements in Europe, Canada and U.S.A. the comparison results shows that in Canada, the RUPDs have more strength compared to ones in Europe and U.S.A. The ECE R.58 used in Europe is applied to single unit truck but not applicable for Canada and U.S.A requirements.

The aim of this paper is to review all available methods used to investigate the performance of RUPDs during car to heavy truck rear impact. Experimental tests and numerical analyses are two significant methods that have been reported in this research area.

Table. 1 RUPDs requirements comparison in U.S.A., Canada and Europe [4]

Requirement	U.S.	Canada	Europe
Applicable standards	FMVSS No. 223/224	CMVSS No. 223	ECE R.58
Applicable vehicles	Trailers	Trailers	Trailers and SUTs
Geometric requirements in unloaded condition			
Ground clearance	560 mm	560 mm	550 mm
Longitudinal distance from rear extremity	305 mm	305 mm	NA
Lateral distance from side of vehicle	100 mm	100 mm	100 mm
Quasi-static load tests			
Point load at P1 (outer edge of guard)	50 kN	50 kN	25 kN
Point load at P2 (center of guard)	50 kN	50 kN	25 kN
Point load at P3 (at the guard supports)	100 kN with no more than 125 mm displacement, 5,650 J energy absorption	NA	100 kN with distance of rear impact guard from vehicle rear extremity of 400 mm after test.
Distributed load	NA	350 kN with no more than 125mm displacement and 20,000 J energy absorption; guard ground clearance less than 560 mm after test.	NA

Fig. 3 demonstrates the requirements of rear impact guard of FMVSS No. 223 which specifies the ground clearance must be not more than 560mm from the ground, forward location from the rear extremity is not more than 305mm and lateral extension be within 100mm of each side [3].

Fig. 4 shows an example for the geometry of a typical rear impact guard of 2600mm wide trailer. It shows the location of points P1, P2, P3 and the average location of the vertical attachment [3].

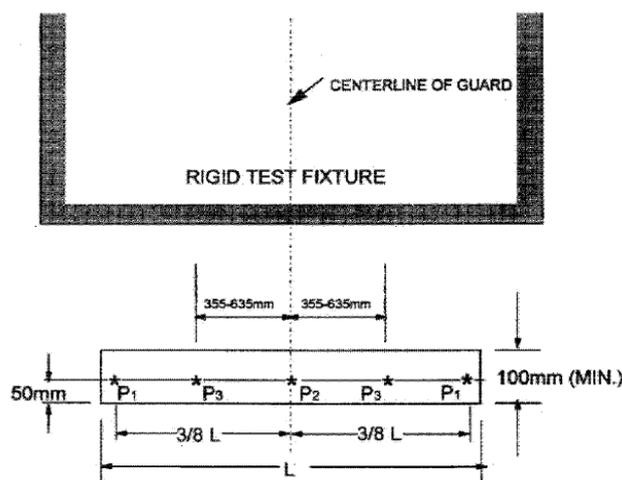


Fig. 3 Requirements of FMVSS No. 223 [3]

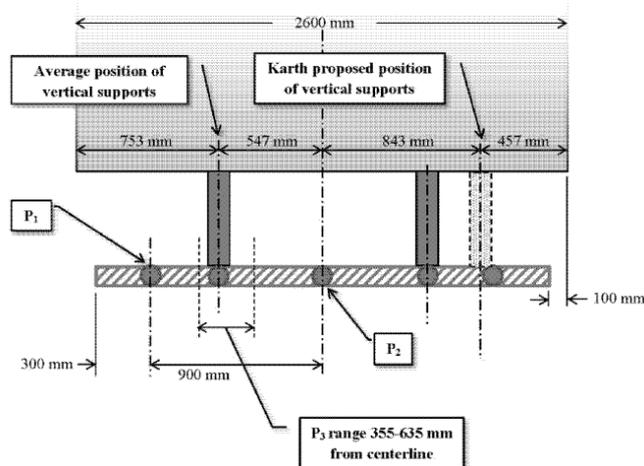


Fig. 4 A typical geometry of rear impact guard of a 2600mm wide trailer based on FVMSS No.223 regulation [3].

