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CRASH COMPATIBILITY BETWEEN HEAVY GOODS VEHICLES AND PASSENGER CARS: STRUCTURAL INTERACTION ANALYSIS AND IN-DEPTH ACCIDENT ANALYSIS

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Abstract

Due to Directive 2000/40/EC, all new Heavy Goods Vehicles must be equipped with Front Underrun Protection according to instructions given by the Economic Commission for Europe Regulation No. 93 after August of 2003. The Front Underrun Protection should prevent the truck overriding the car during a collision and therefore decrease the severity of the accident. A comparison of structures in Heavy Goods Vehicles and passenger cars was undertaken along with in-depth accident investigations using specially made 3D geometric models of the vehicles in position just before a collision. It was found that the regulation is not sufficient to ensure a Front Underrun Protection serves its purpose. The findings were used to develop suggestions for an improvement of the regulation together with guidelines for an improvement of Front Underrun Protection.

Keywords: Crash compatibility, Front underrun protection, FUP, Front underrun protection devise, FUP, Front underrun protection system, FUPS, Overriding, Underrunning, Directive 2000/40/EC, Regulation 93, R93

Résumé

Suite à la directive 2000/40/EC, tous les poids lourds neufs doivent être équipés de protection contre l'encastrement à l'avant selon les instructions de la règle de la commission économique européenne No 93 depuis août 2003. La protection contre l'encastrement à l'avant est faite pour empêcher un camion d'écraser une voiture lors d'un accident et ainsi diminuer la gravité de l'accident. Une comparaison de structures de poids lourds et de voitures a été effectuée parallèlement à des études détaillées d'accidents utilisant des modèles 3D géométriques spécialement élaborés, représentant les véhicules en position juste avant une collision. La règle s'est avérée insuffisante pour assurer que la protection contre l'encastrement à l'avant remplisse son rôle. Les résultats de l'étude ont été utilisés pour suggérer des améliorations de cette règle ainsi que des indications pour améliorer la protection contre l'encastrement à l'avant.

Mots-clés : Compatibilité des véhicules**,** protection anti-encastrement (FUP), dispositif anti-encastrement à l'avant, encastrement, 2000/40/EC, R93, règle 93.

1. Introduction

Compared to all traffic accidents, the number of frontal crashes between Heavy Goods Vehicles (HGV, i.e. trucks with maximum vehicle mass equal to or over 12 tons) and passenger cars occur relatively seldom. Unfortunately, most of these collisions result in death or severe injuries for the passenger car occupants. The reason can be attributed to the great difference between the structure and mass (and thereby stiffness) of the two types of vehicles. Through its deformation, the weaker passenger car absorbs a higher amount of kinetic energy involved in the collision than the truck does. Due to the different structural designs between trucks and cars, their energy absorbers do not coincide. Usually the main longitudinals (longitudinals in following text) of a car are placed at a level that is under a truck's frame rails (rails in following text). The absence of other force resisting parts in the truck's front at the level of the car longitudinals (or even below them) causes overriding of the car by the truck during a collision. The contact forces are directed into the higher placed and softer parts of the car. This is often followed by the contact between the engine of the car and the stiff parts of the truck. Insufficient energy dissipation of the car's front softer structures causes intrusion into occupant compartment while the truck undergoes minimal deformations and little energy absorption.

Rechnitzer (1993) gave a detailed study of accidents between heavy vehicles (defined as vehicles >3.5 tons Gross Vehicle Mass) and passenger cars. The model year of the newest car in frontal crashes was 1989 and most trucks had bullbars. Based on accident investigation, he recommended that trucks should be fitted with an energy absorbing front barrier. Using an analytical model, the performance of a concept energy absorbing (e.a.) under-ride guard was investigated (Rakheja et al, 1999). It was concluded that the proposed guard could take up to 80% of the kinetic energy associated with the car's mass during impact. In the model, a space available in the front of a Cab-Over-Engine truck design (the common truck design in Europe) was not considered. Due to legal demands on vehicle lengths in Europe and the fact that any extension in the front end would decrease the available length for payload, the space for safety equipment is very limited (Forsman, 2002).

