

Pareto Optimization of Heavy Duty Truck Rear Underrun Protection Design for Regulative Load Cases

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ABSTRACT

Rear underrun protection device is crucial for rear impact and rear under-running of the passenger vehicles to the heavy duty trucks. Rear underrun protection device design should obey the safety regulative rules and successfully pass several test conditions. The objective and scope of this paper is the constrained optimization of the design of a rear underrun protection device (RUPD) beam of heavy duty trucks for impact loading using correlated CAE and test methodologies. In order to minimize the design iteration phase of the heavy duty truck RUPD, an effective, real-life testing correlated, finite element model have been constructed via RADIOSS software. Later on, Pareto Optimization has been applied to the finite element model, by constructing designed experiments. The best solution has been selected in terms of cost, manufacturing and performance. Finally, real-life verification testing has been applied for the correlation of the optimum solution.

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INTRODUCTION

RUPD is a rigid part located on the rearmost side of a heavy duty truck in order to protect the passenger cars under-running from rear side of the truck, as seen in [Figure 1](#). Safely designed RUPDs help to avoid the fatal and injury crashes of passenger cars and their under-ride collisions to the truck rear sides. It has been revealed that when a passenger car travels at a speed of 70 km/h and hits to a standing heavy duty truck with zero speed from the full head on, the passenger car will feel a deceleration of 35g or more which will also translate to the passengers inside. This possible life threatening decelerative impact increases directly to 46g or more when the passenger car speed increases from 70 to 100 km/h. Average of around 20g results in fatal outcomes [1]. It is evident that, head on crashes result in high possibly life threatening decelerations, even in urban arterial load environments. RUPD's have two major effects on the outcome of crashes; firstly underrun can expose light vehicle occupants to direct contact with rigid structural parts of the vehicle before the light vehicles crashworthiness has fully come into play, and secondly, components of the heavy vehicle (e.g. Rear axle) can be compromised to the degree that, the vehicle is not controllable in coming to a stop or the vehicle cannot be moved after the collision.

The first has a direct impact on the trauma outcomes of the collision, while the second can either lead to other collisions, or present a hazard to other road users by obstructing traffic.

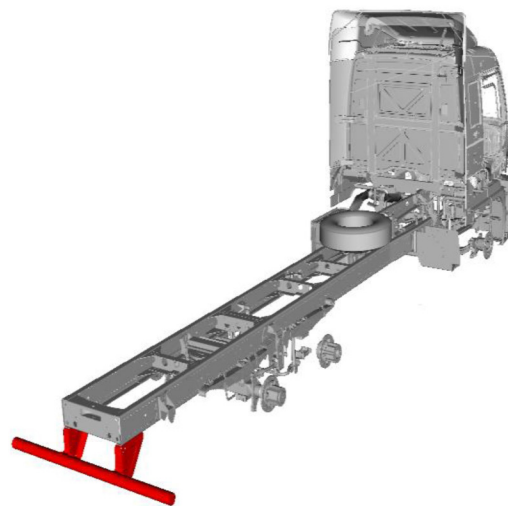


Figure 1. RUPD on a heavy duty truck chassis

Existence of RUPD reduces fatal crash situation by 3% (i.e. without RUPD: 12%, with RUPD: 9%) [2].

The current standards on the RUPD design have been based on the arguments that full width barriers cannot be accommodated due to the likelihood of them catching on posts while turning, etc., and that they cannot be lower due to rear road clearance problems. In order to understand the design requirements of these standards it is evident that, crash situations of the rear impacts should be understood clearly. Rear end impact types can be dissolved into two types: rear end impact (See Figure 2a) and offset rear impact (see Figure 2b). The outcomes of these two crashes are seen in Figure 3 [1].

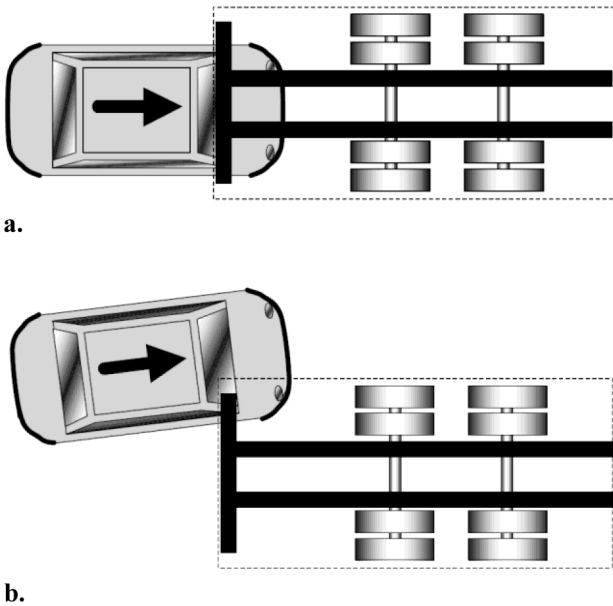


Figure 2. Rear end crash types: a. Rear end crash, b. Offset rear impact crash [1]