II. EXPERIMENTAL TESTS

An early report for fatalities and injuries resulted from cars crashing into trucks rear end was produced by Rechnitzer and Foong. The research aimed to identify the factors contributing to fatalities and injuries resulting from crashes involving cars and trucks, and provide effective action to trucks design in order to reduce injuries severities of road users. Detailed investigation conducted on design of the truck rear end and rear under-run protection device. The study focused on 45 crashes in Australia, 25 fatalities were reported and others included as severe injuries. The findings showed that in most trucks the stiff floor was the cause of serious injuries and fatalities. Also as many rear impacts were not central, the problem with offset impacts were the bent outer end of an RUPD which recommended increasing test load of ECR R-58. Finally they suggested for truck RUPD design to be complied with ECE R-58 regulation and the ground clearance in the range of 300-500 mm maximum to reduce sever injuries and fatalities [5].

The updated report illustrated the injuries severities during full-width and offset rear impact of car to truck which resulted in death consequences due to direct impact with truck rear structure and edge that could act as a cutting device see Fig. 5 and 6. Therefore they recommended for truck body extension to the height of car bumper to ensure the car structure can be fully engaged with rear under-ride protection device [6],

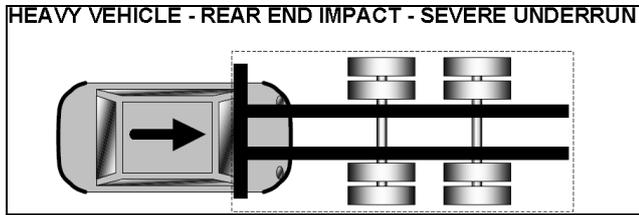


Fig. 5 Rear end impact of full-width [6]

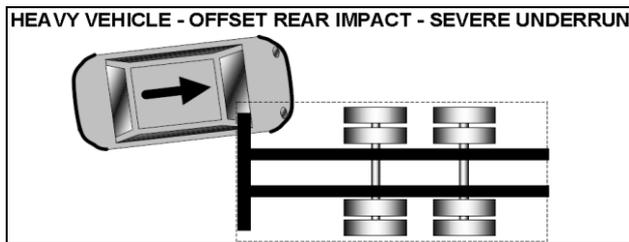


Fig. 6 Offset rear impact [6]

One of the early research on improving the design of truck under-ride guards was suggested by Block and Scmutzler [7]. They suggested the maximum height of truck rear guard ground clearance 18-20 inch instead of 22-inch based on 30 mph (48 km/h) crash test which opposes the NHTSA crash test speed of 35-40 mph (56-64 km/h) in order to protect small vehicles from sliding under truck frame in 40 mph (64 km/h) crashes. The experimental tests were conducted on scaled truck guards with minimum strength and were subjected to a slow-push. Many designs of truck guards were explored such as the use of Belleville spring-washer stacked pistons, rigid foam filled convoluted tube structure, recycled non-metallic synthetics, and cable entrapment platforms. In conclusion the research suggested further developments to improve rear under-ride guards that installed to heavy trucks based on the new NHTSA regulation to prevent under-ride severe injuries and fatalities.

Another experimental test examined different regulations of RUPDs which based on Europe, Brazil and USA requirements. The study investigated the performance of rear under ride of a heavy vehicle that was over 3.5 tons. Moreover the work focused on high capacity crash testing and energy absorbing systems which could reduce injuries during car-to-truck end rear impact, and different crash layouts were introduced such as full-scale and offset. The results showed that the international regulations of RUPDs were limited and recommendation for improvement was provided in this study such as maximum height and width of good RUPDs design [8].

A comparison experiment was conducted for incompatible crash tests between passenger cars and heavy trucks to evaluate the performance of rear under-ride guards or RUPDs which was necessary to meet the requirements of Canadian Standards Association (CSA). Basically the available rear

guard was designed to protect truck tank valves and not for the colliding car protection. Various designs of RUPDs were examined, which were built according to the standard of U.S. FMVSS 223/224. The results showed the 560mm clearance type of RUPD demonstrated good prevention of colliding car from sliding under the heavy truck rear frame at speed of 48 km/h Fig. 7, but failed to stop the Honda Civic at speed of 56 km/h Fig. 8 [9].



Fig. 7 Ford Windstar at 48 km/h [9]



Fig. 8 Honda Civic at 56 km/h [9]

In another comparison experiment was conducted by Atahan [10] investigating four different types of RUPDs used by the Transport Canada Research Center for full-scale crashes. Also different types of vehicles were used in the test such as compact cars, vans and light trucks, and different speeds were examined to evaluate the different new designs of RUPDs. The observation concluded that an RUPD design, which was based on the U.S. FMSS223 minimum requirements, failed during the crash test and could not prevent cars sliding beneath the truck frame especially for the compact vehicles. The recommendation was to conduct further studies to develop comprehensive specifications for RUPDs design which are able to reduce occupants' injuries during car to truck rear impact conditions.