A statistical analysis of truck-car accidents in Europe for a time period between 1995 and 2001 year (Gwehenberger et al., 2003) showed that the percent of fatalities among passenger car occupants was still unacceptable. In response to the problems associated in car-truck frontal accidents, all manufacturers of trucks are obligated to equip HGVs with Front Underrun Protection (FUP) due to Directive 2000/40/EC that took effect in August 2003. The FUP has to obey Economic Commission for Europe Regulation No. 93 (ECE R93). This FUP requirement should offer effective protection of passenger cars against underrunning trucks in the event of frontal collisions. Seven tests carried out within the Improvement of Vehicle Crash Compatibility through the Development of Crash Test Procedures (VC-Compat) project and reported by de Coo et al. (2006) showed that a standard production "rigid" FUP complying to the requirements of the regulation is sufficient to prevent overriding in all laboratory test cases but the dummy injuries generally increase with increasing impact speed and exceeds the safe level in some cases already at a closing speed of 64 km/h. According to Gwehenberger et al. (2003) only 30% percent of fatal car-to-truck head-on crashes occur at closing speed less than 120 km/h while the tests done with FUP devices refer to much lower closing speeds. It seems that there is a need for developing a car occupant device even for higher speeds. More protection for the passenger car is possible if the FUP absorbs energy, as proposed by Rechnitzer (1993). VC-Compat tests with standard production e.a. FUP failed to trigger deformations of the e.a. FUP and therefore could not show a significant benefit of having FUP with energy absorbing capabilities. A test with a special designed FUP device showed some advantages of having e.a. FUP, at least for one test case. However, injury risk based on HARM calculations from fleetwise simulation studies (Schram et al., 2006) showed that an e.a. FUP is beneficial compared to a rigid FUP.

Performing full frontal rigid wall crash tests, Pipkorn et al. (2005) showed that there is a possibility for efficient car passenger protection at frontal impacts up to 80 km/h. This raises the question of what can be done to reduce injuries in car-to-truck accidents at higher speeds than those implemented in the car-truck tests. Where reasonable car protection was observed, the tested passenger cars and trucks had well matching heights of FUPs and car longitudinals. Is this the case in reality? Why did not standard production e.a. FUP perform well in VC-Compat test? Two research questions arise from the preceding discussion:

1) Is a FUP that fulfils the requirements in ECE Regulation No. 93 sufficient to prevent overriding of the passenger cars by trucks and/or decrease the level of severity in real accidents?
2) If the answer to the first question is "no", what should be done in order to obtain a more efficient FUP?

By comparing structures of HGVs and passenger cars that travel on European roads together with detailed in-depth investigation of crashes between FUP equipped HGVs and cars, answers to the two research questions have been investigated.

2. Methodology

The structures of European passenger cars and trucks were analyzed from a structural interaction point of view. The results were also compared to dimensional limits given in the Regulation No. 93. The VC-Compat car and truck structural/geometrical databases have been used as the basis for the analysis of the truck and car structures. The database contains structural information for 55 passenger cars and 98 trucks with a mass greater or equal to 12 tons.

Detailed in-depth accident analyses of head-on crashes between passenger cars and trucks have been performed. Three accident databases were searched: 1) National Automotive Sampling System - Crashworthiness Data System (NASS CDS) the crash database of National Highway Traffic Safety Administration (NHTSA, U.S.A.), 2) Pan-European Co-ordinated Accident and Injury Database (PENDANT - Europe), and 3) fatality accidents from the Swedish Road Administration – Western Region (SRA-WR). The search was restricted to well documented front-front, single impact crashes between a truck equipped with FUP and a passenger car produced later than 1998. An accident is considered well documented when the report included photos of the deformation of both vehicles and information about the situation just before the accident.

The accident analyses were based on the vehicles' structural information and data collected from the accidents. As the structural database does not provide enough structural information about trucks and does not cover all passenger car models involved in the accidents, some of the structural information was taken directly from manufacturers. For every selected case, a 3D geometric model of the vehicles, positioned just before the accident, was made. The models were made using Pro-Engineer Wildfire 2.0 software and are based on real dimensions and data from the accident databases. In the analysis, the emphasis was on the causality of the contact (or its absence) between relevant structural components and their deformations.