Figure 3. a. Rear end crash, b. Offset rear impact crash outcomes

The current regulation standard for the RUPD is ECE-R58 [3]. According to ECE-R58, the distance of the RUPD from the ground should not exceed 550 mm, the distance between the rear of the device and the end of the chassis frame should not exceed 400 mm, the width of the RUP should not be smaller than 100 mm (per side) than the outer lateral side and if the vehicle to be approved is equipped with more than one rear axle the most width axle will be taken into account. If the device is integrated in the frame of the vehicle, the requirement will not apply. Bumper beam diameter should not be smaller than 100 mm, while sharp edges should be avoided for the total design (see Figure 4).

The testing of the RUPD can be either conducted on a vehicle, on a part of the chassis, on a test bench, or via a correlated CAE analysis technique.

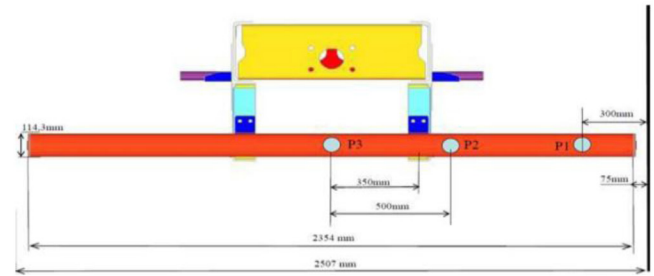


Figure 4. ECE-R58 requirements [3]

There are three load cases for RUPD testing, which are defined in ECE-R58. P1 load case is the worst condition for the RUPD bumper beam. P2 load case is the worst condition for the RUPD beam mounting brackets to chassis frame. P3 load case is applied at the mid-section of the beam, which is not the severest condition at all.

The scope of this study is the optimization of the RUPD beam, only. Therefore, P1 load case is investigated. For that reason, P1 load case results and correlations are represented throughout the study.

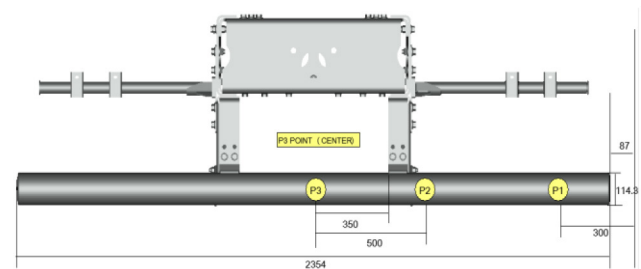


Figure 5. RUPD test loading identification [3]

Experimental testing of RUPD has been widely used to verify the crashworthiness of these parts. Raj et.al [4] have been studied the assessment of dynamic crash tests of a passenger car and a stationary heavy truck fitted with and without RUPD. They have conducted a series of experiments and LS-DYNA simulations and concluded the necessity of the RUPDs. Haenchen et.al [5] developed the deformation energy needed for a car-to-truck collision and pointed out that, there must be an agreement between passenger car manufacturers and truck manufacturers on an adequate height for structural interaction, so that the passenger car and RUPD should have similar heights from the ground. Furthermore, the maximum RUPD height is defined as 550 mm in ECE-R58 standard [3].

Finite element studies of RUPD have been studied by a number of researchers [4, 6, 7, 8]. Glavac et.al. [6] presented a new finite element method at which it is possible to design a RUPD which confirms to ECE R-58 regulations. They used Nastran software with non-linear material modeling and contact elastic and elasto-plastic analysis. Load is applied quasi-statically as pressure in their FE model. Joshi et.al. [7] developed an explicit LS-DYNA FE model in order to reduce the number of iterations during the RUPD design phase. impact loading. Joseph et.al. [8] have studied the optimization

of the load bearing capacity of the RUPD by using LS-DYNA FE analysis. However, their optimization procedure did not base on a regular strategy; otherwise, they have tested six different RUPD designs and selected the best of all as the optimized RUPD design. None of the literature studies have been dealt with the optimization of the RUPD for minimum weight and appropriate performance.