Recently Grzebieta and Rechner proposed a standard for experimental tests of truck under-run devices used in Australia and New Zealand known as AS/NZS 3845.2 regulation. The proposed tests were based on the United State Manual for Assessing Safety Hardware (US MASH) procedure which subjected a sedan car (1500 kg) and a sport utility vehicle (2270 kg) to impact a truck rear under-run device at speed of 70 km/h with 50% and 30% offset scales. The truck under-run device performance was necessarily to comply with certain criteria as detailed in US MASH standard.

These performance criteria could be applied to all trucks used in the public roads in order to protect other users [11].

III. NUMERICAL ANALYSIS

Zuo et. al. used MADYMO software in the early analysis of a car crashed into a truck rear end. The study aimed to reduce the injuries of the car occupants upon truck rear end impact by investigating the effectiveness of the energy-absorbing system that supported the truck rear guard. The numerical analysis simulated a car model crashed a truck rear under-ride guard that attached with energy absorbing system. Two crash speeds were conducted 48 km/h and 75 km/h. A male dummy was used to measure injuries such as head injury criterion, deceleration of head and chest resultants. Also rear guard and energy-absorbing system resultant force and vehicle deceleration were identified. The simulation results were validated against an early experimental test and provided good agreement which proved the simulation model could be used in design optimization for crashworthiness and injuries investigation at low cost. The results presented a deceleration crash pulse was a crucial factor of measurement in determining the effectiveness of energy-absorbing system attached to the rear guard. Moreover the software assisted in the simplification of the mathematical modeling of the crash and could be used to estimate important parameters such resultant force and energy absorption [12].

In another numerical analysis, the explicit LS-DYNA software was used to evaluate the performance of heavy truck RUPD in order to control the speed of impacting vehicle during car-to-truck rear impact at different speeds. The research focused on the deformation in both of the impacting vehicle and RUPD, vehicle deceleration energy absorption and vehicle structure performance. The results showed that impact speed necessarily must be 64 km/h to fully evaluate an RUPD design Fig.9, the diagonal struts attached to the guard support were useful in increasing the impact resistance of the RUPD, the optimum RUPD height was determined to 400 mm even with different impact scales such 50% offset and full-width [13]. The numerical analysis model results were compared with actual crash experimental results that validated the accuracy of the simulation. Finally the research recommended the analysis of different impact conditions such as various impact scales and angles, as well as different types of vehicles with various bumper heights [14].

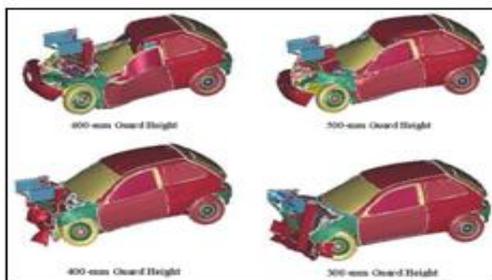


Fig. 9 RUPD behavior with different height at 64 km/h [14]

Numerical analysis was used for design optimization of RUPD which conducted by Liu et al. [15] to investigate inelastic and large deformation of the RUPD material. The

study used Genetic Algorithm of finite element (GA/FE) which was available in LS-DYNA program. The numerical analysis results were validated with experimental results that based on ECE R73 regulation. There were three different designs for the truck rear end, and the results demonstrated acceptable strength of the RUPDs structure. The research concluded that the method of GA/FE could produce good results and shortened the computational time significantly, therefore more complicated crash specifications of passenger car could be simulated.

Another simulation work, LS-Dyna finite element program has been used to model an impact of car-to-truck rear under-ride. The study focused on energy dissipation of the new RUPD design during an impact to reduce injuries imposed on car occupants. A moving barrier (MB) was used to represent a passenger car impacts with the new RUPD at speed of 54 km/h and 50% overlap collision. The numerical analysis results demonstrated good values of 77% crash energy was absorbed by the new RUPD's structure, and the acceleration of MB reached maximum of 22.8g which was 40% lower than the value conducted for a conventional one. Therefore the new RUPD was good in buffering and had the ability of high energy absorption during a (Placeholder1)car to truck rear impact Fig. 10,11 and 12 [16].