3. Structural Interaction Analysis and Discussion

In order to prevent an overriding of a passenger car, a FUP has to be designed in such a way that it is able to stop the longitudinals of passenger cars moving into the space under the rails of the truck. Therefore, it is expected that the FUP cross-member overlaps vertically with car longitudinals during the accident. This was taken into consideration by Regulation 93 but it refers only to unladen trucks allowing maximum FUP cross-member clearance of 400 mm and its section height not less than 120 mm. When comparing the FUP cross-member and car longitudinal relative placements, the overlap in height is fairly good for almost all trucks and cars from the VC-Compat database if the trucks are unladen. The situation changes for fully laden trucks. Despite the fact that almost all trucks obey the regulation, most in the fully laden state have their FUP cross-members placed very low compared to longitudinals of passenger cars, see Figure 1.

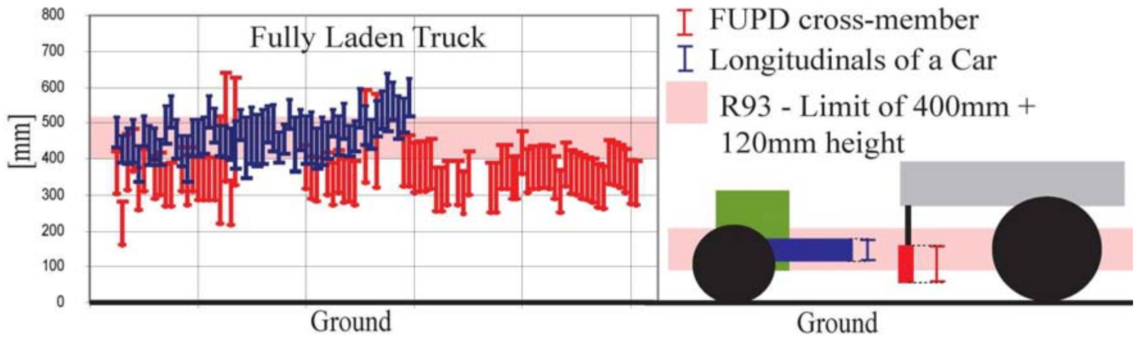

Figure 1 – Comparison between position of FUP cross-members when trucks are fully laden, and longitudinals of cars. A limit for FUP cross-member clearance and its section height in accordance with Regulation 93 is included.

When the rails of fully laden trucks are included, the situation gets worse. Longitudinals of passenger cars are positioned at the level between FUP cross-members and rails of trucks, see Figure 2a.

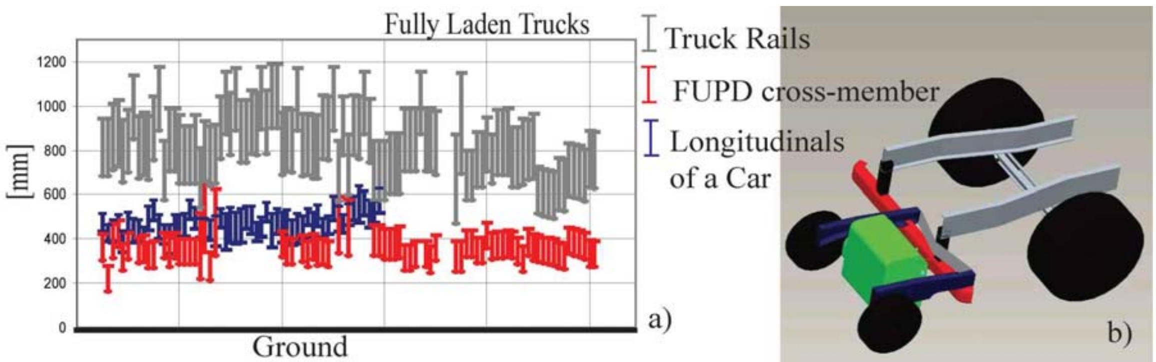

Figure 2 – The longitudinals of cars, rails of trucks and belonging FUP cross-member: a) relative placement b) possible impact scenario.

During a collision this situation may lead to an impact between one of the usually very stiff FUP cross-member supports and the softer parts of the car (see Figure 2b). Both examples imply that it might be useful if the regulation also gives a lower limit of the FUP cross-member clearance and even increases the limit for the section height of the cross-member.

