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ALEKSANDRA KRUSPER Structural Interaction between Vehicles

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An Investigation of Crash Compatibility between Cars and Heavy Goods Vehicles

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Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2014

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

in

Machine and Vehicle Systems

Structural Interaction between Vehicles

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Abstract

While frontal collisions between Heavy Goods Vehicles (HGVs) and passenger cars are rare compared to car-to-car frontal crashes, they are much more severe. Between 43% and 73% of all frontal car-to-truck accidents result in fatalities. The severity is due to crash incompatibility between the vehicles that has been generally agreed to arise from differences in mass, stiffness and geometry and it refers not only to car-to-truck collisions but also to most vehicle-to-vehicle collisions. To address incompatibilities between passenger cars and HGVs, Front Underrun Protective Devices (FUPDs) are obligatory equipment for HGVs produced after August 2003. To date, there is insufficient research describing the efficiency of statutory and energy absorbing (e.a.) FUPDs in real traffic collisions.

The aim of the research presented in this thesis is to understand and suggest improvements for the compatibility between trucks and passenger cars through parametric studies of different design and collision configurations where the compatibility between trucks and cars is seen as an indivisible part of overall crash compatibility between vehicles. The focus was the requirements for energy absorbing FUPDs to overcome the unpredictable behaviour of passenger cars in frontal collisions by studying the links between geometry and stiffness as influenced by crash configuration and structural interaction. The bending stiffness of e.a. FUPD cross-beams, their height, and triggering force for energy absorbing elements were found to be important characteristics of e.a. FUPD that influence the outcome in collisions between HGVs and passenger cars.

The stable response of vehicle structures was identified as an important issue to understand. A new analysis approach, called the RED method, was developed and presented. Using energy absorption and impact forces calculated in FE simulations, the RED method gives more insight into structural deformation processes than other methods and thereby improves the evaluation of vehicle structures. Information derived from the procedure was used to develop two new assessment criteria - Structural Efficiency and Crash Stability – that can be used to objectively quantify the crash response of vehicles. Because the method is based on FE crash simulations it can be used in the development as well as production phase of a vehicle crash structure or even other structures where deformation modes are important. It was shown that these criteria can be used in compatibility rating where a new perspective on compatibility is introduced and applied.

Keywords: crash compatibility, Front Underrun Protection, FUP, Front Underrun Protective Device, FUPD, Heavy Goods Vehicles, HGV, structural interaction, simulation, energy absorption, compatibility assessment.

List of appended papers

The thesis comprises the following five papers, referred to by Roman numerals:

PAPER I

Krusper, A. & Thomson, R., (2008), **"**Crash compatibility between heavy goods vehicles and passenger cars: structural interaction analysis and in-depth accident Analysis", *Proceedings of International Conference on Heavy Vehicles, Paris, France, 2008*

PAPER II

Krusper, A. & Thomson, R., (2010), "Energy-absorbing FUPDs and their interactions with fronts of passenger cars", *International Journal of Crashworthiness,* 15: 6, pp. 635 – 647

PAPER III

Krusper A. & Thomson, R., (2010), "Crash performance of front underrun protective device with a passenger car under different crash configurations - Results of finite element method based simulations", Research report 2010:0*7*, *Chalmers University of Technology*

PAPER IV

Krusper, A. & Thomson, R. (2012), "Truck frontal underride protection – compatibility factors influencing passenger car safety", *International Journal of Crashworthiness*, 17: 2, pp. 217 – 232

PAPER V

Krusper, A., Thomson, R. & Abrahamsson, T. (2013), "An energy based assessment method for dynamic response of impacting structures", *Submitted to International Journal of Crashworthiness*

PAPER VI

Krusper, A. & Thomson, R., (2013), "Further development of the RED method to vehicle structural performance: assessment of crash compatibility", *Submitted to International Journal of Vehicle Safety*

Author's statements of contributions:

Paper I
The in-depth accident analysis, geometrical models and conclusions were made by Krusper. Both authors took part in discussion. The paper was written by both authors.

Paper II
The basic idea for simplified e.a. FUPD is Thomson's. Krusper made the FUPD models and simulation matrix. The simulations, analysis and conclusions were made by Krusper. Both authors took part in discussion. The paper was written by both authors.

Paper III
Krusper made a simulation matrix, FUPD models, performed all simulations except those with smaller cars, corresponding analysis and made conclusions. Simulations with smaller

cars and corresponding analysis and conclusions were made by Thomson. Both authors took part in discussion. The paper was written by both authors.

Paper IV
The FUPD and HGV models were made by Krusper. Krusper performed the simulations, analysis and conclusions. The paper was written by both authors.

Paper V
The idea for the RED method is Krusper's. The calculations, simulations, analysis, and conclusions were made by Krusper. All authors took part in discussion. The paper was written by all authors.

Paper VI
Further development of the RED method and its application is done by Krusper. All the simulations, analysis and conclusions were made by Krusper. Both authors took part in discussion. The paper was written by both authors.

List of complementary papers

In addition to papers I-VI, the following publications resulted from the work carried out in the Ph.D. program:

Paper 1
Thomson, R., Krusper, A., Avramov, N., & Rachid, K., (2008), "The Role of Vehicle Design on Structural Interaction", *Proceedings of International Crashworthiness conference 2008, Kyoto, Japan*

Paper 2
Thomson, R., Krusper, A., O'Brien, S. & Adolph, T., (2012), "The influence of FIMCAR test procedure on other impact types", *D6.4, Final report, FIMCAR project*

Paper 3
Thompson, A., Edwards, M., Wisch, M., Adolph, T., Krusper, A. & Thomson, R., (2011), "Report detailing the analysis of national accident databases", *D1.1, Final version, FIMCAR project*

These publications are not appended to the present thesis. They were used as an input for the research.

Preface

The research presented in this thesis was part of the project "Compatibility between vehicles" and is partially performed in co-operation with project partners: Volvo Car Corporation - VCC, Saab Automobile, Volvo 3P, Scania and Autoliv Research. The project also was partially financed by VINNOVA (Swedish Governmental Agency for Innovation systems), Program for Vehicle research (PFF – Programrådet För fordonsfrskning). It mostly was carried out at SAFER (Vehicle and Traffic Safety Center at Chalmers) between 2006 and 2011 and partially during 2013 and 2014. Participation in European projects VC-Compat (during 2006) and FIMCAR (2009-2011) as well as the visit to NCAC (National Crash Analysis Center)/George Washington University (Septemper 2008 – Mars 2009) contributed to the research.

Acknowledgments

I would like to thank to representatives of the project partners for their contribution to the research, NCAC for sharing their models with the rest of the world and for their hospitality during my work at George Washington University for 6 months, Swedish Road Administration – Western Region (Vägverket-Väst) and Pan-European Co-ordinated Accident and Injury Database (PENDANT – Europe) for allowing me to use their databases, And members of VC-Compat and FIMCAR projects for collaboration.

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Prof. Thomas Abrahamsson was my co-supervisor during the last two years of the study. To him I would like to thank for great discussion concerning development of the RED method.

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The source of great inspiration at the end of my research was my work at Research & Development at VCC during two years period between 2011 and 2013. Thank you Ragnar Crona, Anders Sandahl, Anders Kling and other colleagues from VCC for sharing your experience with me.

Prof. Mats Svensson was a head of the division Vehicle Safety during most of my studies and I would like to thank him for his engagement when it was needed. Marianne Hedfors and Sonja Laakso-Gustafsson have been of great help during my Ph.D. studies. Thank you for that and your kindness. Thank you, all my colleagues at SAFER, for your contribution to the less stressful work and all joyful time we have spent together.

One big thanks to my friends for their support, especially to Violeta.

My brother Alexander I would like to thank for helping me with my first steps in Sweden, for his encouragement and love through all these years and for making me feel that he will be always somewhere there for me.

My mom Marija, my sister Duška and especially my dad Petar taught me the importance of education. Thank you for that and for your love and for your support.

Where would I be if my Susanne was not beside me? Thank you, thank you, and thank you, Susanne, for your love, your support and your unlimited patience.

Aleksandra Krusper
June 10, 2014

Glossary and acronyms

ADAC	Allgemeiner Deutscher Automobil-Club
ADOD	Average Depth of Deformation
Aggressivity	Injury risk faced by the occupants of the struck vehicle in collisions involving two vehicles
AHOF	Average Height of Force
AHOF400	Average Height of Force 400 - A measure of the vertical centroid of forces exerted on the barrier surface for the first 400 mm of crush
Closing speed	Relative approach velocity just before a contact between two colliding vehicles occurs
Compartment stiffness	A magnitude of the forces resisting structural deformation, exhibited by the occupant compartment of a given passenger vehicle
Crashworthiness	The ability of a structure to protect its occupants during an impact (self-protection)
Crash configuration	Relative position of colliding vehicles just before the crash occurred
EEVC	European Enhanced-safety Vehicle Committee
EVC	Enhancing Vehicle-to-Vehicle Crash Compatibility Agreement
FEM	Finite Element Method
FIMCAR	Frontal Impact and Compatibility Assessment Research
FMVSS	Federal Motor Vehicle Safety Standards
Frontal stiffness	Relation between force and displacement during crush of frontal structures
Frontal force	Magnitude of the forces resisting structural deformation, exhibited by the front-end of a given passenger vehicle
FUP	Front Underrun Protection
FUPD	Front Underrun Protective Device
FWDB	Full Width Deformable Barrier
FWRB	Full Width Rigid Barrier
GIDAS	German In-Depth Accident Study
HGV	Heavy Goods Vehicle
IIHS	Insurance Institute for Highway Safety

Kw400	Kw400 is a measure of the work required to crush 400 mm of a vehicles front end
Lateral/vertical fork effect	Horizontal/vertical misalignment of load paths arising during collision
MAIS	Maximum Abbreviated Injury Scale
MPDB	Mobile Progressive deformable Barrier
NCAC	National Crash Analysis Center
NCAP	New Car Assessment Programme
NHTSA	National Highway Traffic Safety Administration
Offset collision	Frontal collision where the vehicles' centrelines do not coincide
ODB	Offset Deformable Barrier
ORB	Override Barrier
PDB	Progressive Deformable Barrier
RED	Relative Equivalent Energy Displacement
Restraint system	Interior vehicle system designed to mitigate injuries in crashes, e.g. seatbelts, airbags, seats, …
RHC	Relative Homogeneity Criteria
SEAS	Secondary Energy Absorbing System
SUV	Sports Utility Vehicle
UN-ECE	United Nations Economic Commission for Europe
UTAC	The Union Technique de l'Automobile du motocycle et du Cycle (Technical Union for the Automobile, Motorcycle and Cycle Industries)
VC-Compat	Vehicle Crash Compatibility
Vehicle structure	Vehicle load paths
WG	Working Group
WP	Working Party

Table of contents

1. Introduction

Years of statistical analyses of traffic accidents involving Heavy Goods Vehicles (HGVs or trucks in further text) show that an unacceptable proportion of the accidents between passenger cars (cars in further text) and HGVs have fatal consequences for the occupants of cars (Rechnitzer, 1993; NHTSA, 1998; Improvement of crash compatibility between cars, 1999; Evans, 2004). Newer analyses show the same trend. Analysing the GIDAS database with accidents involving cars produced after 1991, Thomas (2005) found that 8.4% of all front-front impacts to passenger cars (including front single impacts of passenger car) refer to impacts with trucks and vans. In these types (all front-front impacts to passenger cars) of collisions, trucks and vans cause 16.7% of all MAIS 3+ injuries to car occupants. The relative risk of sustaining serious injuries in frontal car-to-truck (or van) accidents is 7.7%, but the corresponding statistic for front-front car accidents is 2.5% (Thomas, 2005). This suggests that in Germany, frontal car-to-truck accidents are rare compared to other accident types but the percentage of these accidents ending with dead and seriously injured passenger car occupants is high. A similar situation is found in other European countries. VC-Compat conducted a statistical analysis of traffic accidents involving trucks in European countries (Gwehenberger et al. 2003a). In the period between 1995 and 2001, the percentage of the fatalities involving trucks for different European countries was between 12.8% and 18.5% of all fatal road accidents. Approximately half of these (43 – 59%) are frontal car-to-truck accidents for all observed countries. For European countries in 2001, the percentage of fatalities in passenger cars colliding with HGVs was between 47% (United Kingdom) and 73% (Sweden) (Gwehenberger et al., 2003a). Fatalities were more often in rural (65-91%) than urban areas. More than a half of the accidents occur with closing speeds between 80 and 165km/h (Gwehenberger et al., 2003a and 2003b). Most of the fatalities occur in frontal passenger car-to-truck collisions (between 50 and 60% of all car-to-truck collisions). Björnstig at al. (2008) found that that trucks and buses, as a collision partner, killed five times as many as car occupants as passenger cars (as a collision partner) per kilometres driven in northern Sweden. Stigson et al. (2009) showed that a higher proportion of car-HGV crashes in Sweden had velocity changes greater than 45 km/h in comparison to passenger car to passenger car collisions (22% as compared with 2%).