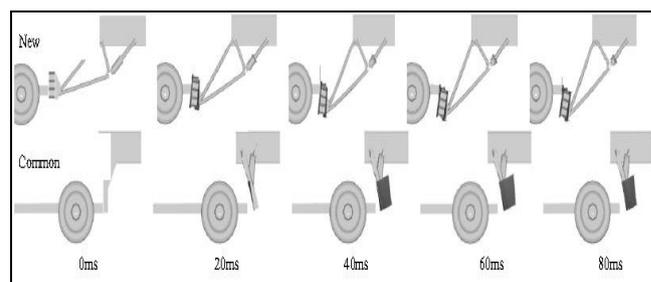


Fig. 10 Dynamic response of RUPDs [16]

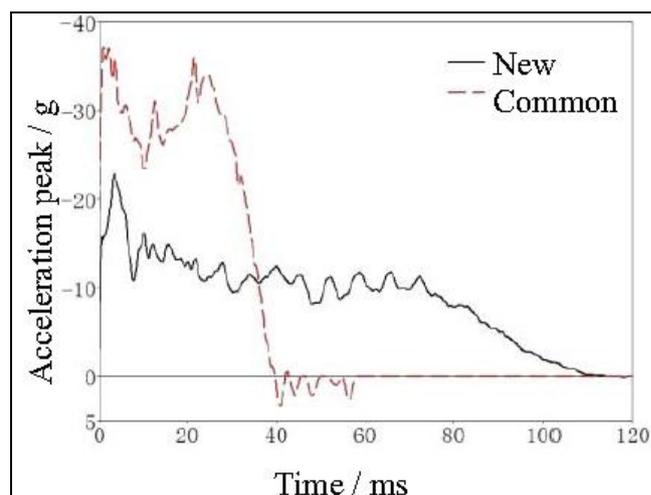


Fig. 11 Acceleration curve of MB [16]

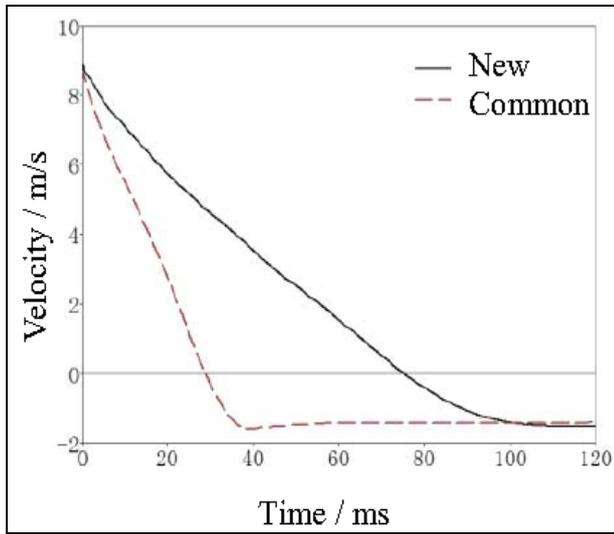


Fig. 12 Velocity curve of MB [16]

Others used finite element method to evaluate a new design of RUPD was based on a bio-inspired method that derived from the structure of sheep horn [17], which had strong structure and good energy absorption capability. The objective of this research was to prevent small car sliding beneath the rear of a heavy truck which could mitigate injuries and death during a car to truck rear impact. The study focused on the microstructure and mechanical properties of a horn sample. Therefore the new RUPD was designed using bionic principle of both micro and macro levels, a finite element model of the new RUPD was developed and examined based on the stress distribution on the structure. The numerical analysis showed remarkable strength of the new RUPD which demonstrated effective protection for passenger cars during under ride crashes.

Khore et. al. conducted a research on a truck rear under run protection device RUPD system to improve the safety during car to truck rear impact. The study investigated different materials and structural designs to improve the energy absorption capability during a crash. Various programs were used in the simulation process such as Pro-E for modeling, Altair Hyper for meshing and the analysis carried out by LS-Dyna finite element. The analysis subjected the RUPD for static testing with variable loads and points. The outcome established the simulation method and demonstrated the pattern of RUPD energy absorption during a crash which absorbed most of the impact energy. The optimized RUPD design in this study met the regulation in which maximum displacement was 50 mm [18]. Finally the numerical analysis helped in the reduction of development cost as compared to experimental testing [19], [20].

In this numerical analysis, P. Sen et al. (2014) conducted design optimization for Trucks' RUPD during an accident with a passenger car. The aim of the research was to improve RUPD safety system and protect car occupants from fatal injuries. Different types of materials and design structures were examined in order to enable the new RUPDs to absorb more energy during a car impact with rear end of a truck. Moreover the mechanical properties and failure rate of used materials were examined. The design structure used in this study was based on the Economic Commission Europe

Regulation-58 (ECE R 58) Fig.13. The final results showed acceptable level of deformation of the new RUPS structure against the applied load [21].