A comparison between placements of the car engine to the rails of the trucks (Figure 3) shows the possibility of contact between the car engine and truck rails during a collision. The contact happens for unladen and fully laden trucks. Figure 3 is showing the situation for fully laden trucks. The resulting contact between these two structures might cause intrusions into the car's occupant compartment. It might be useful to consider modification of the front design of trucks. By raising only the front portion of truck rails (as presented in Figure 3b), the contact between car engine and truck rails will be prevented. In the proposed design, even the section height of the FUP cross-member could be increased and could therefore cover a wider range of positions of passenger cars' longitudinals.

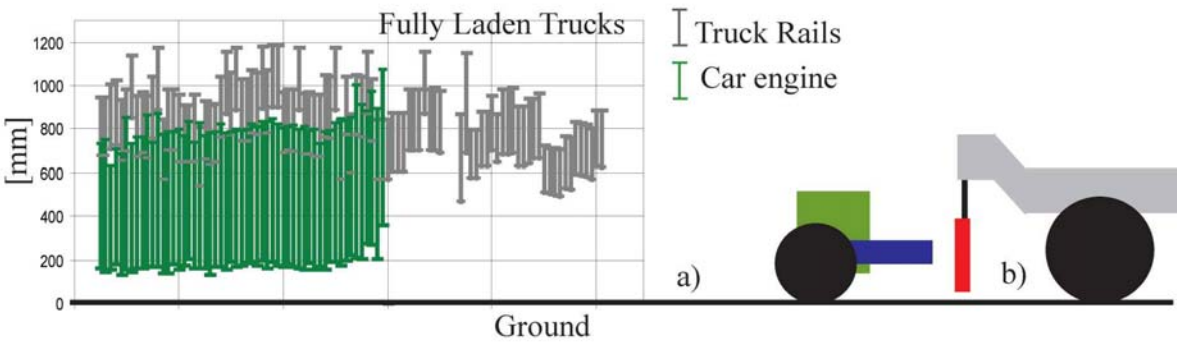

Figure 3 – Engines of cars and rails of trucks: a) relative placement, b) proposed modification of front truck design

4. In-Depth Accident Analysis and Discussion

In the NASS database there were no cases satisfying the search criteria (see Section 2). The SRA-WR database contained three cases satisfying the criteria of which two were also found in the PENDANT database. Besides these three cases, one more accident case from the SRA-WR database has been investigated although the truck involved in the accident was not equipped with a FUP. All accidents resulted in passenger car driver death, while truck drivers survived with minor injuries. There were no other occupants in the cars or trucks.

A short description of every accident is given below with photos, 3D models of the vehicles, and a discussion.

Accident Case I: A half laden truck (model year 2000) with trailer was involved in a frontal collision with a passenger car (model year 1998). The overlap for the car was 100% and 50% for the truck. The crash was severe and fatal for the car driver. The speed of the truck was 80 km/h while the car was travelling at a speed of approximately 90 km/h. The clearance and a section height of the FUP cross-member (for half laden truck) fitted well with the longitudinals of the car. The car was overridden by the truck at its left side (see Figure 4). During the collision, the connection between the truck's left cross-member support and base bracket was broken. The FUP bent down and let the car underride the truck, striking the left suspension bracket of the truck. This caused bending of lower suspension arm. The car bounced up and came into contact with the upper part of the front of the truck (highlighted in Figure 4e). The right longitudinal of the car was untouched, while the left one was deformed on the upper side but remained straight (highlighted in Figure 4d). The car compartment experienced intrusions. The car's subframe did not come into contact with any of truck parts.