In general, the causation of the death and severe injuries in the passenger cars are high intrusion (Hobbs, 1993) into the occupant compartment and/or high level of acceleration during the collision (Thomas, 2005; Delannoy et al., 2005). Sometimes there is a significant difference in the level of damage and/or acceleration between vehicles that crashed into each other, emphasized by significant differences in injury severities. There are cases where occupants of one vehicle are killed as a consequence of the accident while occupants of the other (similar) collision partner survive with minor injuries (Edwards et al., 2002; Pastor and Cuerden, 2004). When significant differences appear, crash incompatibility between the vehicles involved is identified. A general definition for incompatibility is inefficient energy absorption in the collision partners.

The high mass of a HGV (>12 t), introduces a greater amount of kinetic energy than a passenger car involved in a collision. Due to the different structural designs of trucks and cars, their energy absorbers do not coincide. Usually the main longitudinals of a car are placed at a level that is under a truck frame. 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 (Figure 1). The contact forces are primatily directed into the higher and much softer parts of the car. This is often followed by the contact between engine of the car and the stiff parts of the truck. Inefficient energy dissipation of the car's softer structures causes intrusion into the occupant compartment while the truck's stiffer structure experiences minimal deformations and little energy absorption. Similar crash behaviour is observed for car-to-car collisions when vertical misalignment of the longitudinals exists between the vehicles involved. Here, "crash behaviour" is the car structure's response when interacting with another structure during a crash.

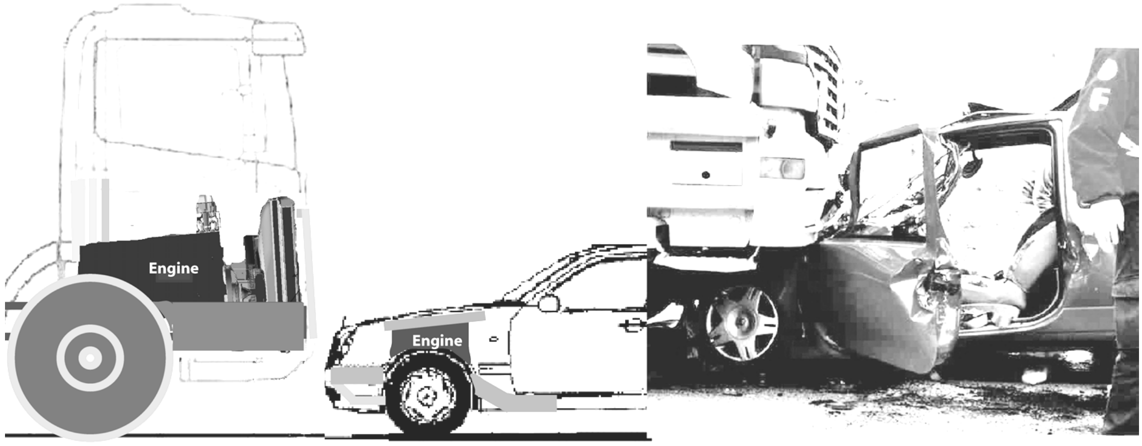

Figure 1*: Vertical misalignment between load paths of a passenger car and a truck (left) and its consequence (right)*

Horizontal misalignment of longitudinals causes "fork effect", which results from the contact between softer parts of the one vehicle (between longitudinals) and stiffer parts of another vehicle (one of the longitudinals) and vice versa. This results in inefficient energy dissipation and decreases the self- and partner-protection of both vehicles. The fork effect occurs even when two similar vehicles collide (Lindquist et al., 2003). The result is energy absorbed by the occupant compartment and accompanying intrusions. Edwards et al. (2002), Summers et al. (2003) found that passenger cars are very sensitive to even slight variations in the impact configuration resulting in unpredictable crash outcome. The inefficient energy absorption can decrease the ability of the vehicle to protect its occupants (i.e., decreased self-protection) but also increases its aggressivity against its partner (i.e., decreased partner-protection). It is essentially a problem in all types of vehicle-to-vehicle accidents, but front-to-front accidents result often in more fatalities compared to other types of accident (Improvement of crash compatibility between cars, 1999; Thomas, 2005; O'Brien, 2010).

1.1. Review of previous research

The crash compatibility issue was first detected in the late 1960s (O'Neill, 2009). Different groups and individuals started research on the compatibility between passenger cars somewhat later and the research has been continuing over the following five decades (Frei et al. 1999, Sekine et al., 2006). The goal of the research has been to decrease the crash incompatibility between vehicles, i.e., to make them more crash compatible.

There are few definitions of compatibility. Van der Sluis (2000) gathered the definitions identified in the period 1985 to 2000. The two definitions generally accepted by researchers in the field were:

1. “Vehicles in collision can be said to be incompatible if the deformation and structural characteristics cause the occupant loads to be unequally distributed between the vehicles.” (Shearlaw and Thomas, 1996)

2. “(Compatibility is) the capability of cars to protect their occupants in crashes, while at the same time produce as little harm as possible to occupants of opponent cars”. (Van der Sluis, 2000)

During years of research on compatibility, many different factors (vehicle mass, mass ratio, vehicle size, closing speed, front-end stiffness, lateral/vertical fork-effect, longitudinal/transverse engine, etc.) were considered to influence compatibility. The effect of these factors have been studied through theory, statistical analysis of traffic accident data, in-depth traffic accident analyses, crash tests, and crash simulations (van der Sluis, 2000). While some researchers tried to determine which one of the factors like mass, stiffness, closing speed etc., is the dominant factor causing incompatibility (Evans and Frick, 1992; Zobel, 1998; Barbat et al., 2003), Jewkes (1998) considered the influence of four factors (vehicle mass, structure, local stiffness and geometry) on occupant injury based on simplified mathematical models of a car. In recent years, structural interaction, stiffness and passenger compartment strength were the focus for research regarding compatibility (Hirayama et al., 2003, EEVC, 2003). This led to three more essential factors: difference in mass, difference in stiffness and difference in geometry but other terms were added such as: homogeneity, front-end force levels, stiffness and compartment strength (Thomas, 2005; Mohan et al., 2007; Mohan, 2008; O’Brien, 2010).

The influence of differences in mass and stiffness (i.e. deformation force) on compatibility has been investigated by means of basic physical principals (Verma et al., 2004). Differences in stiffness between vehicles is the result of the current self-protection tests and is connected to the mass of the vehicles (Faerber, 2003; Delannoy and Faure, 2003, Delannoy et al., 2005) Heavier vehicles in general have higher stiffnesses compared to lighter vehicles. When vehicles of different stiffnesses collide, the lighter vehicle, as the softer one, absorbs a higher share of the collision’s kinetic energy than the heavier. Also, Thomas (2005) confirmed that mass ratio and not the mass of the vehicle itself influences the change in velocity for the two vehicles and therefore compatibility. Méndez et al. (2010) found that newer cars are more aggressive but also heavier compared to older cars.

Recently, the compartment stiffness has been included to the list of the factors influencing overall front-end stiffness of the vehicles and therefore compatibility. An increased compartment stiffness of the lighter vehicle is necessary to force the front of the heavier vehicle to deform as described in the bulkhead concept first introduced by Zobel (1998).

Differences in the geometry of vehicles cause misalignment of the load paths of the vehicles. Not being aligned, the elements designed to absorb the kinetic energy through their deformation are not exposed to sufficient resistance forces and remain intact or they deform in a mode that does not lead to appropriate exploitation of their ability to take up the energy. The consequence is inefficient energy absorption. Some researchers performing in-depth accident analyses emphasize the importance of dynamic vertical misalignment on structural interaction even when the structures are vertically and horizontally aligned when the vehicles are statically positioned together (Edwards et al., 2002; Faerber, 2003; Avery and Weekes, 2006).

Because, inefficient energy absorption caused by lateral misalignment (fork effect) in offset collisions may occur even when two vehicles of the same geometry collide, it is not possible to consider differences in geometry as a direct factor influencing compatibility. The term "structural interaction", a consequence of the relative geometries of the vehicles during the collisions, is used instead.

Good structural interaction is seen as prerequisite for efficient energy absorption and mostly implies pure geometrical alignment of load paths belonging to two colliding vehicles (Zobel, 1998; Seyer et al., 2003; Jenefeldt and Thomson, 2004; Mizuno and Arai 2008). Thomas (2005) and O'Brian (2010) refer to structural interaction as a measure of compatibility and not just a factor influencing compatibility. Thomas considers structural interaction as "a phenomenon describing the efficiency of energy dissipation within existing deformation-zones of passenger vehicle during a collision". In any case, structural interaction is seen as an important issue regarding compatibility that is influenced by front-end geometry and stiffness. Structural interaction includes even the dynamic behaviour of the structures during the whole impact event (Delannoy et al. 2001).

The Frontal Impact and Compatibility Assessment Research (FIMCAR) project extended the compatibility requirements to include compartment strength, load spreading, and further energy absorption. Accordingly, stable and predictable response becomes a more important issue in crash compatibility. Based on the FIMCAR tests, Sandqvist et al. (2012) showed that "multiple load paths exhibited a much more stable response in frontal impacts and could tolerate larger variations in structural misalignment than a single load path vehicle before serious degradation in performance was observed". The importance of predictable car crash behaviour is given in a very concise way by Edwards et al. (2002): "If impacting cars could be made to interact properly, their performance in accidents would become more predictable, in terms of energy absorption and deceleration. Apart from the resulting reduction in intrusion, this would help advanced restraint systems to perform correctly and predictably."

Research on compatibility among cars of similar body structures is mostly concentrated on developing a test procedure for measuring the self-protection and partner-protection of vehicles, which should force production of more compatible vehicles. As a measurement of the level of a car's self-protection capabilities in frontal collisions, different tests are used. In Europe it is United Nations Economic Commission for Europe Regulation 94 (UN-ECE 94) but most of the manufacturers try to design their cars to satisfy the Euro NCAP frontal test criteria (Euro NCAP, 2014). In U.S.A. it is FMVSS 208, US NCAP (GLOBAL NCAP, 2014) and IIHS frontal crash tests (IIHS, 2008). All tests are performed by running a vehicle into a fixed barrier.

The barrier in a US NCAP frontal test is Full Width Rigid Barrier (FWRB) and the impact speed is 56 km/h. In the Regulation 94, Euro NCAP and IIHS frontal test (IIHS, 2008), the barrier is an Offset Deformable Barrier (ODB). The overlap in the test is 40% of the vehicle width and the impact speed is 56 km/h in UN-ECE 94 and 64 km/h in the other tests. The tests cause the heavier vehicles to be stiffer compared to those of lower mass (Zobel et al., 2005; Delannoy et al., 2007).

The FWRB and ODB tests are considered to complement each other. The FWRB test has a severer crash pulse, while the Euro NCAP test is considered to be a good method of establishing the integrity of occupant compartment structure (Lindquist et al., 2004) and both are used for ranking vehicle self-protection.

Efforts are being made to develop other barrier tests and corresponding metrics and criteria that should comprise even partner-protection, e.g.: EEVC barrier (in usage for UN-ECE 94, Euro NCAP, FMVSS 208, IIHS Offset Barrier Test), ADAC barrier (Klanner, 1996), PDB (Delannoy et al., 2005, 2007), FWDB (Edwards et al., 2008; Mizuno et al., 2008), AHOF and AHOF400 (Mohan et al., 2007; Mohan, 2008), Kw400 (Mohan, 2008), AHOD, ADOD, RHC (Thomson et al., 2007), aggressivity factor (UTAC, 2004), etc.

The latest attempts to develop partner protection tests in Europe have been made within the VC-Compat and FIMCAR projects. Thomson et al. (2007) described the compatibility assessment approach deliberated within VC-Compat project based on a FWDB or/and PDB test. A new proposal on compatibility assessment based on FWDB and ODB test was developed within FIMCAR project (Thomson et al., 2013). Even a Mobile PDB (MPDB) has been considered within the project and an assessment protocol is given (Uittenbogaard and Vermissen, 2013).

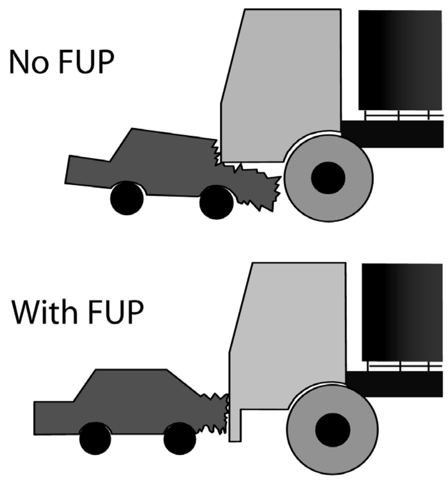

Figure 2: *Motivation for Front Underrun Protection (Wrige, 2003)*

There is a large difference between the mass, structure (geometry) and stiffness of HGV's and passenger cars. It is not feasible to change the mass due to the different purposes of the vehicles. To overcome at least geometric differences, the Front Underrun Protection (FUP) on HGVs was suggested. The FUP implemented on HGVs is the solution widely accepted as a structure to match the HGV's front structure with the front-end of a passenger car. The purpose of a FUP is to prevent overriding of the passenger car by HGV. The Economic Commission for Europe Directive 661/2009/EC[1] and corresponding Regulation No. 93 is a result of research on compatibility between passenger vehicles and HGVs. The directive and the regulation concern an installation and component testing of a special device on HGVs that should give Front Underrun Protection to passenger vehicles colliding with HGVs (Figure 2). The regulation gives a guideline for testing of statutory rigid FUPD. Figure 3 shows the placement, direction and magnitude of the loads to be applied on FUPD cross-beam together with highest allowed ground clearance. Notations N2 and N3 refers to HGVs of mass between 3.5 and 12 t, and larger than 12 t, respectively.

