PASSIVE SAFETY OF TRUCKS IN FRONTAL AND REAR-END COLLISIONS WITH CARS

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ABSTRACT

The regulation ECE-R 93 defines the rigid front underride guard as a minimum requirement for commercial vehicles to prevent cars from underriding in frontal crashes. It is evident that the benefit of such protective devices can be substantially improved by an energy-absorbing design. In fact it leads to lower loads for the driver and passenger in the case of a frontal accident between a car and a commercial vehicle. The measured dummy loads should indicate "green manikins" corresponding to EURO NCAP frontal rating test at a closing velocity of 64 kph.

Against this background, the effect of the energy-absorbing front underride guard of a MAN TG-A series was analyzed with two full scale tests. In both tests a Volkswagen Golf IV impacted with 70 % frontal overlap at a speed of 42 to 43 kph against the truck driving at a speed of 21 kph. While absorbing energy, the front underride protection of the MAN and the front structure of the Golf performed well. The compartment of the Golf remained intact without any severe intrusions. As expected the dummy responses in the MAN were extremely low. The dummy responses for the Golf occupants didn't exceed their corresponding biomechanical limits. These results show the protection benefit of an energy-absorbing front underride guard (which is in production now) for impacts on state-of-the-art cars (medium sized, so called "compact class").

The presentation gives additional information for real world accidents regarding truck/car impacts, accident reconstruction, historical development of front and rear underride guards for heavy trucks and a future prospects preview.

In the near future an energy absorbing rear underride protection will be on focus. Numerical simulations of such a protection device show the possible benefit on a significant higher level than for the front underride guard.

INTRODUCTION

Regarding real-world crashes involving heavy trucks and cars, it becomes obvious that front to front impacts play a significant role. Underride protection as part of the trucks front can reduce the risk for car occupants in such situations.

Technical definitions and demands on a rigid front underride protection are described in the regulation ECE-R 93. Such devices will be prescribed for trucks first registered in the European Community as of August 10th 2003. An energy absorbing front underride protection could reduce load and intrusion of an impacting car and increase the safety level for the car occupants.

MAN and the technical university of Berlin started with several crash tests in 1987 to get basic knowledge of the protection potential of such underride protection parts. Latest results have been received by crash tests which were performed at the DEKRA crash test centre in the year of 2000 with the new MAN TG-A and a Volkswagen Golf IV.

Ongoing further development is focused on the rear underride protection of heavy trucks. Technical definitions and demands for a rigid device are described in ECE-R 58. But to absorb additional energy, similar layout principles like the successfully used enhanced energy absorbing front underride protection can lead to a substantial improvement in rear impacts as well.

ACCIDENT STATISTICS

The official German Federal statistics indicate motor vehicles of delivery and lorry (including trucks) of all weight categories, also below 3.5 metric tons of gross vehicle weight (GVW) with different constructions (superstructure), articulated vehicle engines and other tractors (out of agricultural) in each case with and without trailer as a goods motor vehicle. For the year 1991, the first year after the reunification in Germany, these statistics show about 16,916 crashes with injured parties involving a car and a goods motor vehicle, table 1. This figure increased by 15 % to 19,413 until the year 2001. An increment of accidents occurring on urban and rural roads (out of Autobahn) is observable. Approximately half of the accidents took place in the urban area.

Table 1.
Crashes with severely injured or killed car occupants involving a car and a goods motor vehicle* (German Federal Statistics)

Year	1991	1995	1999	2000	2001
Accidents					
Urban	8,212	9,597	10,354	10,100	9,794
Rural without Autobahn	5,765	6,895	7,087	6,699	6,642
Autobahn only	2,939	2,805	3,226	3,017	2,977
Severely injured car occupants					
Urban	1,424	1,435	1,250	1,134	980
Rural without Autobahn	2,232	2,509	2,153	1,895	1,868
Autobahn only	1,139	1,028	859	739	706
Killed car occupants					
Urban	99	84	62	70	58
Rural without Autobahn	446	500	375	394	388
Autobahn only	253	127	121	117	95

* Definition of goods motor vehicle:
Delivery vans and motor lorries with standard body motor lorries with special body (e.g., tank truck, silo truck) semi-trailer truck with or without trailer other tractors (without agricultural tractor)

In the year 2001 the figure of seriously injured car occupants in accidents involving goods motor vehicles and cars amounted 3,554. Most of these accidents took place in rural areas. 541 car occupants were killed in crashes between a goods motor vehicle and a car in this year, most of them also in rural area. Between 1991 and 2001 the figure of killed car passengers was reduced from 798 to 541, a decrease of 32 %. In the same period the figure of seriously injured car occupants was reduced from 4,795 to 3,554, a decrease of 26 %. Although this is a positive trend, the absolute figures are still on an unacceptable high level.