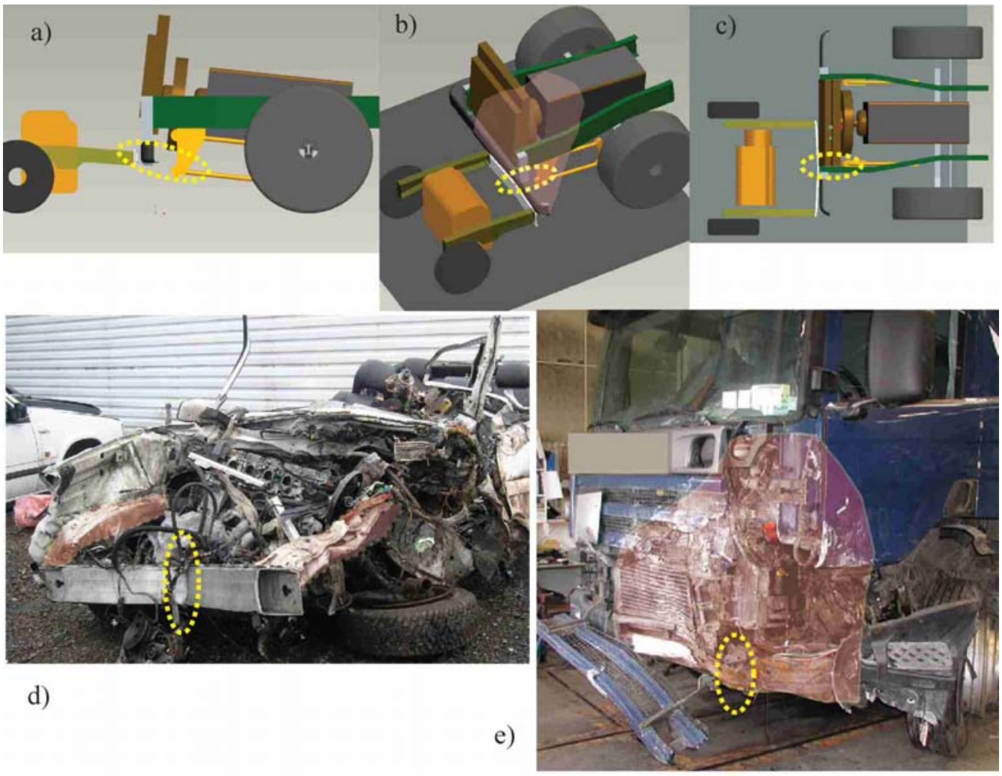

Figure 4 – Case I. 3D geometric models of the vehicles at the position just before the accident: a) side view, b) isometric view, c) top view. The vehicles after the accident: d) the car, and e), f) the truck. The dashed ellipses indicate matching impact points.

The FUP of the truck passed tests at points P2 and P3 but failed at point P1 according to Regulation 93. As the point P1 refers to outmost part of the FUP cross-member it does not look like that was the main reason for FUP failure.

Accident Case II: The case refers to a head-on collision between a fully laden truck (model year 2002) with trailer and a passenger car (model year 2001) with an impact angle between 15^o and $30^{o.}$ The truck speed was 60 km/h and the car was traveling at approximately 70 km/h. Even though the FUP on the truck was the same as in Case I and the passenger car had a structure similar to the car in Case I, the passenger car was not overridden. Both longitudinals of the car were deformed. The left one deformed in such a way that allowed efficient energy absorption and the right one was partly bent up (highlighted in Figure 5c). The car compartment was subjected to intrusions and the driver of the passenger car died in the accident.

As in the previous case, longitudinals of the car and the FUP cross-member matched well in height. The force applied at left base bracket of the FUP was lower than in the previous case due to the lower speed and the impact angle different from 0^o (Figure 5b, dashed arrows). The impact angle, smaller overlap and weaker outward side of the FUP cross-member caused the vehicle to turn around the left truck corner and then contact the truck suspension which then bent inward but did not break. The FUP and a component of the suspension system at the level of the car longitudinals caused almost even deformation of the car front (see Figure 5). The car compartment was subjected to intrusions. It seems that even in this case the speed was too high for only the car to take up almost all the kinetic energy.