[1] Earlier 2000/40/EC

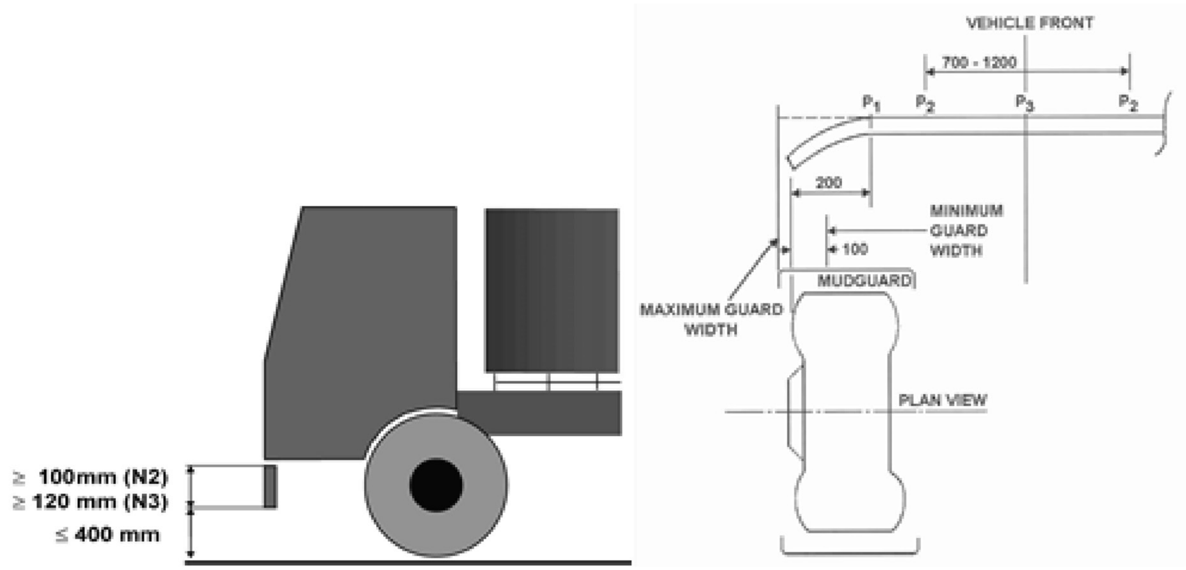

Figure 3: *Regulation 93 – Dimension limits and forces that FUPD has to sustained in the static component test.*

Although, the Regulation 93 refers to rigid FUPD a backward movement of its cross-beam is allowed in the direction of the load for a maximum of 400 mm (extreme position). The ground clearance should not exceed 450 mm at the cross-beam's extreme position.

Studies summarized in EEVC WG 14 (2000) have shown that a crash with a closing speed of 75 km/h and 75% horizontal overlap (referred to as a typical accident crash configuration) is survivable for the occupants of passenger cars in most cases if the truck is equipped with an e.a. FUPD able to absorb up to 40% of the crashes' kinetic energy. By comparing acceleration pulses, it was found that the optimal length of the FUPD e.a. elements is around 360 mm with a trigger force of 200 kN. In the study, intrusion could not be distinguished from car displacement and therefore it was not considered. Providing an additional energy absorption in the accident through the e.a. FUPD has been considered as beneficial in comparison to a rigid FUPD (Rechnitzer, 1993; Schram et al., 2006). Gweheneberg et al. (2003b) estimated the benefit of an e.a. FUPD in frontal car to HGVs accidents if the HGVs in all accidents were equipped with e.a. FUPD characteristics proposed by EEVC WG 14 (1996). It was found that the reduction would be 10-11%, i.e. 190 – 240 fatalities and 30%, i.e. 1497 seriously injured in Germany. A similar result on potential benefits of FUPD (15% and 30% respectively for reduced fatalities and serious injuries) was given by Haworth and Simmons (2003) in Australia. Based on accident investigation, Rechnitzer (1993), and Lambert and Rechnitzer (2000) suggested higher values for load forces (400 at P1, 300 at P2 and 200 at P3 point in Figure 3), and lower ground upper clearance (350 mm) and proposed absorption capacity requirement for e.a. FUPD of 100kJ and 500-600 mm stroke length. The tests conducted by VC-Compat showed that production rigid FUP device meeting R93 could offer underride protection to all passenger cars in the test configurations (de Coo et. al., 2005 and 2006). The measurements made on dummies in test vehicles were in the survivable zone up to speed of 64 km/h. The test with a production e.a. FUPD did not give expected results since the e.a. elements were not triggered. One test with a specially produced e.a. FUPD with elements made of aluminium foam gave satisfactory results regarding underriding and dummy injuries. Within the same project, one test was made by VOLVO with e.a. FUPD (Anderson, 2003) but few details were provided about the device.

Secondary Energy Absorbing Systems (SEAS) are seen as a solution for reducing the consequences of crash incompatibility caused by geometrical misalignment between passenger cars and the taller (and generally heavier) SUVs, vans, and pickups (Mohan et al., 2007; Mizuno et al., 2008; Patel at al. 2009). The SEAS is considered as a lower extension of energy absorbing structures for higher vehicles. The idea is to provide stiff structures in the same vertical area as car longitudinals. The research regarding SEAS is still in the development phase. NHTSA is evaluating an ORB test procedure to evaluate the strength and energy absorbing characteristics of SEAS (Patel at al. 2009). In 2003 EVC (Enhancing Vehicle Compatibility) group consisting of nearly every major automaker represented in the U.S. market made a voluntary commitment to improve vehicle safety. The commitment requires that energy-absorbing structures of light trucks overlap with a defined vertical area defined in US regulations (Part 581 zone) that will potentially result in better interaction with car structures (Barbat, 2005; Nolan et al., 2012).

The situation regarding vehicle compatibility is usually presented by quantities referring indirectly to the compatibility such as: vehicle aggressivity or/and crashworthiness (self-protection) (Fredette et al., 2008; Méndez et al. 2010; Huang et al. 2011), fatality risk (Baker et al., 2008; Greenwell, 2012), total secondary safety index (Newstead et al., 2011), etc. Direct methods for evaluation of compatibility have been suggested by Thomas (2005) and O'Brian (2010). Thomas (2005) equates the level of structural interaction with compatibility. The level of structural interaction is evaluated through comparison of energy absorbed by the front-end of the vehicle in a vehicle to vehicle crash test and the one obtained in crash test against rigid barrier with the assumption that compartment integrity is preserved. O'Brian (2010) proposed a definition of the compatible collision for two vehicles based on the comparison of injury risk for accidents with the same crash configuration as a corresponding barrier test. The collision is considered compatible if the injury risk calculated for the accidents is equal or lower than one calculated in the test.

1.2. Limitations in previous research

One of two generally accepted definition of vehicle (in)compatibility (Section 1.1.) can be applied on only passenger to passenger car compatibility. The first definition stating that a incompatibility is present whenever the occupant loads are unequally distributed between the vehicles, makes compatibility between passenger cars and HGVs, and passenger cars and SUVs, Vans or pickups unachievable. Therefore, the first definition has to be limited to only passenger cars.

The research on crash compatibility between passenger cars has started much earlier in comparison to research on crash compatibility between passenger cars and other vehicles (like HGVs). This has resulted in different test procedures for different vehicle types and influences the vehicle design (Section 1.1.). Despite the common aim of all three approaches to decrease the crash severity for passenger car occupants, different methods were developed for evaluating proposed countermeasures. To increase car to car compatibility FWDB and ODB tests have been suggested recently. The ORB test is suggested for evaluation of SEAS while Regulation 93 describes another test for the evaluation of FUPD. Using different methods is not suitable for comparing the compatibility performance of different countermeasures because they consider different parameters. To confirm if a countermeasure improves compatibility, a common method for compatibility measurement is needed.

The component tests for FUPD, required by the Regulation No. 93, have been criticized for having low performance criteria for the stiffness of the FUPD (Rechnitzer, 1993). The regulation does not include requirements for energy absorption of the FUPD despite the evidence showing benefits of an e.a. FUPD (Rechnitzer, 1993; Schram et al., 2006). More stingent requirements are suggested by Rechnitzer but are based only on accident investigations and are not confirmed by real tests or crash simulations. The accidents investigated did not involve trucks with FUPD. Crash tests between FUPD equipped trucks and passenger cars are few and insufficient to predict the ability of FUPD to mitigate the crash severity between these two types of vehicle. Even fewer tests were done with e.a. FUPD. Further, neither statistical nor in-depth accident analysis between car and HGVs equipped with FUPD are available. Therefore, there is little or no information about FUP efficiency in real traffic collisions.

The two widely used definitions of compatibility (Section 1.1.) contain some ambiguousness. The first definition states that an incompatibility is present whenever the occupant loads are unequally distributed between the vehicles. The structures of vehicles not defined as passenger vehicles (HGVs, SUVs, pickups, vans) have been developed in accordance to their purpose and crash compatibility with passenger cars is not incorporated in their design. Their structures differ very much from a passenger car's. Loads on passengers of two vehicles where one of the vehicles is a passenger car and another is non-passenger defined car will never be equally loaded in the collision. Therefore, the first definition can be applied only to passenger car to passenger car accidents. Practically, even if colliding vehicles are of the same structures and masses it is difficult to define the meaning of "unequally distributed" as an opposite to "to be equally distributed" deformation between the vehicles.

The second definition, in Section 1.1., refers to self- and partner-protection, which is widely accepted as a goal of compatibility but it is impossible to distinguish self-protection from partner protection without a large body of accident data (Zobel, 1998) and implies information only about crashed vehicles that have been in production some time.

So far, based on in-depth analysis of car to car accidents, tests or simulations, it is possible to conclude which pairs of cars are compatible and which are not but it is not possible to quantify and compare the compatibility of one pair of cars to another. Calculation of aggressivity, self-protection, fatality risk, total secondary safety index, etc. based on statistical methods may indicate where to put the focus in research of compatibility, e.g. whose (in which types of car) occupants are most vulnerable These statistical methods are not able to apply the findings to specific car structures.

Barrier tests like FWRB (US-NCAP) and ODB (FMVSS 208, Euro NCAP, etc.) can be used for measuring the self-protection of a car. Car crash tests against FWDB, PDB, etc., suggested as one measurement of partner protection, might lead to an increase in car to car compatibility. However, the specific level reached in self- and partner-protection for the two cars does not say anything about the compatibility between these two cars when they crash into each other.

The two methods suggested by Thomas (2005) and O'Brien (2010) to quantify compatibility between two cars were limited. Thomas' approach does not consider force-deformation relationships and is limited to the cases where the occupant compartment integrity is preserved. O'Brian's suggestion assumes there is historic collision data available. Neither of the methods gives deeper correlation between compatibility, vehicle structure and its structural interaction with the collision partner.

1.3. The aim of the thesis and its objectives

The global vision of the thesis is to define characteristics (geometry, stiffness, triggering force, etc.) of an effective energy absorbing FUPD that is able to prevent overriding of passenger cars by a truck and design to mitigate the crash severity. The compatibility between passenger cars and HGVs has to be considered as an indivisible part of overall crash compatibility.

To work towards the vision described above, the objectives of the thesis are to define and quantify the parameters influencing structural interaction in frontal impacts between passenger cars and e.a. FUPD equipped HGVs by means of crash simulations. It has to be conducted in a way that will take into consideration the vehicle performance (structural interaction and resulting acceleration and intrusions) in different impact configurations. Structural interaction between vehicles has been found to be a crucial factor influencing crash outcome and therefore has a central role in the thesis.

2. Research methods

The overview of the research method is presented in Figure 4. The first step in the research was to understand the current situation regarding accidents between passenger cars and FUPD equipped HGVs with a focus on a structural interaction between FUPD and front-ends of passenger cars during collisions. Two analyses were made: structural (geometrical) analyses regarding load paths in passenger cars and HGVs that belong to European fleet and in-depth analysis of frontal accidents between passenger cars and FUPD equipped HGVs. This was explored in Paper I.

The crash behaviour of the front-end of the passenger car in frontal collisions has some weaknesses (sensitive to change of vertical and horizontal overlaps and fork-effect) leading to unpredictable crash outcomes in these types of collision. To understand the behaviour of passenger cars the series of crash simulations between two identical passenger cars under different crash configurations were run. The results are presented in complementary Paper 1 and used as an input to Papers II and III.