Information regarding details of the crash configuration are not available from the Federal Statistics. Therefore additional In-depth studies are necessary. The German Insurer Association GDV has published results of an In-Depth-Study of 508 accidents involving a truck and a car in Bavaria (Germany).

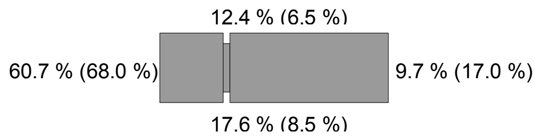
29.7 % of these accidents have been front to front crashes, table 2 (LANGWIEDER und GWEHENBERGER, 2001). 30.8 % of the 582 severely injured or killed car occupants were injured or killed at this impact configuration. 19.5 % of the trucks crashed into the cars side, 15.6 % have been crashes with the truck front impacting the rear of the car.

Altogether the front of the trucks was involved in 64.8 % of the examined accidents and 66.2 % of all severely injured or killed car passengers.

Table 2.
Crash configurations in truck/car crashes in Bavaria (LANGWIEDER and GWEHENBERGER)

Impact Configuration	Accidents		Severely injured and killed car occupants	
Front / Front	151	29.7 %	179	30.8 %
Front / Side	99	19.5 %	115	19.8 %
Front / Rear	79	15.6 %	91	15.6 %
Rear / Front	61	12.0 %	73	12.5 %
Side / Front	61	12.0 %	71	12.2 %
Others (e. g. grazed)	57	11.2 %	53	9.1 %
Sum	508	100 %	582	100 %

Other In-depth studies of truck/car accidents show that 60.7 % of the analyzed accidents have been crashes where the car was bumped by the front of the truck, figure 1 (SCHRIEVER and ALBER, 1993). Amongst the severest crashes (with fatalities) the share of impacts against the truck front is 68 %.



All analyzed truck/car crashes (fatal truck/car crashes)

Figure 1. Distribution of the struck side of the truck in real world truck/car crashes (SCHRIEVER and ALBER, 1993)

Against this background the In-depth studies clarify that the compatibility of a truck front (with front underride protection) plays a very important role in front crashes with cars. Front-to-front crashes of trucks and passenger cars on rural roads are of capital importance.

FORMER CRASH TESTS

In 1987 the truck manufacturer MAN co-operates with the Technical University of Berlin on a series of crash tests to analyze the potential of a front underride protection to reduce the injury risk for car occupants in a front to front crash with a truck. The example shown in figure 2 illustrates a test with a car (Volkswagen Passat) impacting at a velocity of 42 kph into a MAN truck driving at 20 kph (closing velocity 60 kph). In awareness of the current ECE regulations with the description of a rigid underride protection it is remarkable, that already at that time a version of a kinetic energy absorbing device has been tested.

Figure 2. Former truck-to-car crash test MAN and Technical University of Berlin, 1987

In the second half of the 90ies a rigid front underride protection was tested in co-operation of MAN and TÜV Bavaria with a MAN F2000 truck and a Volkswagen Golf II, figure 3. At these tests the Golf II crashed with a closing velocity of 50 kph and 70 % overlap of its front against the front of the stationary Truck. These crash tests proved, that there is a real benefit to avoid that the car underrides the truck. The mount, geometry and stability of the front underride protection was the presupposition that the front bumper, cross members and longitudinals of the car shored up here. In this way the front structure of the car was able to work as designed with the so called "crumple zone" to change kinetic energy into deformation.

Figure 3. Former crash test MAN F2000 versus Volkswagen Golf II, co-operation of MAN and TÜV Bavaria, 1994

This front underride protection system could be purchased by the truck customers as a supplementary equipment. The additional weight of this construction was approximately 55 kg. Due to the extra weight most of the customers did not order this equipment. That's why most of the MAN F2000 run without the rigid front underride protection system.