Pareto Optimization is a widely used multi-objective optimization technique when conflicting objectives are present in a problem. In such cases, the solution forms a surface, which is called as the “Pareto Front”, of which any optimal solution in the Pareto Front does not lead to a simultaneous worsening of the conflicting objectives. Instead of generating a single optimal solution, many solutions are generated to satisfy the Pareto Optimality Criterion. According to this criterion, a solution point P is accepted only if there are no solutions better than P with respect to all the objectives. For example, even if P is worse than another solution P1 with respect to one objective, P is accepted provided that it is better than P1 in at least one objective. Thus each Pareto optimal solution is good in some respect [9, 10].

Pareto Optimization is applicable in design optimization studies. Corteille et.al. [11], developed a robust design of an engine mount system by using the multi-objective Pareto optimization method. They have used Frontier and Matlab software in order to execute their analysis. They have applied several constraints such as packaging constraints, threshold values of displacements of the engine mounts and the rotation of the engine, etc. Siano et.al. [12], performed a constrained multi-objective optimization of a two-stroke diesel engine in ModeFRONTIER™. In their study, maximum pressure of the engine is constrained to 126 bar and the minimum engine power is constrained to 108 kW. Manzan and Pinto [13], applied a genetic optimization of external shading devices via ModeFRONTIER™ software. They have constrained the height of the shading device to be minimum. In order to minimize the stress concentrations at notches and corners, Taylor et.al. [14] developed a multi-objective optimization study in ModeFRONTIER™ software. Multi-objective Pareto Optimization is also used by Abdoli and Dulikravich [15], to design micro heat exchangers under the constraints of maximized total heat removed, minimized total pressure drop and temperature non-uniformity on hot surface.

To apply Pareto Optimization, it is necessary to construct a series of designed experiments, so called Design of Experiments (DoE) in the beginning of the study. Design of experiments helps to identify the important causes and variables over the product, process, materials, etc., and helps to determine the main effects and interaction effects over the response [16].

EXPERIMENTAL TEST SETUP

In order to test RUPD according to ECE-R58 regulation, a test rig is constructed. Half chassis frame platform with a RUPD was rigidly mounted on the rigid test plate. 250 kN, hydraulic MTS™ actuator is also mounted on the same rigid test plate. The actuator is placed in parallel to the ground. A ball joint is attached to the tip of the hydraulic actuator in order to protect its shaft from transverse forces. In conjunction with ECE-R58 regulation, a test mandrel is machined in dimensions as 250 mm in height, 200 mm wide, and 10 mm thickness, with a radius of curvature of 5 ± 1 mm at the vertical edges. The test mandrel is mounted to the tip of the piston via four bolt connections. It was possible to attach the hydraulic actuator to a suitable location which is explained in ECE-R58 load application points. Those points are clearly represented in Figure 5.

Three replicative tests for P1 and P2 load cases are developed consequently, whereas, P3 load case was not necessary to be applied for the correlation study, as it is concluded by the team. In order to preserve the accuracy of the tests, every part on the RUPD for every test, has been renewed, except the chassis frame. The loading procedure of regulative test force, which is defined in ECE-R58, is presented in Table 1.

Table 1. Regulative Load Cases [3]

Load Case	Time (s)	Force (kN)
P1	0-5-7-9	0-50-50-60
P2	0-5-7-9	0-100-100-120

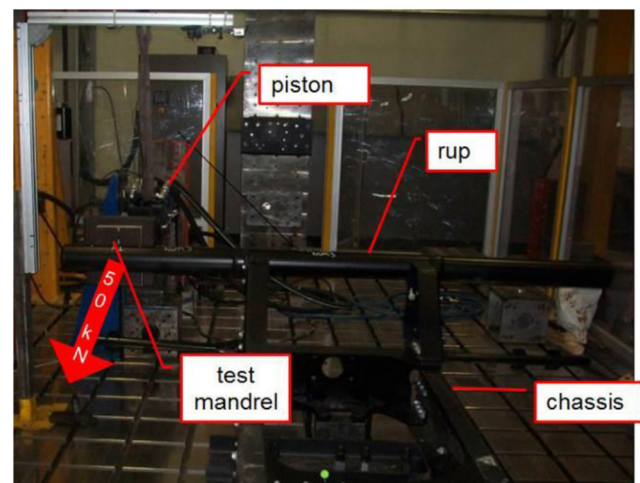


Figure 6. RUPD test rig

FE MODEL

In order to analyze the structural integrity and optimization of the RUPD system, a non-linear finite element model is developed using the commercially available code RADIOSS. The model is composed of a relevant portion of the stiffer truck chassis, on which the RUPD is mounted. The chassis portion is