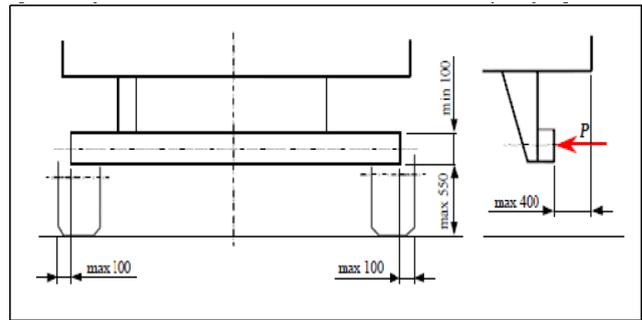


Fig. 13 Design of RUPD base ECE No.58 [21]

This implicit numerical analysis used ANSYS program to model Aluminum foam material in building a rear under run protection device (RUPD) to improve the crashworthiness of vehicles [22]. This material was selected due its high strength and stiffness, and also it offers lightweight structure which improves fuel consumption in addition to passengers' protection. The study used ANSYS software to model and evaluate the new RUPD design, and impact force was applied of full length of the RUPD structure. The results demonstrated good stresses and deformation values that were in the permissible range. Therefore the sliding of colliding car could be reduced during truck rear end impact [23].

In a different numerical analysis, finite elements programs such as Hypermesh and LS-Dyna were used to investigate the performance of a new RUPD design with guardrail that attached to a tanker trucks carrying dangerous goods, see Fig. 14. The study focused on tank deformation and energy absorption during rear impact in order to improve crashworthiness and protect other road users. The simulation results showed that installing the new RUPD helped in blocking deformation effects and improved energy absorption which could protect the tank during a collision [24].

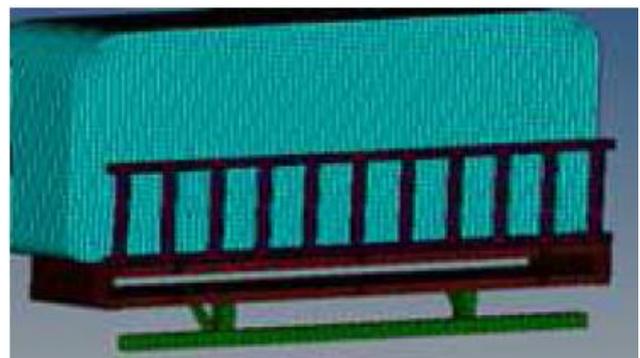


Fig. 14 Rear guard rail system [24]

In this study, a different material was introduced in the analysis of trucks RUPDs. Gombi et. al. used carbon fiber reinforced plastic material to replace steel that most manufacturers apply in RUPDs' design.

The composite material could offer weight reduction, strong and stiff RUPD which required for modern lightweight structures and occupants safety. The model of RUPD was produced by Catia, finite element model was generated by Hypermesh and the simulation analysis was carried out by LS-Dyna. The outcome demonstrated that the Carbon RUPD could absorb 50% of kinetic energy compared to steel RUPD absorbed 90%, however the carbon model weighted 15 kg and steel one was 75 kg. The light weight RUPD increased vehicle mileage due to low fuel consumption and good efficiency which made it the potential material for truck RUPD design. Also the study recommended to investigate the effect of energy absorption for different orientations and impact scales [25].

Another recent research of RUPD development, the non-linear finite element analysis software known as Radioss was used [26] to evaluate the RUPD design when subjected to consecutive loads at five points based on ECE Regulation 58 Fig. 15. The loads were determined by the Gross Vehicle Weight (GVW), 25% of GVW load was applied for P2 and 12.5% for P1 and P2. The study focused on strain mapping produced by the loads at five points which could lead to the design optimization of truck RUPD. The results showed that maximum displacement was 30mm at P1 which was in the allowable range; also maximum strain at P1 was 3.5%. At P2 and P3 the maximum displacements were found within the allowable range [27].