The aim of Paper II and III was to investigate theoretical possibilities of FUPD, i.e. the possibilities of e.a. FUPD to mitigate the crash severity against passenger car under different crash configurations without car interaction with hard HGV structures surrounding the FUPD. Based on findings from the Paper I, but also the findings from the research based on car to car crashes (complementary Paper 1), the simplified FE model of e.a. FUPD was made. The series of crash simulations between passenger car and FUPD were run under different crash configurations. Also, the influence of stiffness and heights of FUPD cross-sections were studied.

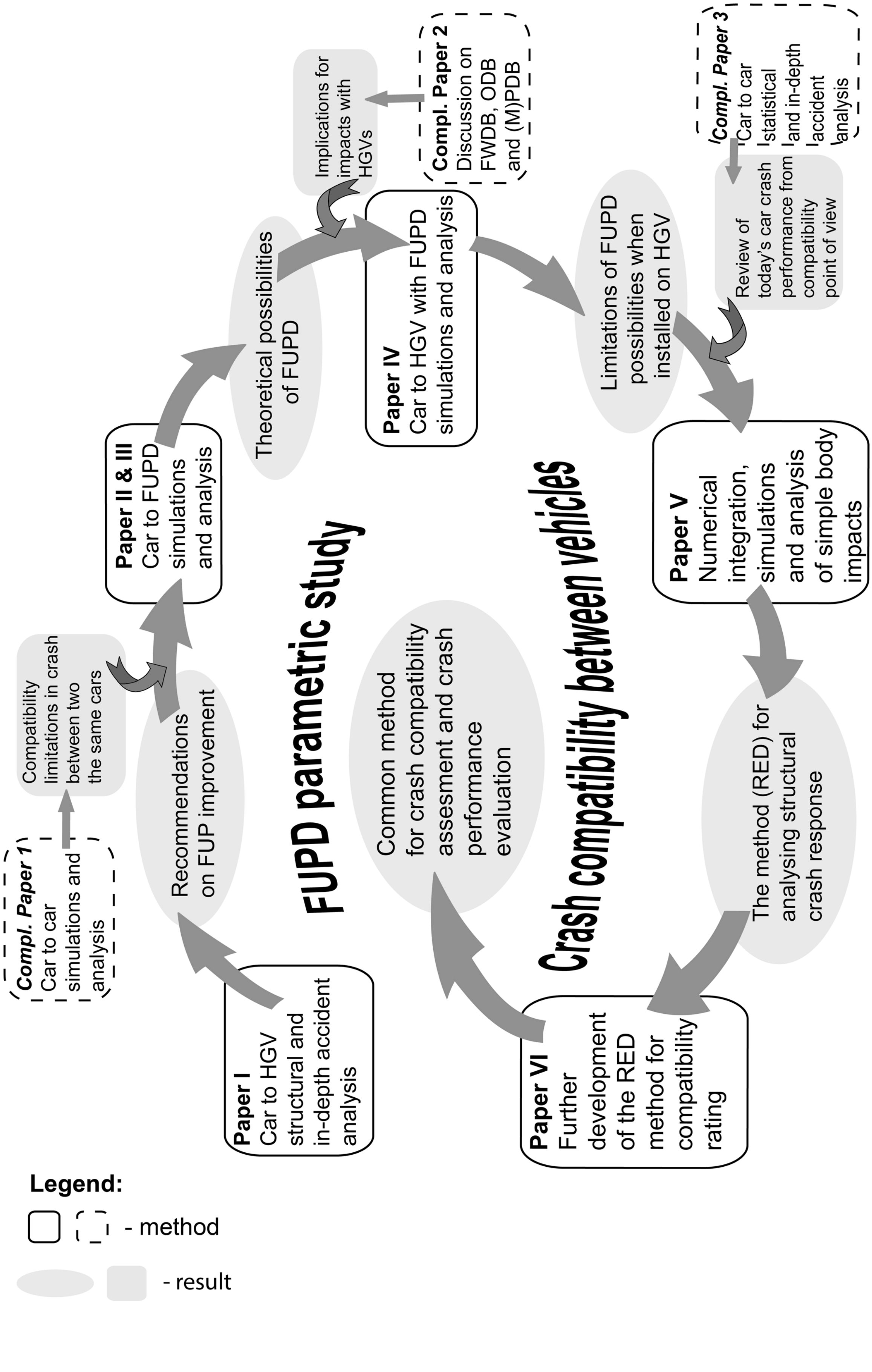

Figure 4: *Methods and results of the studies contributing to the thesis*

After a satisfactory structure for FUPD was found, the series of simulations were run between a passenger car and FUPD, which was installed, in a simplified HGV model. The aim was to investigate the influence of HGV structure on FUPD performance and compare it to the theoretical performance of the FUPD studied in the previous two papers (II and III). The results are presented in Paper IV. To be sure that the suggested compatibility characteristics of e.a. FUPD are not in contradiction to the future barrier compatibility tests, the research undertaken in complementary Paper 2 has been reviewed.

Complementary Paper 3 is one of the results from the FIMCAR project. The paper presents the results coming from statistical and in-depth analysis of car to car frontal crashes. The statistical analysis was made on the crash cases from Great Britain and Germany involving late model vehicles. The goal was to find out if car to car crashes still exhibit problems related to crash compatibility.

The goal of the last two articles, Paper V and VI, was to find a method for measuring compatibility that could be part of an objective structural interaction evaluation process. Paper V deals with the theory behind a method to extract structural performance data from FE simulations, while the development and application of the method to the measurement of compatibility is presented in the Paper VI.

The whole research method in the thesis is based on understanding the links: geometry and stiffness – crash configuration – structural interaction – crash response.

3. Summary of the appended papers

The six appended papers are summarized in this section. The importance of the results of study for each of the papers are discussed further in Section 4.

Paper I

"Crash Compatibility between Heavy Goods Vehicles and Passenger Cars: Structural Interaction Analysis and In-Depth Accident Analysis"
Proceedings of International Conference on Heavy Vehicles, Paris, France, 2008

The aim of the paper was to examine the current situation regarding the efficiency of FUPD in traffic accidents and depending on findings propose the future steps in FUPD development. Since the construction of FUPDs is based on UN ECE Regulation 93, the following two questions were set as guidelines through the research:

1) Is a FUPD, obeying the requirements in 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?

Two analyses, structural analysis of HGVs and passenger cars, and in-depth analysis of accidents between HGVs equipped with FUPD and passenger cars were made. For the structural analysis, VC-Compat's database of car and HGV geometry of European vehicles was used. Comparing the relative placements of loading paths of passenger cars and FUPD cross-beams on HGVs (Figure 5) it was found that Regulation 93 considers only an unloaded

HGV's geometrical measurements when defining the geometry of FUPD cross-member. The placement of the loading paths in HGVs and passenger cars are such that the fork effect can be developed due to passenger car front-end and FUPD support configurations. The placement of passenger car and truck engines also have a vertical overlap which, in severe collisions, may lead to the contact of the engines and probably to higher intrusions.

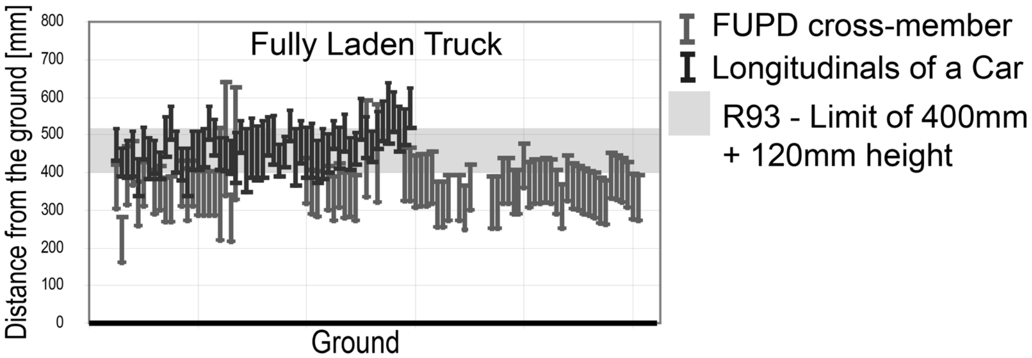

Figure 5: *A graphical presentation of relative position between car longitudinals and FUPD cross-beam for fully laden trucks based on the geometrical database*

For the in-depth accident analysis, 3-D geometrical models of the vehicles were made in their relative positions at the moment just before the accident occurred. The models were based on the structural dimensions from the structural database, information from manufactures of the vehicles, police reports and the photos of the accident place and vehicles after the accidents. The models helped in understanding the mechanisms and reasons for poor structural interaction between the front of the passenger car and FUPD of the HGV involved in the accident.

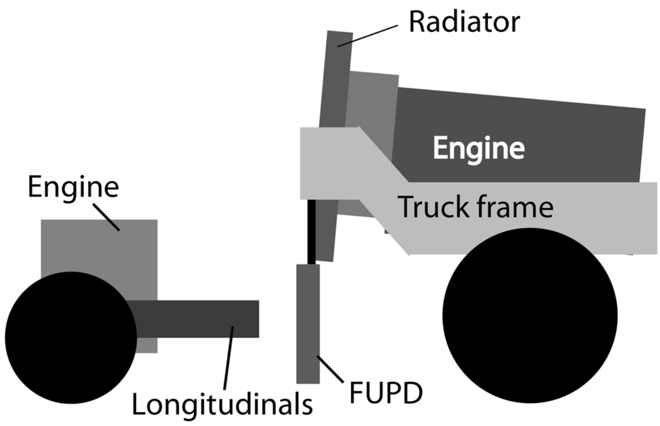

Figure 6: *Proposed modification of front truck design*

The frame of a fully laden truck is lower than in the unladen condition, reducing the ground clearance of its FUPD. As a consequence, initial overlap between the FUPD cross-beam and car longitudinals becomes very small or disappears. Figure 5 shows both, a survey of fully laden truck structure positions and the prescribed maximum limit of a FUPD ground clearance. Raising the front part of the HGV's frame (Figure 6) would allow better interaction between FUP and front structure of the car but also bring the radiator of the truck in contact with car giving it a new role as an additional energy absorbing element. Because, all investigated accidents occurred under high closing speeds, the need for energy absorbing

FUPD was raised suggesting that a requirement for energy absorption should be included in the Regulation 93.

In-depth accident analyses showed that the FUPD cross-member bending stiffness and the stiffness of its supports were insufficient to prevent the overriding of the passenger car involved in the analysed accidents. The low stiffness of the FUPD caused even fork effects in one of the accidents investigated. These and other findings from the analyses resulted in the final answer to the first question - the FUP designed according to ECE Regulation 93 is not always sufficient to prevent overriding of the passenger car or mitigate severity of the crash. The answer to the second question is summarized in the list of recommendations that includes suggestions to increase the requirement for the bending stiffness of the FUP cross-member, consider geometry of laden trucks regarding the cross-member upper but also apply lower geometric limits.

Paper II

"**Energy-Absorbing FUPDs and their Interactions with Fronts of Passenger Cars**"
International Journal of Crashworthiness, 15:6, pp. 635 – 647, 2010

Studies performed by EEVC WG 14[2] have shown that a crash between trucks and passenger cars with the closing speed of 75 km/h is survivable for the occupants of passenger cars if the truck is equipped with an energy absorbing underrun protection system with a 360 mm long stroke. Other characteristics an e.a. FUP device should have - how it behaves in a crash against a passenger car front and what possibilities it can offer to mitigate crash severity by interacting with the car structures - were questions addressed by this work. The objectives were to find a satisfactory bending stiffness for an e.a. FUPD by means of FE simulations of crashes between car and e.a. FUPD as well as to estimate the theoretical potential of an e.a. FUPD to decrease the crash severity through improved structural interaction. To make this part of the work feasible, it was limited to different crash configurations by only varying the horizontal overlap between colliding structures.

Two groups of simulations were conducted. In all simulations, the model of simplified FUPD was used. The e.a. FUPD is modelled as a beam with a square cross-section supported by two springs with six degrees of freedom allowing only plastic deformations. The axial stiffness of the springs (FUPD e.a. supports) was varied until it satisfied a requirement that one support is bottomed out for a car impact of 75 km/h and 75% overlap, while for full overlap neither of the supports should be bottomed out. Lateral and rotational stiffnesses were chosen to be sufficiently high to prevent any rotation and lateral translation. The finally chosen stiffness of FUPD e.a. supports. is shown by Figure 7.