CURRENT REGULATION ECE-R 93

The industry as well as the accident research and policy agreed that an European ECE regulation is necessary to get a standard basic protection for trucks and passenger cars. Therefore the regulation ECE-R 93 has been developed in which the mount, the dimensions and the static stability performance of a rigid front underride protection is accurately defined, figure 4.

More than 15 years after these crash tests, carried out 1987 in cooperation with MAN and the Technical University of Berlin, this regulation will become obligatory as of August 10th 2003. As of this time a rigid front underride protection system is prescribed for all trucks of the category N_2 (permissible maximum weight from 3.5 metric tons to 12.0 metric tons) and of the category N_3 (permissible maximum weight more than 12.0 metric tons) in Europe.

Goods vehicle categories N_2 **(3,5 - 12 t)**, N_3 **(> 12 t)**

P_1, P_3 : 50 % GVW* max. 80 kN

P_2: 100 % GVW* max. 160 kN

*** Gross vehicle weight**

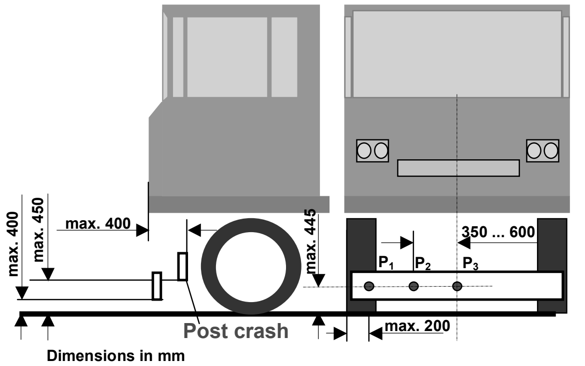


Figure 4. Mount dimensions, global dimensions and static test forces for the front underride protection described in ECE-R 93

CRASH TESTS MAN TG-A versus Volkswagen Golf IV

The MAN TG-A model series was launched in the year 2000. All heavy trucks of this model series are equipped with a front underride protection, designed to meet and exceed the technical regulation ECE-R 93. Additionally the MAN front underride protection is able to absorb energy. The design layout of the energy absorbing elements is based on the principle of a folding box-beam with optimized imperfections, figure 5 (KUPPA et al., 2001). The extra weight of this front underride protection system is 40 kg.

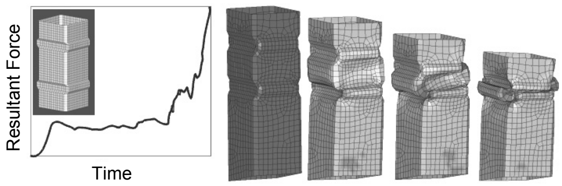


Figure 5. Deformation process of a folding box-beam with optimized imperfections

In an offset front-to-front collision between the truck and the car the front underride protection can change 58 kJ energy into deformation. During the tests described later in this paper, 47 kJ energy were absorbed by this device. Figure 6 shows the entire front underride protection device and some of its parts in the deformed post-crash shape.

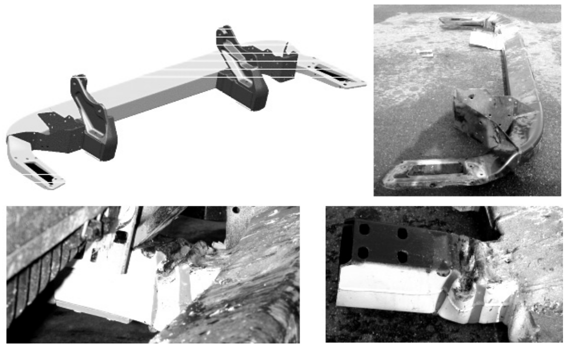


Figure 6. Energy-absorbing front underride protection device of the MAN TG-A model series

To analyze and demonstrate the benefit of this protection device, two full-scale tests were carried out at the DEKRA Crash test centre in the year 2000, figure 7. In both tests a Volkswagen Golf IV impacted with 70 % frontal overlap and a speed between 42 and 43 kph against the front of the truck, driving with a speed of 21 kph. The closing velocity was therefore between 63 and 64 kph. The truck was occupied with a belted Dummy (Hybrid III, 50th percentile male) at the driver seat. The car occupants were represented by two belted dummies (Hybrid III, 50th percentile male) at the driver and front-passenger seat.