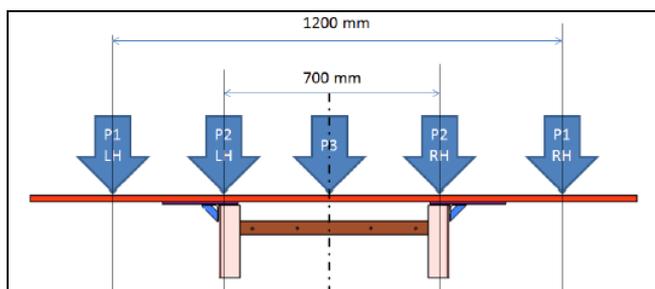


Fig. 15 Load application and location of P1, P2 and P3 [27]

A new method of numerical analysis used to evaluate the performance of car crashworthiness during car-to-truck rear end impact with different impact scales were introduced in this research. The numerical analysis (by LS-Dyna software) focused mainly on impact speeds, passenger compartment intrusion load path and deformation process during rear end impact for mid-sized sedan car. Six kinds of offset-scales were introduced 80%, 70%, 60%, 50%, 40% and 30% with impact speed of 56 km/h (35 mph), these scales significantly could affect the car crashworthiness, see Fig. 16. The results showed that the worst case scenario was impact offset-scale of 30% in which under-ride depth exceeded 3000 mm Fig. 17, therefore A-Pillar was completely destroyed that showed the truck RUPD failed to decelerate the impacting car. Finally the research suggested improvements for a truck RUPD design and offset collision forms should be considered during assessment process [28].

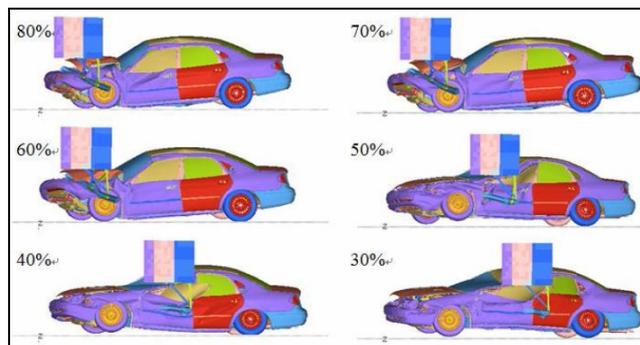


Fig. 16 Different offset-scales of collision [28]

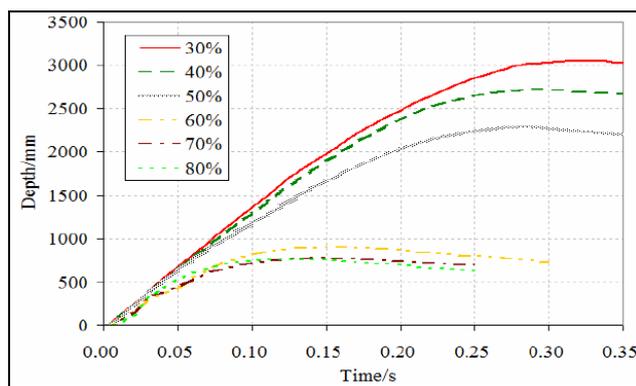


Fig. 17 Under-ride depth for different offset impacts [28]

Jaju and Pandare analyzed a design of rear under-ride protection device using the explicit LS-DYAN software to improve the structural strength and integrity of truck RUPD, which was based on the Economic Commission for Europe (ECE R58) regulation. The study subjected the RUPD model for different regulatory loads, and focused on plastic strain and von-mises stress (see Fig. 18) to evaluate the failure limit and strength [29]. The results demonstrated good behaviors that passed the RUPD design. If the current structure failed the test, additional material was recommended to achieve the targeted load.

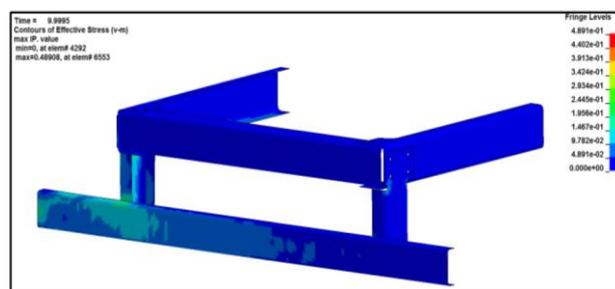


Fig. 18 Von-Mises Stress distribution for P1

The use of finite element analysis to evaluate the structural strength and failure of RUPD could reduce experimental works such as prototyping as well as testing cost [30], [31]. Moreover the simulation model was recommended to further improvement by refining mesh size and accurate welding points to predict better results [32].