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[2] Enhanced European Vehicle Safety Committee Working Group 14: Truck Underrun Protection

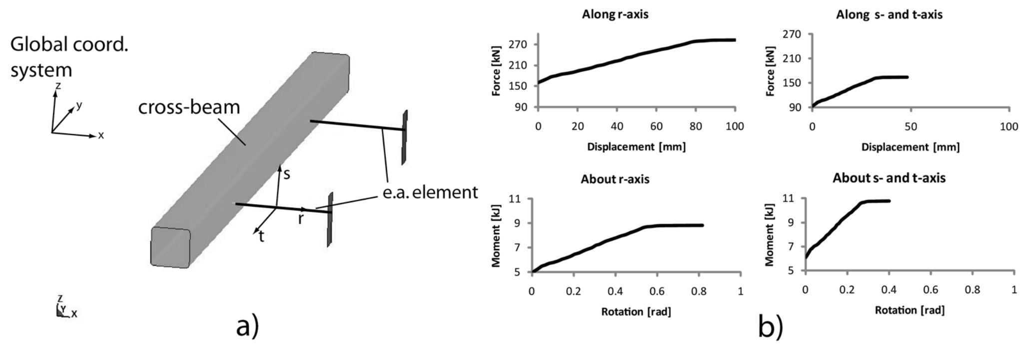

Figure 7: *Model of simplified e.a. FUPD: (a) e.a. FUPD consisting of FUPD cross-beam and FUPD e.a. elements (modelled as springs) and (b) force/moment versus displacement/rotation characteristics of the e.a. elements (springs)*

In the baseline group of simulations, the level of self-protection of the car impacting a FWRB barrier at a speed of 75 km/h was compared to the impact against an e.a. FUPD with rigid cross-beam. The influence of failure of the mounts between the car's sub-frame and longitudinals due to structural interaction was investigated by simulations of the crash between the car and e.a. FUPD with rigid cross-beam under impact speed of 75 km/h.

Another group of simulations included simulations between e.a. FUPD with deformable cross-beams and passenger cars with impact speeds of 75 km/h. Different bending stiffnesses of the cross-beam were considered (rigid, cross-beam of 5 and 7 mm wall thickness) and simulations were run with different horizontal overlaps.

Since a model of the dummy was not included in the simulations, the intrusions into occupant compartment were used as an indicator of severity (Huelke and Compton 1995, van der Sluis 2000). To clarify and understand structural interaction and the performance of the component models, acceleration, ride-down distance, forces and moments in vehicle's load paths and e.a. FUPD supports, and deformations on FUPD cross-beam were used.

Car-to-FWRB simulations for impact speeds of 75 km/h showed severe deformations of the sill and significantly limited the car safety. It was shown that an e.a. FUPD can absorb up to 34% of the total kinetic energy and thereby reduce the severity of the crash compared to FWRB cases. The force needed to activate the deformations of the e.a. supports was defined as an important factor influencing structural interaction. The timing of the triggering force was shown as important for the deformation of the sill. The sill started to deform later in the FUPD case than the FWRB and caused less severe deformations of the sill leaving more survival space for the occupants. The simulations with failure of the car's sub-frame mounts showed more intrusions than when the failure was not introduced indicating the importance of the sub-frame even in these kinds of collision.

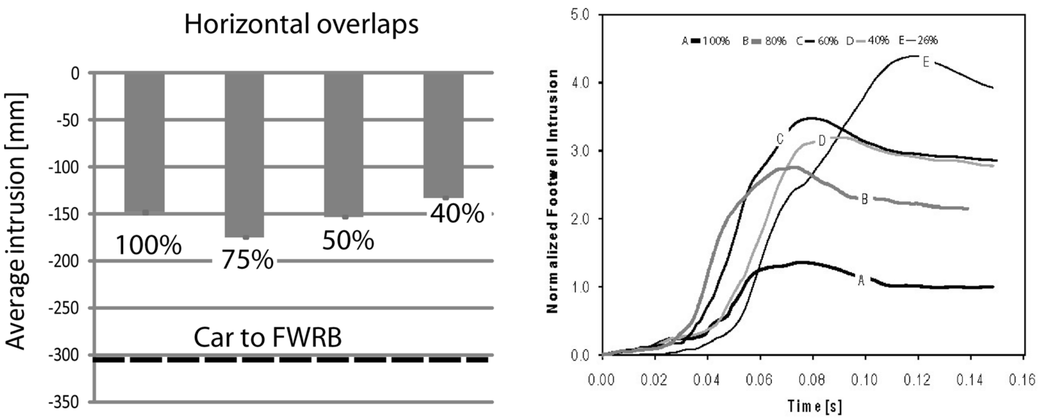

Figure 8: *a) Average intrusions from car to e.a. FUPD for different horizontal overlaps in comparison to intrusions caused by impact into FWRB b) Normalized (to intrusions for full overlap) footwell intrusions from car-to-car simulations for different horizontal overlaps (complementary Paper 1)*

The right choice of the FUPD cross-beam bending stiffness can eliminate the fork effect that was seen in car-to-car collisions and decreases the intrusions. It was shown that a completely rigid FUPD cross-beam caused more intrusions than a deformable cross-beam of higher bending stiffness but caused less intrusions compared to deformable cross-beam with a lower bending stiffness. In the case of small horizontal overlaps, intrusions were decreased due to bending deformations of the FUPD cross-beam followed by vehicle rotation. The intrusion decreased with decreasing horizontal overlap (Figure 8a) which was not seen in earlier performed car-to-car simulations (Figure 8b) (complementary Paper 1). It was noticed that the bending of the idealised FUPD cross-beam for lower horizontal overlaps allows rotation and "glance off" which reduces deformations of the car. Some of the original impact energy remains in the post-impact kinetic energy and is not directed into structural deformation energy.

Paper III

"Crash Performance of Front Underrun Protective Device with a Passenger Car Under Different Crash Configurations – Results of Finite Element Method Based Simulations"
Research report 2010:07, Chalmers University of Technology, Göteborg, 2010

The study performed in this work is a continuation of the work done in Paper II. After a structure for FUPD satisfying different horizontal overlaps was found, a simulation based study was performed to further understand the crash performance for e.a. FUPDs under other impact configurations.

Crash simulations based on the finite element method (FEM) were performed using a passenger car model and model of an e.a. FUPD. The car-truck structural analysis and in-depth analysis of the front-front accidents between passenger cars and FUPD equipped HGVs presented in Paper I were the basis for simulation matrix. Simulation results describing passenger car crash performance in complementary Paper 1 identified critical crash configurations for the passenger car structures. The passenger car model from these activities was used to quantify the FUPD performance. Crash speeds of 56 and 75 km/h applied on the passenger car model were used in the simulations while the FUPD was fixed at the end of energy absorbing elements fixed to a rigid support.

Two variables defining impact configuration have been varied: horizontal and vertical overlaps between the front end of the passenger car and FUPD. To investigate the influence of the size of impact area on the crash performance, the cross-section height of the FUPD cross-beam has been varied while the stiffness of the cross-beam was kept the same.

The bending stiffness that was found satisfactory in Paper II for a cross-beam of 120 mm was also implemented on a cross-beam of 240 mm height. To assure the same bending stiffness for the different cross-beams a simple bending test was applied on both beams (Figure 9a). The thickness for cross-beam of 240 mm was varied until it gave a response similar the response of cross-beam of 120 mm height (Figure 9b).

The speed of 56 km/h was used only for the case where the car was run against FUPD of 120 mm height. The speed of 75 km/h was used for quantifying the performance of FUPDs of both heights (120 and 240 mm).

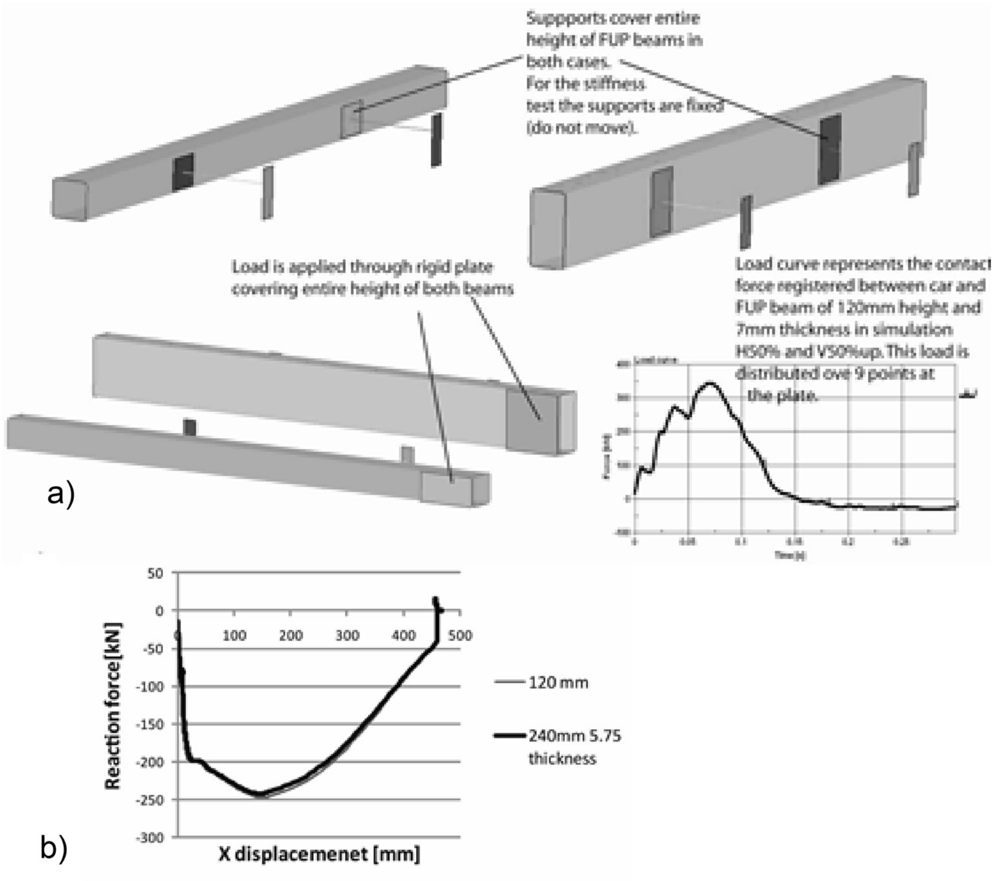

Figure 9: *a) Set-up of the bending test simulation with a loading curve; b) Displacement of the FUPD cross-beam end for the different cross-beam heights under bending test*

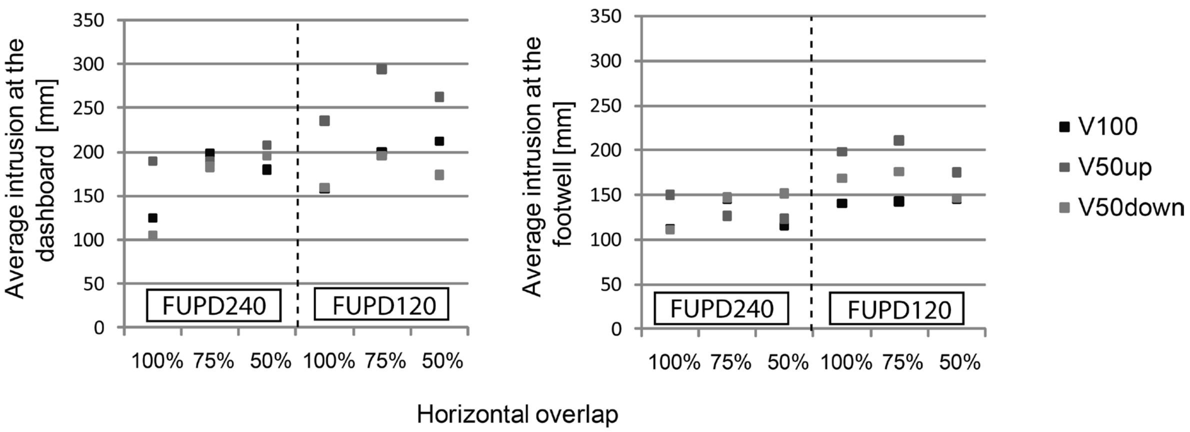

Figure 10: *Average intrusions at firewall for different crash configurations in impact between the car and FUPD of two cross-beam sizes*

The results (Figure 10) showed that, contrary to car-to-car impacts (Figure 8b), the intrusions obtained for different horizontal overlaps follow the same pattern for both speeds indicating that the behaviour of the car is less dependent on crash configuration when it impacts the e.a. FUPD than when it impacts another car. The stiffness characteristics of the investigated e.a. FUPD were tuned for impacts with car for higher speeds. Therefore, the advantage of an e.a. FUPD as an impact partner is greater for the higher speed in comparison to FWRB. The impact with an e.a. FUPD caused higher intrusions in the dashboard region of the car in comparison to footwell (for the same case) and is opposite to the case when the car impacts the FWRB. The acceleration-displacement curve for 56 km/h shows a lower but somewhat delayed acceleration peak of the car impacting e.a. FUPD in comparison to the car impacting FWRB.