Test	SH 00.105	SH 00.106
Truck MAN TG-A XXL		
Mass	15,150 kg	15,150 kg
Velocity	21.1 kph	21.3 kph
Driver dummy	Hybrid III 50th percentile male	
Car VW Golf IV		
Mass	1,330 kg	1,378 kg
Velocity	42.2 kph	42.6 kph
Overlap	70 %	70 %
Driver and Passenger dummy	Hybrid III 50th percentile male	

Figure 7. Crash test MAN TG-A XXL versus Volkswagen Golf IV, carried out in the year 2000 at DEKRA Crash Test Center in co-operation with MAN

Both tests resulted in similar kinematics and deformations during the crash. The belt pretensioners and airbags for the driver and passenger of the Golf IV were activated in time and performed well as part of the restraint system. Figure 8 shows the side view to the situation at 68 ms after start of the impact for both tests no. SH 00.105 and SH 00.106.

Figure 8. Situation at 68 ms after start of impact for both crash tests SH 00.105 and SH 00.106

Figure 9a and figure 9b shows the vehicles in their final position after the crash tests.

Figure 9a. Final position of the vehicles after the crash test SH 00.105

Figure 9b. Final position of the vehicles after the crash test SH 00.106

Vehicle damages

The crashes resulted in minor damage at the front of the truck, figure 10. Both crashes were analyzed according to the law of conservation of momentum and Energy Equivalent Speed (EES). The practicability and validity of this accident reconstruction method for front-to-front collisions between a truck and a passenger car was verified with reconstructed real-world crash tests (BERG and BÜHREN, 1996). Some analyses of the collision phase as part of the accident reconstruction came to plausible results with a corresponding Energy Equivalent Speed (EES) for the truck in a range between 7 to 10 kph. A numerical FEM simulation done by MAN lead to similar results according to the deformation of the front underride protection parts.

Figure 10. Damages at the front of the MAN TG-A. Energy Equivalent Speed EES in the range between 7 to 10 kph.

The cars were significantly deformed in their frontal structure, figure 11. As designed, this deformation occurred with a controlled transformation from kinetic energy into deformation. The passenger compartment remained intact in both tests. The survival space for the car occupants remained in good condition. The analysis of the collision as part of the accident reconstruction lead to plausible results with a corresponding Energy Equivalent Speed (EES) for the Golf IV in a range between 51 to 55 kph. This corresponds to known deformations of state of the art medium sized cars in the so called "compact class" resulting from several safety crash tests, e.g. the EURO NCAP frontal offset crash at 64 kph and 50 % overlap against a deformable barrier or the 48 kph full frontal test against the rigid barrier according to FMVSS 208 (see also internet http://www.euroncap.com/tests.htm and http://www.nhtsa.com).

Figure 11. Damages at the Volkswagen Golf IV, Energy Equivalent Speed EES in the range between 51 to 55 kph

Vehicle kinematics

The video analysis indicated a Δv in the range of 5 kph to 6 kph for the truck and a Δv of 64 kph for the Golf IV for the x-direction (parallel to the longitudinal axis of the vehicles), figure 12 and 13.

The measured deceleration of the vehicles during the collision is shown in figure 14. The maximum peak value was in a range of 4.9 to 6.0 g for the MAN TG-A and 41.7 and 53.8 g for the Golf IV.

VW Golf IV: $v_{K,x}$ = 42 kph; v'_x = -22 kph; Δv_x = 64 kph

MAN TG-A: $v_{K,x}$ = -21 kph; v'_x = -16 kph; Δv_x = 5 kph

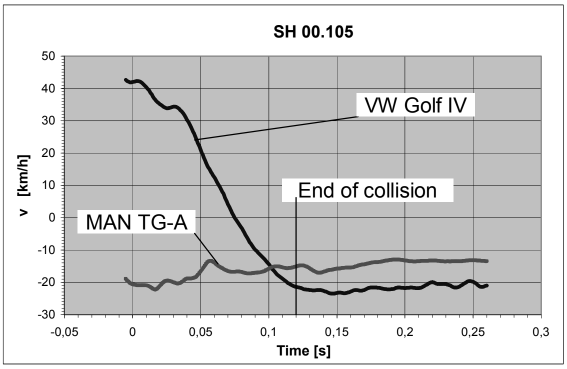


Figure 12. Impact velocity $v_{K,x}$, velocity at the end of the collision v'_x and change of velocity Δv_x, all in x-direction for truck and car in crash test SH 00.105 as result of video analysis.