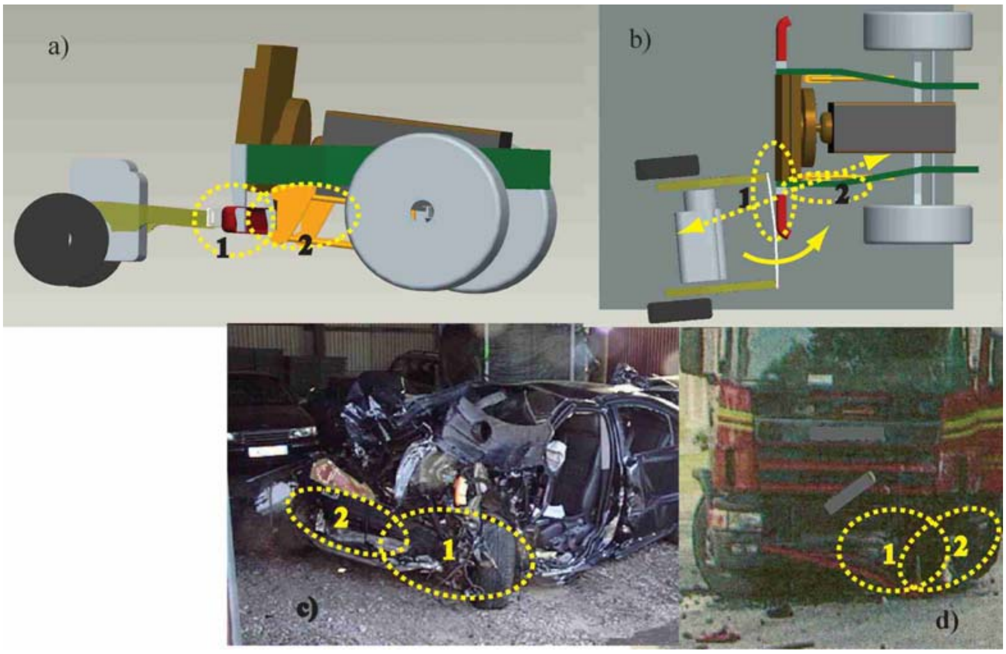

Figure 5 – Case II. 3D geometric models of the vehicles at the position just before the accident: a) side view, b) top view. The vehicles after the accident: c) the car and d) the truck. The dashed ellipses indicate the matching impact points before and after car rotation.

Accident Case III: A truck (model year 2003) and trailer collided with a passenger car (model year 1998). The truck was equipped with an energy absorbing FUP. Both, the calculated Equivalent Energy Speed for the passenger car and closing speed were about 115 km/h. Both vehicles traveled with speeds less than or equal to 90 km/h. The offset was approximately 75%. The passenger car driver died in the accident.

The left energy absorbing (e.a.) element of the FUP was completely crushed. The crushed body of the left e.a. element completely filled the space between the FUP cross-member and the left suspension element (Figure 6). The cross-member bent horizontally in front of the left e.a. element and remained straight on its right side. The right e.a. element remained untouched. The car was not overridden but was severely crushed. Most of the impact force was focused on the left front side of the car. The passenger compartment was subjected to intrusions.

A solution for a more efficient energy absorbing (e.a.) FUP might be a FUP with a cross-member of high bending resistance supported by energy absorbing structures at more than two points. The supports should be placed beside the suspensions instead in front of them in order to use all available space between suspensions and the cross-member. The cross-member must be forced to move parallel to its mounting position. This will enable simultaneous deformation of all the e. a. elements (See Figure 7).