For the all but one crash configuration, the e.a. FUPD with cross-beam of 240 mm FUPD has a lower acceleration pulse compared to the results from simulation with e.a. FUPD with 120 mm cross-beam. Despite the lower acceleration pulse, the e.a. FUPD with a larger cross-beam is able to absorb higher amounts of kinetic energy than one with a smaller cross-beam. The intrusions are also, in general, lower in the case when a larger cross-beam is used in comparison to the car impacting an FUPD with a smaller cross-beam (Figure 10). Intrusion values are more similar for different vertical overlaps for the car impacting FUPD with larger cross-beam indicating more stable behaviour than when impacting the FUPD with a smaller cross-beam.

Paper IV

"Truck Frontal Underride Protection – Compatibility Factors Influencing Passenger Car Safety", *International Journal of Crashworthiness*, 17: 2, pp. 217 – 232

To complement the previous study of the idealised impact of a car and an e.a. FUPD, the total truck and FUPD structure was simulated with impacts of passenger cars. Similar to the previous study, different collision configurations were studied aiming to investigate how the striking car interacts with the stiffer components of the truck. The results from the previous studies were used to evaluate the difference in e.a. FUPD efficiency between the situation when the truck was not present and the situation when the e.a. FUPD was integrated into the truck. The model of an e.a. FUPD used in the previous study showed good performance interacting with a passenger car. Therefore, poor performance of the FUPD when interacting with a passenger car and truck structures can only be a result of additional interactions with truck structures. For the purpose of the study, a simple model of truck front was made. The dimensions were based on the dimensions taken from real vehicles.

The main parameters investigated in this simulation series were vertical and horizontal alignment of the car and FUPD when it is installed on the truck, vertical distance between the FUPD and the rigid truck frame, vertical height (cross section) of the FUPD cross-beam and the influence of deformable truck rails. A part of the simulation series was intended to investigate effects of not only both impact speed and vehicle mass but also the e.a. element's force levels. Impact speeds of 75 km/h were studied for a mid-size car (Ford Taurus). A smaller 900 kg (Geo Metro) and a 1330 kg car (Dodge Neon) were used at 56 km/h to investigate an FUPD activation force for light vehicles. These older models exhibited weak compartments, nit truly reflecting modern vehicles, and were not used for higher impact speeds.

The accident analysis in VC-Compat showed that most collisions occur for horizontal overlaps where less than 50% of a truck and 75% of a car's fronts are involved. This is in agreement with another accident investigation where a horizontal overlap of 75% (relative to the car) and a closing speed of 75 km/h were found as a typical crash configuration. Therefore, all the simulations were run as done previously with a closing speed of 75 km/h. The vertical overlaps considered are 50% where the FUPD was placed either higher or lower than the car logitudinals. The horizontal overlap was varied between 50 and 75% but even 100% overlap was run to ensure that the performance of e.a. FUPD does not show any unexpected signs of deterioration for full overlap.

The simulation results indicated the clear advantage of a larger (240 mm) cross-beam on FUPD disappears when the FUPD is mounted on the truck with rigid frame (Figure 11). The larger cross-beam interferes with the truck radiator, disturbing free deformation of the e.a. elements. A small offset between the FUPD and truck frames is undesirable while the advantage of having deformable truck frames increases with FUPD – frame offset. The results indicated that an offset between the FUPD and frame of at least 220 mm is needed (Figure 12). Stiff truck frame rails have more influence on FUPD performance under different vertical overlaps than deformable ones (Figure 11 and Figure 12). Maximum deformation of e.a. elements was 270 mm, which implies that the available stroke of 300 mm could not be efficiently used. Since the maximum resistance force of e.a. elements in the travelling direction was reached, the only reason that the available deformation distance could not be used is that the FUPD movement was restricted by surrounding truck structures. For smaller horizontal overlap the reduced deformation of the FUPD cross-beam for car-to-rigid frame truck is also prevented by the stiffer truck parts and the car continues to translate instead of rotating, resulting in more car deformations.

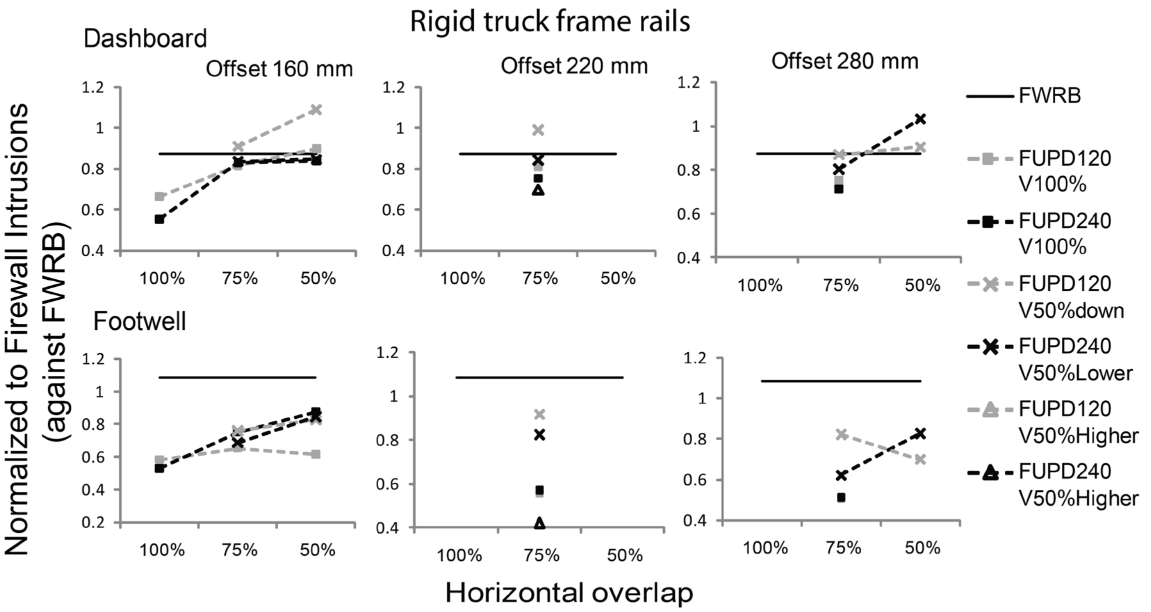

Figure 11: *Calculated intrusions of the dashboard and footwell of the car impacting the truck with rigid frame rails*

Based on the longitudinal FUPD spring forces of 284 kN used in these simulations, future small vehicles should have compartment strengths of at least 350–400 kN if these spring stiffness are to be considered. Current compatibility research is promoting stronger small car compartments and 350–400 kN is the minimum recommendation from the VC-Compat project.

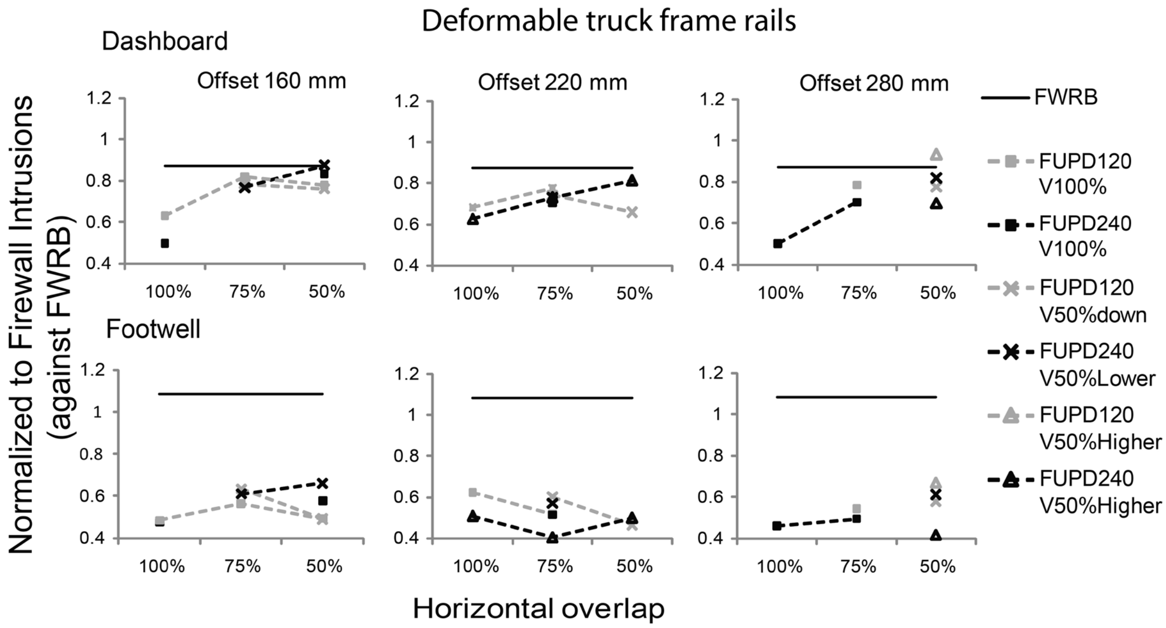

Figure 12: *Calculated intrusions of the dashboard and footwell of the car impacting the truck with deformable frame rails*

Paper V

"An Energy Based Assessment Tool for Dynamic Response of Impacting Structures", *Submitted to International Journal of Crashworthiness*

The crash response of vehicle structures has been an area of considerable research regarding assessment methods. Crash test data is limited to sensors placed on discrete components and high speed video information. While the former gives time based information at specific points and the latter gives qualitative information of the response mode, finite model analysis is the only tool able to provide detailed, micro and macro level information of the structure during a crash. Therefore the goal was to develop new assessment tools to exploit the information available from Finite Element crash simulations and thereby expand the scope of vehicle crashworthiness analysis which can be fed back to the design phase of the vehicle.

There are two deformation modes of special interest for automotive crash structures: local and global buckling. Local buckling is a deformation mode characterized by many bending segments lying close to each other within the body. As a consequence, the part maintains its global orientation from the beginning during the deformation process. Global buckling is characterized by local deformations that introduce large changes to the structure's global orientation with rigid body motions of some of the material. In the case of global buckling, the deformation is accompanied by the displacement of the structure's end which is larger than in the case of local buckling, for the same amount of dissipated energy.

A metric was developed to evaluate relation between the deformation of a structure and the energy converted to plastic work. If one knows the internal energy and contact force a-priori, a new quantity can be calculated from these parameters:

$$\Delta\varepsilon_i = \Delta E_i / F_i \qquad (1)$$

The new quantity is named the Equivalent Energy Displacement increment $\Delta\varepsilon_i$ and is an artificial quantity directly proportional to total Internal Energy increment ΔE_i and inversely proportional to generated force F_i in impact direction (Equation 1) in the i^{th} time step. As such, it can be said that the Equivalent Energy Displacement increment represents the amount of local deformation developed in time step i. The difference between this quantity and actual displacement increment of the unaffected zone is named Relative Equivalent Energy Displacement (RED). The RED increment $\Delta\rho_t$ shows the difference between the amount of deformation and displacement increment $\Delta\varepsilon_i$ in time step i. This difference is the basis for a new established method – RED (Relative Effective Displacement) method.

Crash simulations of two simple crash bodies were performed. The first body exhibited local buckling as predominant deformation mode. In the second run the body was inclined relative to impact direction (x-axis) and exhibited a combination of local buckling and, global buckling and bending mode. The second body exhibited global and bending mode. The RED method was applied on the results generating the RED curve (Figure 13 and Figure 14) which form could be clearly connected to the observed deformation modes. A plot of RED increment versus displacement can be considered a visual representation of the observations made on deformation modes. It was noted that local buckling was associated with a RED curve that had a mean value of zero, while global buckling produces a RED curve that has a negative value.