Recent simulation works related to trucks' RUPDs, the explicit finite element program LS-DYNA has been used for the numerical analysis of rear under ride protection devises RUPDs [33]. The research works focused on RUPDs performance during a car impact with rear of a heavy vehicle, where energy absorption of RUPDs was evaluated. Different regulations for RUPD were used, such as Federal Motor Vehicle Safety Standards 223/224 (FMVSS 223/224) and Economic Commission Europe Regulation-58 (ECE R 85) Fig. 19. The layout configuration of the car impact with rear of a heavy truck used was full width of the car frontal area Fig. 20. The results showed good improvement of new RUPDs' designs which enhanced the crashworthiness and mitigated occupant compartment intrusion during the rear impact [1], [34]. Moreover, another finite element software known as ABAQUAS was used to analyze RUPD performance (with same above scenario) demonstrated more stable results as impact speed increased [34].

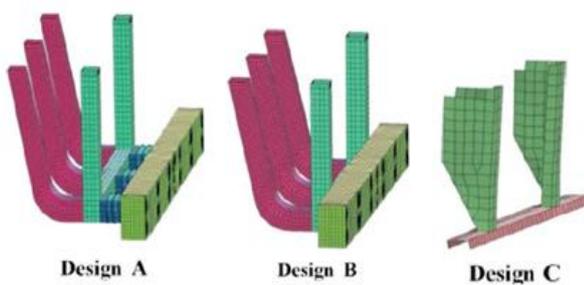


Fig. 19 Different design of RUPDs [34]

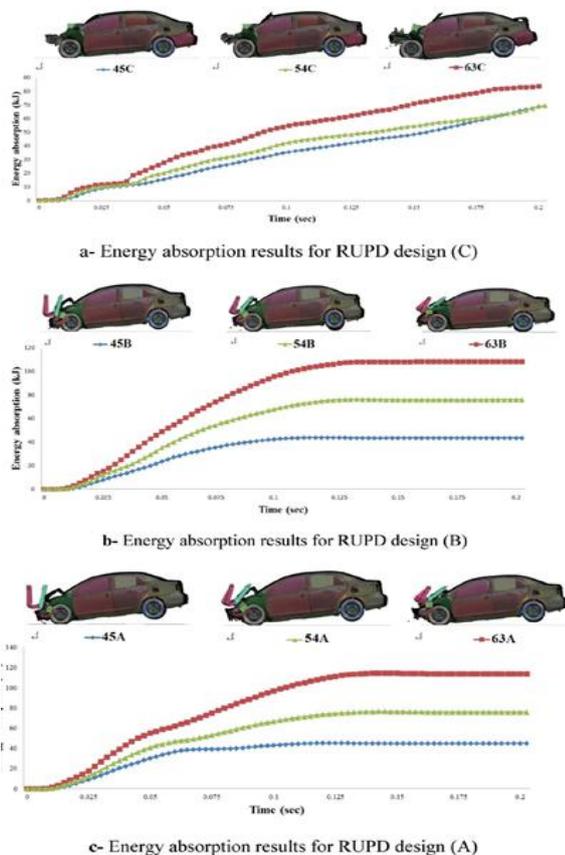


Fig. 20 Energy absorption results of different RUPDs designs [34]

Moreover ANSYS program used by R. Mohod to evaluated RUPD models which subjected the new designs for explicit dynamic loading coupled with different load distributions to ensure the safety of car passengers when the car impacting the rear of a heavy truck. The study investigated the energy absorption of RUPDs during a rear crash by introducing different materials and structural designs that constructed the new RUPD. Moreover the research work was based on India Standard IS 14812-2005 regulation which was derived from ECE R 58. The results showed the new RUPD design demonstrated acceptable level of internal energy and stress distribution [35], [36]. Other researchers used Solid-Work Simulation to investigate truck RUPD with different types of materials and designs such as E38/FE410/FE69 grades of steel for the RUPD, and rubber, aluminum and steel for supporting system of the RUPD [37]. The research focused on the various suitable materials and structural design that played as major factors in influencing energy absorption capability during car to truck rear end impact. The results showed that FE690 steel RUPD with steel support demonstrated good performance in deformation stress and strain as compared to others. The system showed less stress distribution which could avoid damaging the landing gear and promote longer service life. In another similar method used in this study, the displacement at P1, P2 and P3 were 1.747 mm, 2.92 mm and 5.521 mm which less than the maximum of 40mm. Also the stresses at same points were 16.7MPa, 48MPa and 34.4MPa respectively that were less than maximum allowable stress of 355Mpa based on ECE 58 regulation [38]. Furthermore an investigation on truck RUPD performance with various shapes and thickness were introduced to evaluate the energy absorption capability during car to truck rear end impact [39]. The study used explicit finite element software known as LS-Dyna to model the impacting scenarios of a car and a truck; it focused on the RUPD energy absorption and displacement, velocity and deceleration of impacting vehicle. The changing in RUPS structural design had better energy absorption which helped in reducing the level of occupants' injury during car to truck rear end impact. This good performance was produced by the curved RUPD, Fig. 21, with 3 mm thickness which demonstrated good energy absorption of 111 MJ of internal energy and 396 mm displacement, see Fig. 22 and 23. Moreover the RUPD decreased the amount of transferred impact energy to the car that offered better safety during such a crash. Finally in such research the numerical analysis offered reduction in time and cost of development that required in experimental tests [39].