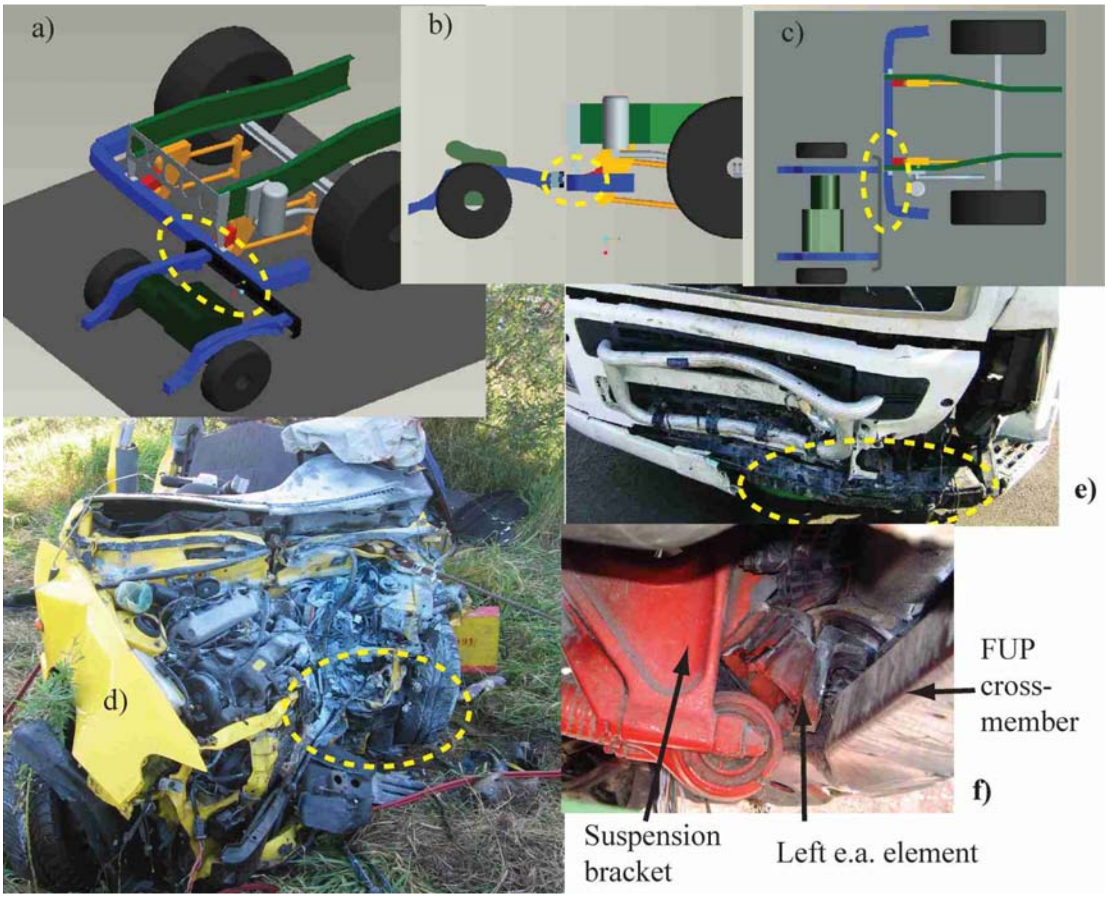

Figure 6 – Case III. 3D geometric models of the vehicles at the position just before the accident: a) isometric view, b) side view c) top view. Photos of the vehicles after the accident: d) the car and e) the truck, and f) deformed left e. a. element. The dashed ellipses indicate the matching impact point.

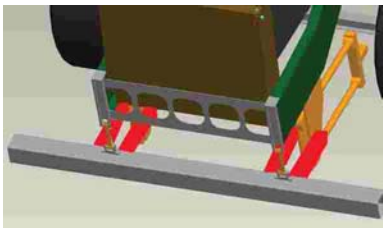

Figure 7 – Proposal for a more efficient e. a. FUP. Energy absorbing elements are represented by red parts

Accident Case IV: A truck (model year 2000) travelled at a speed of 93 km/h when a truck driver noticed a passenger car (model year 2000) coming from the opposite side. After hard braking, the speed of the truck was reduced to 40 km/h. The speed of the passenger car was unknown. There were no intrusions into occupant compartment. The passenger car driver did not use a seat belt and died as a result of the accident.

The truck was not equipped with a FUP. Although longitudinals of the car were placed at a level under any hard part of truck the passenger car was not overridden in the accident. The car was stopped by contact between the car engine and truck radiator which was supported by the truck engine. Forsman (2002) pointed out that truck radiator systems are often engaged in crash decreasing an impact force. It might be that in this crash some amount of the kinetic energy was also absorbed by the truck cooler components. If the car engine was placed on the right side (see Figure 8), instead the gearbox, it would have hit the truck rails and probably caused intrusions into the occupant compartment. This again suggests the need to consider modification of the front design of trucks in order to prevent contact between their stiff rails and the engine of passenger cars (see Section 3).