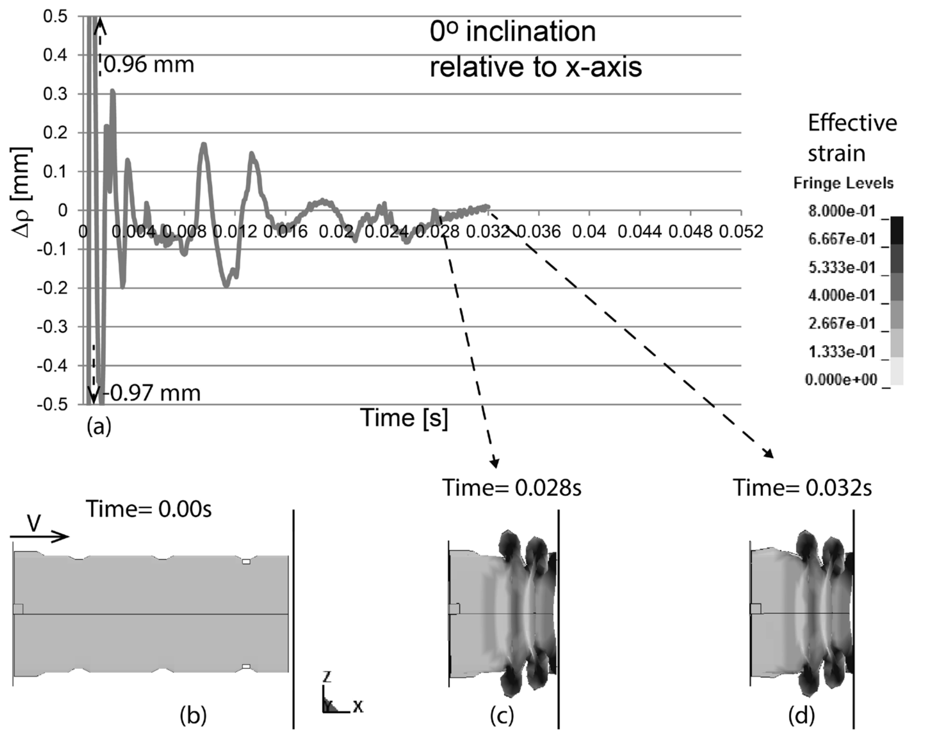

Figure 13: *Crash body 1 - 0º inclination relative to x-axis. (a) RED curve, (b) initial state just before impact, and states at approximate time points when (c) the buckling stops and (d) displacement reaches its maximum value, respectively at lower row with effective strain fringe pattern.*

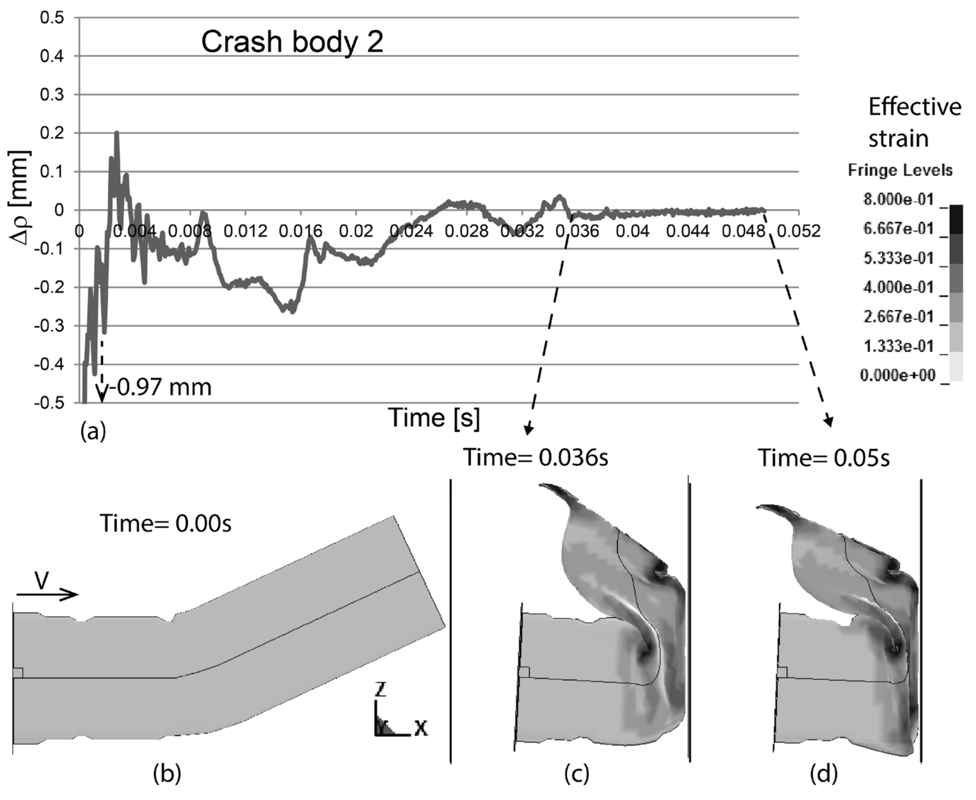

Figure 14: *Crash Body 2. (a) RED curve, (b) initial state just before impact, and states at approximate time points when (c) the buckling stops and (d) displacement reaches its maximum value, respectively at lower row with effective strain fringe pattern*

It was shown that the RED method is unique since it can be used to detect changes in deformation modes of simple crash bodies. The change in deformation modes is related to the ability of the structure to absorb the kinetic energy in the system. Compared to other simulation outputs and analysis approaches, RED plots can identify the transition between deformation modes more precisely. The RED analysis quantifies the crash response processes in a manner that should allow the vehicle designer to identify critical conditions (in terms of time and/or deformation) in the crash response. Knowing when the structure changes its response allows vehicle designers to target the components needing modifications.

Paper VI

"Further Development of the RED Method to Vehicle Structural Performance: Assessment of Crash Compatibility", *Submitted to International Journal of Vehicle Safety*

No accepted test or assessment method for measuring compatibility has been developed to date. One of the important factors that is not possible to evaluate during or after a barrier test is if the exhibited structural response of the car in a barrier test is predictable and stable. When developing vehicle structures for crash loading, many design iterations are required. The number of iterations could be reduced if more an effective analysis procedure was available. Consequently, two research needs (aims) were identified:

1. The design process requires a method that can describe how the structure behaves over time and indicate the different phases in the deformation process.

2. A method to measure the ability of a car to deform in stable manner in a crash against other car is needed. This measurement should quantify the level of compatibility and facilitate objective comparison to other crash cases.

The objectives of this study were to further develop a procedure based on the RED method (Paper V) that assesses the structural response of complex structures under large deformations. The RED method should be easily applied to existing engineering processes for application in both the development and post-production phases of a products lifecycle. The analysis should evaluate vehicle crash compatibility in both barrier and car-to-car tests and allow ranking of different vehicles or vehicle combinations.

In the structural response of today's cars three deformation phases could be distinguished in form of the RED curve corresponding to the deformation of the three sets of car components: Phase I - the far forward car structure (structure in front of longitudinals, i.e. mainly crash boxes), Phase II - longitudinals and sub-frame and eventually back structure, and Phase III - end of the deformation (Figure 15).

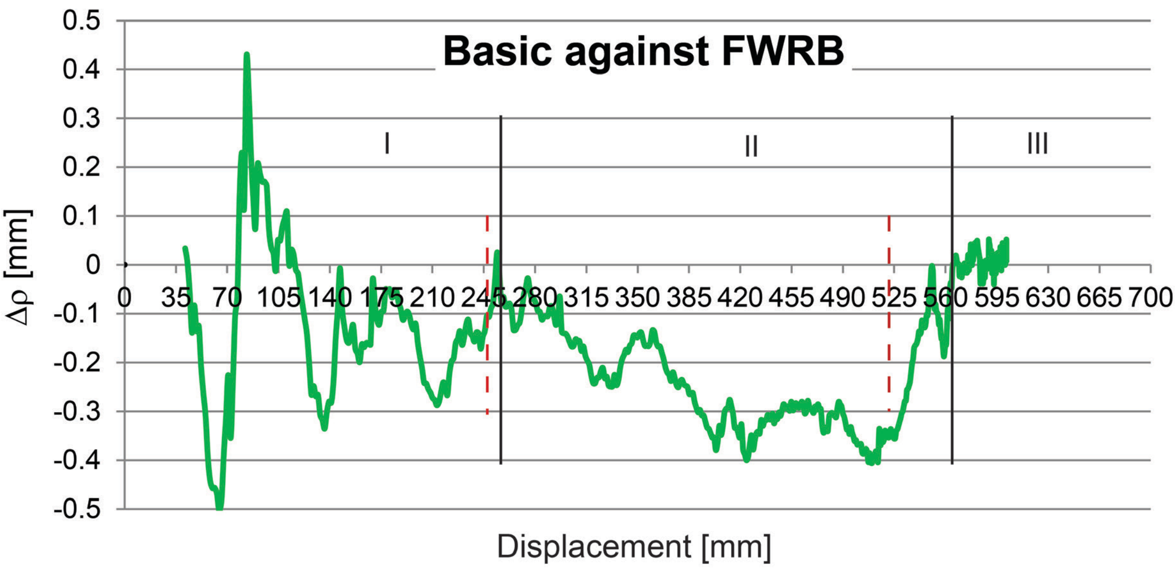

Figure 15: *An example of RED curve (Basic model against FWRB)*

For a given vehicle, the length initially available for deformation is constant for a particular set of car components (e.g. car longitudinals and sub-frame) to deform regardless of crash outcome. This fact is used to calculate a new parameter, Structural Efficiency. For the car against FWRB crashes, actual deformation lengths are normalized to available deformation length for each set of car components (or phase) to give an indication of how good the structure is really designed for the crash against the barrier. While available deformation length can be calculated from the vehicle geometry, the actual deformation length can be read from the RED curve where the segment between two deformation phases represents an actual deformation length. Structural Efficiency can be used for objective ranking of vehicle performance against a barrier. The RED curve is obtained from simulation with higher sampling rate (rcforce and matsum files –LSTC, 2007) than visual presentations (animation) due to computational expense and memory availability. As such, it gives more precise information on the moment when deformation mode changes occur than other methods representing a useful tool for a designer.

When the RED method is used to evaluate the level of compatibility in car to car crashes, the car's ability to preserve its crash behaviour exhibited against the barrier is evaluated. This parameter can be expressed as a quantity called Crash Stability and can be considered as a measurement of the robustness of the vehicle structures. The barrier test setup has to correspond to car-to-car crash setup for this process to be conducted. In this study, the Crash Stability is the comparison between the deformed length observed from the RED curve for a car crashing another car and the one observed from the RED curve when it was crashed against FWRB. Calculated in this way, Crash stability is a parameter showing how predictable the crash performance (behaviour) is. The vehicle is judged as stable when its crash performance in car-car crash is closer to behaviour seen in the crash against the barrier. The Crash Stability value for each pair of cars is then used for relative compatibility ranking.

From crash simulations of three car models against barrier and against each other a compatibility ranking was made. Two cars showing good Crash Stability produces higher compatibility rank among other pairs of vehicles. The ranking (Table 1) reflected the intrusions found on each pair of cars. There is some difference between the ranking and intrusions. The FWRB test is not developed to promote partner- but self-protection and the method can only assess what a reference test assesses

Table 1: *Relative compatibility ranking calculated from the performed simulations*

(1) Impact case	(2) Vehicle	(3) Crash Stability	(4) Sum of (3) for the impact case	(5) Relative Compatibility Rating for the impact case
Basic against Basic	Basic(1)	0.734	1.363	1
	Basic(2)	0.628		
Basic against ExSub	Basic	1.805	3.885	4
	ExSub	2.080		
Basic against ShSub	Basic	1.217	1.881	2
	ShSub	0.664		
ExSub against ShSub	ExSub	1.479	2.376	3
	ShSub	0.897		

It is left to adapt the RED method to cases when the colliding vehicles have different masses or a vehicle impacts a deformable barrier. The examples used to assess the method are such that the reference displacements can be considered equivalent to movement of the vehicle due to deformation of its front. There is no foreseen restriction of the RED to impacts where the contact interface is moving during the crash event but a suitable reference frame must be identified and can be considered the next evolutionary step for the method.

4. Discussion

Crash compatibility is a challenge for vehicle safety, regardless of vehicle size and collision partner. Previous research (Edwards et al. 2002) has shown that compatibility issues can be observed when identical vehicles collide and this is exacerbated when the collision partners have differing masses, geometries, and architectures. The results of Paper I highlighted the real world compatibility issues in HGV crashes with passenger cars. Both structural interaction and mass differences between the vehicle types are a challenge for vehicle designers.

The requirement of rigid FUPDs on HGVs is an important step towards improving structural interaction in frontal crashes with cars. The additional load path in the truck reduces the risk of overriding a car since the longitudinals of the passenger car have a reaction surface that was not available in older truck designs. The introduction of energy absorbing elements in the FUPD could further increase compatibility by better managing the energy dissipation in the high energy crashes that are associated with HGVs and passenger cars. This thesis has shown that energy absorbing FUPDs are able to provide higher levels of safety than rigid FUPDs, but only when good structural interaction is assured.

The quest for compatibility requires a method for assessing and quantifying compatibility. To date, there has been progress in defining the factors that describe compatibility but no objective test or analysis procedure exists. Furthermore, compatibility between HGVs and passenger cars has been treated separately from the compatibility between other vehicles. There is a clear need for method that can describe crashworthiness designs in vehicles. The method should be independent of vehicle design and provide quantitative data that can be compared to other vehicles or crash configurations.

The following discussion is organized into three main areas. Firstly, a discussion on compatibility issues will identify the main areas that need to be addressed. Secondly, the interactions between the compatibility issues and other parameters that define a crash but cannot be controlled by the designer are presented. Finally, the development of the RED method is provided to show how vehicles can be designed and evaluated to enhance compatibility by assessing the vehicle structures for different load cases.