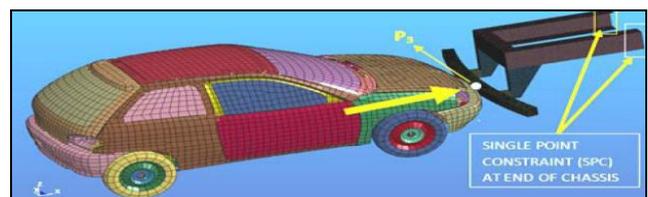


Fig. 21 Curved RUPD [39]

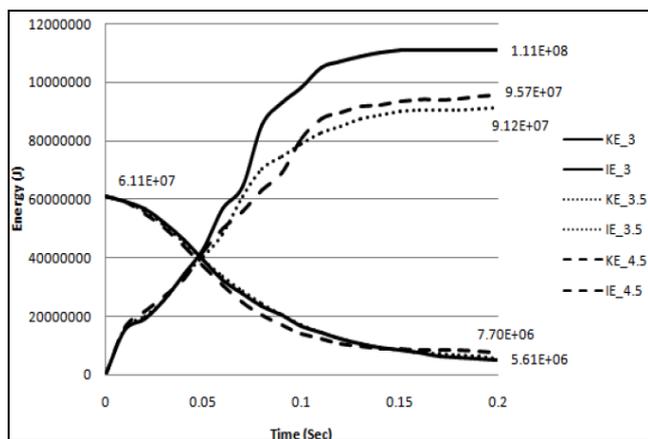


Fig. 22 Global Energies for the RUPD [39]

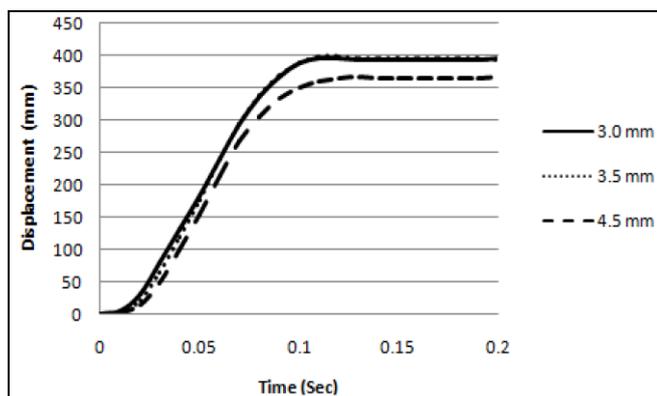


Fig. 23 Displacement of the RUPD [39]

IV. CONCLUSION

The article highlighted the available methods of analysis for RUPDs’ performance during car to truck rear impact. The two main methods are the experimental tests and numerical simulation analysis. It is observed that the research on performance evaluation of trucks RUPDs were limited to full-scale impact width, but very view researchers conducted analyses for offset scaled crashes between colliding passenger cars and trucks’ rear end. The most severe crash when involving offset scaled crash of 30% which can cause passenger compartment intrusion resulting in fatalities [4], [28]. Moreover the previous studies focused on certain impact speeds ranged from 48 km/h to 64 km/h for full width impact tests, but the highest impact speed was 75 km/h full width analysis conducted by simulation [12]. Hence high impact speeds of 64 km/h with different impact scales were recommended to efficiently evaluate the performance of trucks RUPDs and ensure the safety of car occupants during car to truck rear impact [13]. Furthermore tests were mostly limited to mid-sized and compact passenger cars such as 2010 Chevrolet Malibu and 2010 Toyota Yaris, thus it is recommended to evaluate truck RUPD performance when impacting with different types of vehicles that varies in bumper heights such as MPVs, SUVs, light trucks and short front-end vehicles [14].

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