VW Golf IV: $v_{K,x}$ = 42 kph, v'_x = -22 kph; Δv_x = 64 kph

MAN TG-A: $v_{K,x}$ = -21 kph; v'_x = -15 kph; Δv_x = 6 kph

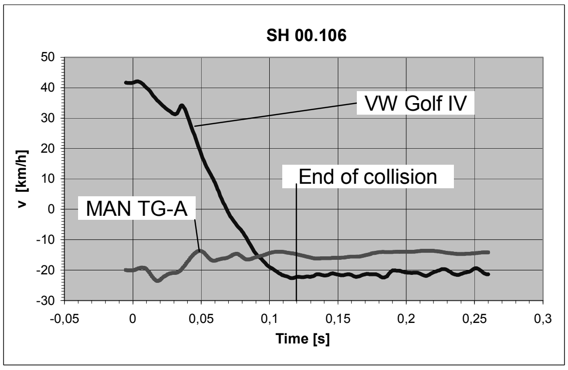


Figure 13. Impact velocity $v_{K,x}$, velocity at the end of the collision v'_x and change of velocity Δv_x, all in x-direction for truck and car in crash test SH 00.106 as result of video analysis.

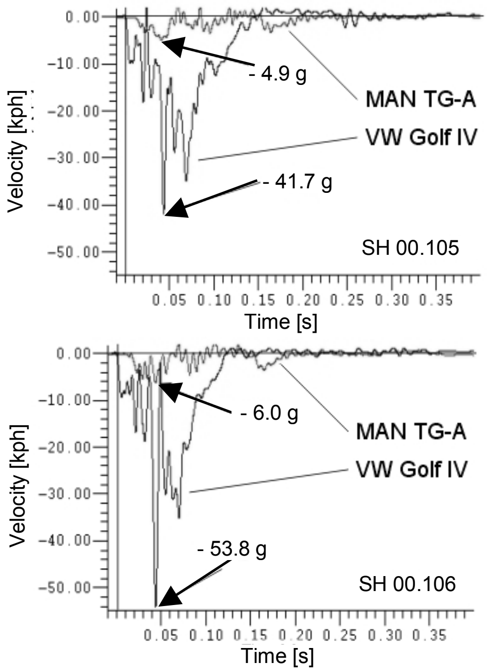


Figure 14. Measured decelerations of the vehicles during the collision

Dummy loads

Figure 15 shows the measured head loads of the truck and car occupants. As shown in these diagrams the Head Injury Criterion (HIC) of the truck driver dummy was very low, HIC = 1. The HIC value of the car driver dummy was between HIC = 288 and HIC = 510 and the resulting acceleration (3-ms-value) a_{3ms} = 44 g and a_{3ms} = 60 g. The corresponding values for the passenger were between HIC = 269 and HIC = 242 and a_{3ms} = 41 g and a_{3ms} = 42 g. All these measured values lay far below the biomechanical limits of 1000 for the HIC respectively 80 g for a_{3ms}.

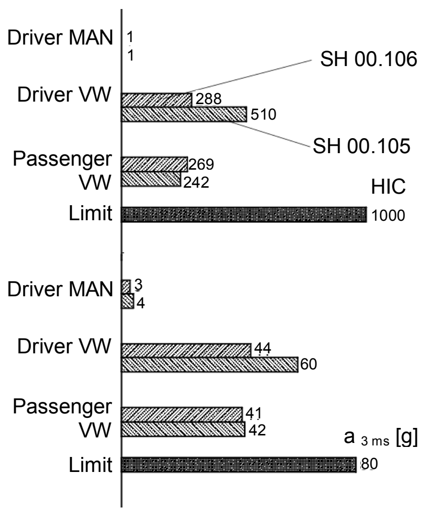


Figure 15. Measured dummy head loads

The measured dummy chest loads show the same tendency, figure 16. For example, the measured value a_{3ms} for the truck driver was a_{3ms} = 2 g respectively a_{3ms} = 3 g, for the car driver a_{3ms} = 45 g respectively a_{3ms} = 41 g and for the passenger of the car a_{3ms} = 42 g respectively a_{3ms} = 37 g. The corresponding limit is a_{3ms} = 60 g.