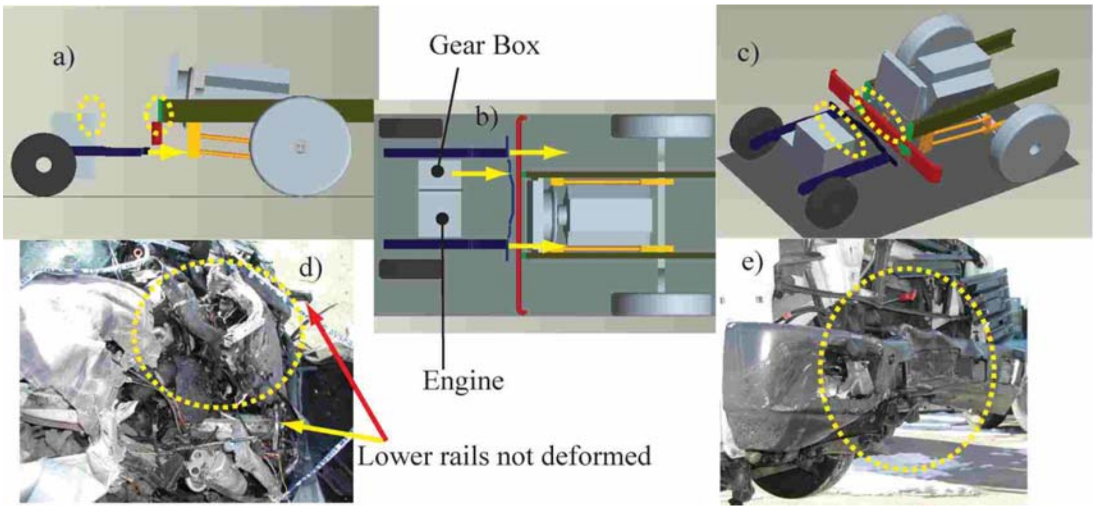

Figure 8 – Case IV. 3D geometric models of the vehicles at the position just before the accident: a) side view, b) top view c) isometric view. The vehicles after the accident: d) the car and e) the truck. The dashed ellipses indicate the matching impact points.

The previously proposed modification with the raised rails might be of benefit. The raised rails prevent contact between a car engine and rails of the truck but allow contact between a car engine and a truck radiator for a larger range of lateral overlaps (see Figure 9).

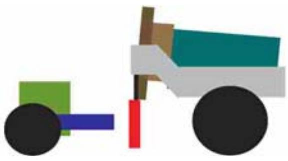

Figure 9 – Solution proposed for making use of truck cooler as energy absorbing element during an accident

5. Conclusions and Suggestions

The answer to the first research question – is a FUP designed according to ECE Regulation 93 sufficient - is “not always”. The second research question was to identify improvements for FUP design and performance addressing the deficiencies identified. The conclusions from this work are listed below and are followed by suggestions how to improve the efficiency of a FUP:

- Regulation 93 prescribes the upper limit for the FUP cross-beam clearance for trucks in their unladen state. Due to vertical settling of the truck due to the load, the FUP cross-beam clearance for most fully laden trucks are under the longitudinals for most of the cars. This might be solved if the regulation also restricts a lower limit of the FUP cross-member clearance as well as increases the limit of a section height of FUP cross-member.

- Regulation 93 does not say anything about the amount of kinetic energy that should be absorbed by the FUP and most truck manufacturers concentrate on the production of statutory "rigid" FUPs. The investigation of the crash cases in this paper showed that a statutory "rigid" FUP has to have a high bending stiffness and be able to resist higher forces than currently specified by Regulation 93. Otherwise, the FUP will not be sufficient to prevent overriding of a passenger car in all frontal crash situations.
- Statistics and investigated crash cases have showed that even higher closing speeds should be considered when designing and testing FUPs. Regulation 93 should contain specifications about energy absorbing limits for a FUP. Unfortunately insufficient information is available in the accident databases to identify impact speed distributions for car-truck impacts. As a first step, available car-car impact speed distributions should be further reviewed and modified to include car-truck mass ratios.
- It might be useful to include the truck radiator as an energy absorbing element in head-on crashes and also prevent contact between a car engine and truck rails by raising the frontal portion of the rails as suggested previously.
- Energy absorbing FUPs did not perform as expected in crash tests. To increase the amount of kinetic energy absorption, an energy absorbing FUP with more than two energy absorbing elements and a more efficient exploitation of available space has been suggested.

Certainly Regulation 93 is not sufficient to ensure a Front Underrun Protection serves its purpose for all crash conditions. An improvement of the regulation must be considered and production of energy absorbing FUPs should be encouraged instead of the statutory "rigid" FUPs. Further work in improving the regulations can be addressed through parametric studies of truck-car structural interactions. The proposed design changes are under investigation to determine if they are technically feasible and suitable for commercial production.

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