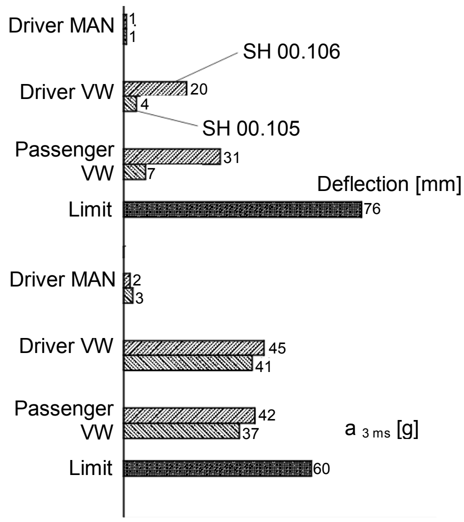


Figure 16. Measured dummy chest loads

As shown in figure 17 the loads (compressive force) for the right and left femur of the truck driver dummy were also very low: F = 0.1 kN respectively F = 0.2 kN. For the car driver dummy this measure ranges between F = 1.8 kN to 2.4 kN and for the passenger dummy F = 0.4 to 1.8 kN. The corresponding limit is F = 10 kN.

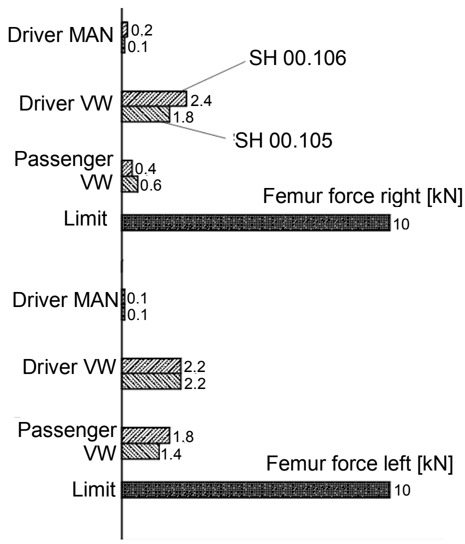


Figure 17. Measured compressive forces for the right and left femur of the dummies

The measurements show very low loads for the truck driver dummy at a glance. According to the measured data of the car driver and the car passenger dummy, all loads lay under their corresponding biomechanical limits. In general the measured loads of the dummies lay in the range of such results of good performing cars for a EURO NCAP crash test (frontal collision with 64 kph against a deformable barrier). Of course, the good results for the car occupant dummies are not only a result of the front underride protection of the truck but also a result of the high passive safety level of the Volkswagen Golf IV.

REAR UNDERRIDE PROTECTION

Rear underride protection is mandatory for trucks in Germany since many years now. This item was already analyzed in former crash tests done by MAN in co-operation with the Technical University of Berlin in the year 1987, Figure 18.

Figure 18. Crash tests conducted by MAN in co-operation with the Technical University of Berlin in the year 1987 to analyse the benefit potential of truck rear-underride protection

The current European Regulation ECE-R 58 (published on April 18th, 1979) describes the geometry and the static test forces for a rigid rear underride protection, Figure 19.

But despite this protection some severe real world crashes occur first of all at high closing velocities on rural roads, especially the Autobahn. Amongst the severe accidents involving trucks and cars the share of crashes onto the rear end of a truck cannot be neglected, see table 2 and figure 1. As a result of in-depth studies of such crashes it has become obvious that the demands described in the current version of ECE-R 58 should be improved to meet the real world requirements more effectively.

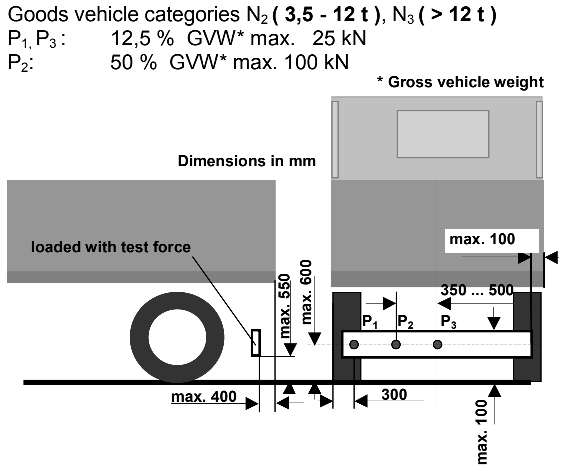


Figure 19. Mount dimensions, global dimensions and static test forces for the rear underride protection described in ECE-R 58

The performance of the rear underride protection can be improved by modifications of the ground clearance and static test loads. Therefore a proposal was agreed by the committee for motorized vehicles (Fachausschuss Kraftfahrzeugtechnik FKT) advising the German national secretary of traffic, table 3.

Table 3.
Proposal for improving the European Regulation ECR-R 58

	Trucks with air-suspension	Trucks with steel-spring suspension
Maximum ground clearance of rear underrun protection (unloaded condition)	450 mm	550 mm
Maximum height of points of test force application	500 mm	600 mm
Static test forces P_1, P_3 Static test force P_2	25 % of GWV, max 50 kN 50 % of GWV, max 200 kN	

The allowed ground clearance should be reduced from 550 mm to 450 m for trucks with air suspension (and remain at 550 mm for those with conventional steel springs) in unloaded condition. The static test forces should be doubled.

Experiences prove that the proposed ground clearance meets practical demands. But the test loads could be more reinforced. In addition, the use of energy absorbing parts give the potential to improve the performance of rear underride protection (KUPPA et al., 2001).

MAN developed an energy absorbing rear underride protection, figure 20, following the results from accident research and using the experience with the front underride protection as described before.

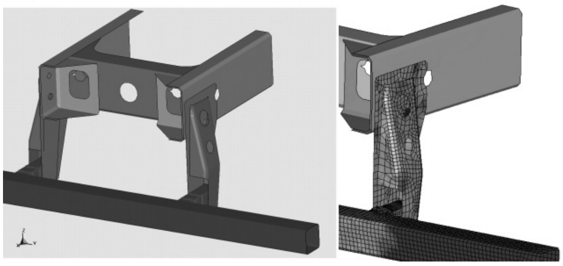


Figure 20. Numerical FEM simulation for an advanced energy absorbing rear underride protection

This device do not only meet the requirements of the proposed amendments of ECE-R 58 (see table 2). It is designed to avoid fatal and severe injuries of car occupants for a closing velocity between the truck and a car up to 74 kph. The underride protection should be able to absorb 40 % of the total kinetic energy of such a crash. Demands on weight optimisation and the mounting of the same underride protection part to several trucks with different heights of their supporting frame parts were also taken into account.

Latest results of numerical FEM simulation pointed out a maximum energy absorbing capacity of 78 kJ for this advanced rear underride protection device. This energy absorbing capacity is larger than that for the front underride protection device (see earlier description). This is due to the fact that not only the folding box beams but also the mount brackets are involved in the energy absorption of the entire system.

Hardware tests to prove the results of the FEM simulation and to demonstrate the benefit potential in rear and crashes with trucks and cars will follow.

SUMMARY AND FUTURE PROSPECTS

With regard to avoid or minimise the outcomes of traffic accidents involving trucks and other road users the so called partner protection is of very importance. Accident researchers and developing engineers have identified that the underrun protection with improved performance plays an important role in this context.

With the energy absorbing front underrun protection device that is already under production for the current MAN TG-A series and a new rear underrun protection device, the potential of such advanced systems is shown. Full scale crash tests have proven the results of the numerical simulations for the energy absorbing front underride protection. Full-scale tests to demonstrate the performance of the energy absorbing rear underride protection device will follow soon.

Accident researchers from the German Insurance Companies (GDV) have estimated the figure of killed persons in car to truck-rear-end crashes in the European Community to be in a range up to 350 for the year 1997. It was found that an improved rigid rear underride protection device fixed at all trucks could save a minimum of one third ($^1/_3$) of the killed and injured persons. This could save social costs of approx. 75 million EURO per year.

For a rigid front underride protection at all trucks a corresponding benefit was found to save 924 lives and 19,080 severe injured persons. An energy absorbing front underride protection could save 1,176 killed persons and 23,760 severe injured.

It is the new task for the accident research to observe the performance of the new and advanced systems and their additional benefits for a better partner protection in the whole range of complex real-world accidents.

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