4.1. Structural interaction problems arising from the real accidents in connection to the passenger car frontal crash performance, and e.a. FUPD as a countermeasure for the problems

Structural interaction problems in frontal collisions between passenger cars and HGVs can be divided into geometrical and energy absorption issues. Their description and possible countermeasures are presented using the results of this thesis as a foundation for further discussion

4.1.1 Geometry

The structural analysis performed in Paper I was based on VC-Compat database of car and HGV geometry of European vehicles. Comparing car longitudinals to FUPD placement, it was found that Regulation 93 accounted for the geometry of the HGVs when they are unladen. The consequence is that the cross-beams of most FUPDs do not coincide with the car's load paths when the HGVs are fully laden. The FUPD structure is rigidly linked to the HGV's frame and becomes lower as load is applied to the HGV. This results in most of the FUPD cross-beams lying at a level under the longitudinals of the car. Not having direct contact with load paths of the car, the FUP as structure became useless. Neither of the previous studies (Rechnitzer, 1993; EEVC WG 14, 1996; Lambert and Rechnitzer, 2000) on car and truck compatibility considered position of FUPDs on fully laden trucks. This was not even considered within the VC-Compat project. To prevent FUPD ground clearance from being too low, a suggestion (Paper I) was made to introduce the lower limit for the clearance of the FUPD cross-beam in the Regulation 93 to take into account the clearance of the truck frames even when the trucks are fully laden. In the current regulation there is no lower limit for the clearance and it is up to the manufacturer to decide how low the FUPD will be placed.

In Papers I-IV, the vertical alignment of the car's longitudinals and cross-beams of the FUPD was varied. Using the vertical cross section of the car's longitudinal as a reference, three vertical overlaps were considered for the FUPD: 50% below, 50% above, and vertically aligned with the car's longitudinals. The 50% overlap is larger than the average value of overlaps for FUPDs of fully laden trucks and longitudinals of passenger cars (Figure 5). Such a relatively large overlap causes larger intrusions and higher acceleration peaks compared to almost all cases where the structures are aligned. The presence of the main truck frame worsens the situation when they interact with the car and better results are achieved if the truck frame rails are at least partially deformable.

The sensitivity of the car structure to changes in vertical overlap against the FUPD is inherited from characteristics observed in car to car crashes even if identical vehicles impact each other. In Complementary Paper 1 the vertical misalignment simulations showed non-monotonic relationships between the intrusion and overlap of the longitudinals. This was particularly true for the under-running car as the result of a small interaction area with the sub-frame. The in-depth accident analysis performed in Complementary Paper 3 presented an example of the frontal crash between the two identical cars. Due to vertical misalignment, one of the cars was over-ridden. As a consequence, the driver of the over-ridden car sustained fatal injuries.

One conclusion from Paper I was that a lower limit for the FUPD ground clearance should be introduced with a requirement for a larger FUP cross-member section height. This will allow FUPD cross-beams to cover a wider range of passenger car longitudinal positions. A larger cross-beam section should also mitigate the consequences of braking which may cause statically aligned structures to shift vertically and fall out of alignment. In Paper III it was shown that the e.a. FUPD with larger cross-beam (240 mm cross-beam cross section height) has a clear advantage over the e.a. FUPD with smaller cross beam (120 mm). This can be considered an ideal case where the front truck structure is not present. The advantage disappears when the car front interacts with both an e.a. FUPD and the surrounding truck structures. The situation changes in favour of larger cross-section beam if deformable truck frame rails are introduced. Even in this case, the performance of the FUPD is below its theoretical potential (Paper IV).

The process of changing the analysis scope from car to FUPD only, to HGV with FUPD and rigid frame, and finally crash partner and HGV/FUPD showed the limitations in previous work. Rehnitzer (1993) and Lambert and Rechnitzer (2000) suggested an e.a. FUPD stroke of 500-600 mm was acceptable, and EVC WG14 lowered this to 360 mm. The work presented herein showed recommended stroke is not possible to utilize due to a lack in free length under the truck frames in the longitudinal direction. Even if sufficient space was available, simulations in this study showed that contact between the truck structure and FUPD is unavoidable, limiting e.a. FUPD performance.

The in-depth accident analysis presented in Complementary Paper 3 showed that poor structural interaction is still a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap.

In the all accidents analysed in Paper I, the vertical overlap between the car longitudinals and FUPD cross-beams was fairly good. In one of the cases it was still found that the underrunning of the passenger car was not prevented. In that case the FUPD cross-beam support on the struck side was too weak to resist the impact and failed, allowing the car to pass under the cross-beam lower surface. Not enough crossbeam support was seen as a direct consequence of an insufficient load required in the component tests covered by Regulation 93 and is in agreement with findings of other researchers suggesting that the test load for the rigid FUPD should be increased (Rechnitzer, 1993; Lambert and Rechnitzer, 2000). Paper I showed that similar failures within the car structures (connections between car sub-frame and the longitudinals) are of importance. This underlines the need for all designed parts to resist the impact forces without failure, otherwise stable structural interaction cannot be achieved even if the colliding structures are vertically aligned.

It was seen in real car-to-truck collisions (Paper I) that crash interactions are not limited to the car and FUPD installed on the truck. Other parts such the engine, frame and sometimes the radiator of HGVs interact with a passenger car. A proposal was made (Paper I) to raise the front part of the frame of HGVs (Figure 6). Such a design would remove the contact between rigid frame of the truck and the car, allowing the theoretical possibilities of the e.a. FUPD to be exploited. Simulations showed that a larger gap between truck frame rails and FUPD cross-beam is more desirable (Figure 11) reducing the contact between the FUPD cross-beam and surrounding truck structures. This is even more effective in combination with deformable truck frame (Figure 12).

Simulations of crashes between two identical vehicles (Complementary Paper 1) showed that the fork effect is not the only problem when vehicles of different stiffness collide. The fork effect can be seen when a passenger car's front structure is unable to cope with horizontal misalignment (complementary Paper 3). In the case of collisions between HGVs and passenger cars, only the passenger car's compartment is exposed to higher intrusions. This allows more freedom in designing the e.a. FUPD from HGVs occupant safety point of view compared to car design which is bounded by other aspects of its occupant safety, e.g. acceleration. Therefore, an additional effort can be put on e.a. FUPD design in order to mitigate the consequences of fork effect in car to HGVs crashes.

The issues identified regarding interactions between Regulation 93 compliant FUPDs and surrounding truck front structures and the fork-effect in recent real accidents shows the advantage of performing an in-depth analysis of car to HGVs accidents. These kinds of finding were not possible in in-depth analysis performed previously (Rechnitzer 1993, Lambert and Rechnitzer, 2000; Gwehenberger et al. 2003a and 2003b).

Implications of the three compatibility assessment test candidates, proposed within FIMCAR project, for impacts between the passenger cars and HGVs are discussed in complementary Paper 4. The FWDB metric is expected to encourage car structures above 400 mm which is the upper limit for the lower surface of the FUPD cross-beam. Together with the suggested increase of the cross-beam cross section height (Paper I and IV) the structures of the car above 400 mm will benefit the structural interaction in car-to-HGVs crashes.

4.1.2 Energy absorption

One goal of compatibility is to have each collision partner absorb a share of the kinetic energy in the crash. In the case of a FUPD, the main factors affecting energy absorption are initial activation of the FUPD (force in which FUPD e.a. supports start to deform), the slope of the force-deflection curve for the e.a. FUPD (stiffness), and the deformation length. Each parameter has been studied in previous research. Newew findings are presented in this thesis

From the structural analyses performed in Paper I it was found that the stroke length of the energy absorbing elements on an e.a. FUPD cannot be longer than 300 mm due to available space at the front of the truck. This is less than the suggested optimal length of 360 mm proposed in earlier research (EEVC WG 14, 1996). It limits the energy absorbing abilities of the e.a. FUPD, but later on it was shown (Paper IV) that the maximum deformation of e.a. elements in simulations was 270 mm which implies that the available stroke of 300 mm could not be efficiently used. The FUPD movement was restricted by the car's interaction with the surrounding truck structures.

Initial investigations into the structural properties of FUPDs were undertaken based on characteristics of car front structures. In particular, if one considers the available information about car front stiffness (van der Zweep et al., 2006) and the highest force requirement described in Regulation 93 the activation force of 160 kN for the HGV crossbeam support appears to be a suitable lower limit to ensure energy dissipation in the truck structures. Results of the research (Paper I-IV) indicate that 160 kN is an appropriate triggering force for the e.a elements of a FUPD.

In the simulations of crashes between e.a. FUPD and small vehicles (Paper IV), FUPD spring forces of 284 kN were obtained. The passenger compartment of the car should not deform under these conditions indicating that the recommendations of the VC-Compat project for compartment strengths of at least 350-400 kN are appropriate (VC-Compat, 2001). The triggering force of 160 kN is much lower than the test load forces for e.a. FUPDs suggested by Lambert and Rechnitzer (2000). They suggested forces of 400, 300 and 200 kN in P1, P2 and P3 points (Figure 3) respectively. These forces might be too high for small vehicles. It is important that both vehicles deform and absorb energy during a collision and it is therefore important that truck e.a. FUPDs start to deform and absorb energy at an appropriate time in the collision.

Even though the contact surface between a passenger car and an e.a. FUPD was much smaller compared to the contact surface in the impact between passenger car and FWRB, the former case was less severe. The simulations showed that the e.a. FUPD with the sufficiently stiff cross-beam and energy absorbing supports could absorb up to 34% of collision's total kinetic energy (Paper II). The triggering force of e.a. FUPD elements was found to be an important factor influencing the deformation mode of the longitudinals of the car. The chosen triggering force caused deformation of FUPD's e.a. elements to start at such a moment that helped crumpling (local buckling) of the longitudinal to initiate later in time and delayed the timing of the peak force in the sill. This caused the sill to deform less than in the case when the vehicle impacted the FWRB. The energy equivalent speed (EES) calculated for the case with e.a. FUPD was 66 km/h and indicated that it is possible to 'squeeze' more safety out of the car than it is available for the design case (56 km/h).

A scenario contributing to the fork effect was seen in one of the accidents investigated in Paper I where the bending stiffness of the FUPD cross-beam was insufficient. The horizontal overlap was such that the cross-beam support on the impacted side was positioned between the longitudinals of the passenger car. Since, the FUPD support was stiffer than both the FUPD cross-beam and the passenger car's bumper cross beam, the cross-beams bent around the truck's FUPD support and led to the fork effect. One more time the necessity of increasing the magnitude of the point loads component tests required in Regulation 93 was raised (Rechnitzer, 1993). The results from simulations in Paper II showed that the FUPD cross-beam with the lowest bending stiffness (5 mm cross-beam thickness) does not cause the fork effect but bends too much and too early to provide desirable structural interaction. The excessive bending results in lower energy dissipation in the energy absorbing elements of FUPD. The consequence was higher intrusions into the occupant compartment of the car in comparison to the intrusions when a stiffer (7 mm thickness) cross-beam was used. The e.a. FUPD with 7 mm thickness showed advantages even in comparison with the rigid cross-beam and has been used in all the simulations in Papers II-IV for cross-beam of 120 mm.

The different stiffness of the FUPD cross-beam was considered in the simulations between e.a. FUPD and passenger car. It was found that rigid FUPD cross-beam causes less intrusion than a deformable one with a low bending stiffness. A deformable beam with a higher bending stiffness gave better results (smaller intrusions) than a completely rigid cross-beam. The weakest deformable cross beam exhibited too much bending. The energy absorbed by deforming the cross-beam was important to reduce the intrusions into passenger compartment of the impacting car, but still the cross-beam had to have a sufficiently high bending stiffness to prevent the fork effect.

In all the simulations of frontal crash under different horizontal overlaps, the car showed better crash performance (more predictable distribution of intrusions) when it was run against e.a. FUPD (with 7 mm thick cross-beam and triggering force of 160 kN) than when it was run against itself (Complementary Paper 1) . The reason can be that the FUPD cross-beam bending stiffness allows better horizontal spreading of the forces when interacting with the car front.

Proposing the raising of the forward elements of the HGV frame (Figure 6) was meant to allow the radiator of the truck to be used as an additional energy absorbing element. If an e.a. FUPD is used, raising the frame of the truck will allow better exploitation of e.a. capabilities of a FUPD. The simulations showed that if the truck frame rails deform during the crash, the radiator is able to take up some kinetic energy. However, the energy absorbed by the truck frame and the radiator is less influential on crash outcome than the fact that a deformable frame allows more deflection space for the FUPD than the case for the rigid truck frame rails.

The characteristics of e.a. FUPD as a result of the research performed for the thesis are general guidelines for a FUPD that are supposed to prevent overriding of the passenger car by HGV and decrease the severity of these types of impact. The suggested FUPD characteristics are seen as a prerequisite for an improved structural interaction. When these are satisfied, the limit on FUPD performance lies on available stroke of e.a. elements and depends on space available in the front of a truck.

To estimate the benefits of e.a. FUPD presented in this thesis the same logic applied by Gwehenberger et al. (2003b) (Section 1.1.) may be used. Assuming that e.a. FUPD is able to absorb 40% of kinetic energy involved in the crash (suggested in EEVC WG14, 2000), Gwehenberger et al. (2003b) estimated that reduction would be 10-11%, i.e. 190 – 240 fatalities and 30%, i.e. 1497 seriously injured in Germany. The e.a. FUPD could absorb 89 kJ (Figure 16) (or 27% of kinetic energy) which corresponds to reduction in 6.8-7.4%, i.e. 125-137 fatalities and 20%, i.e. 998 seriously injured.

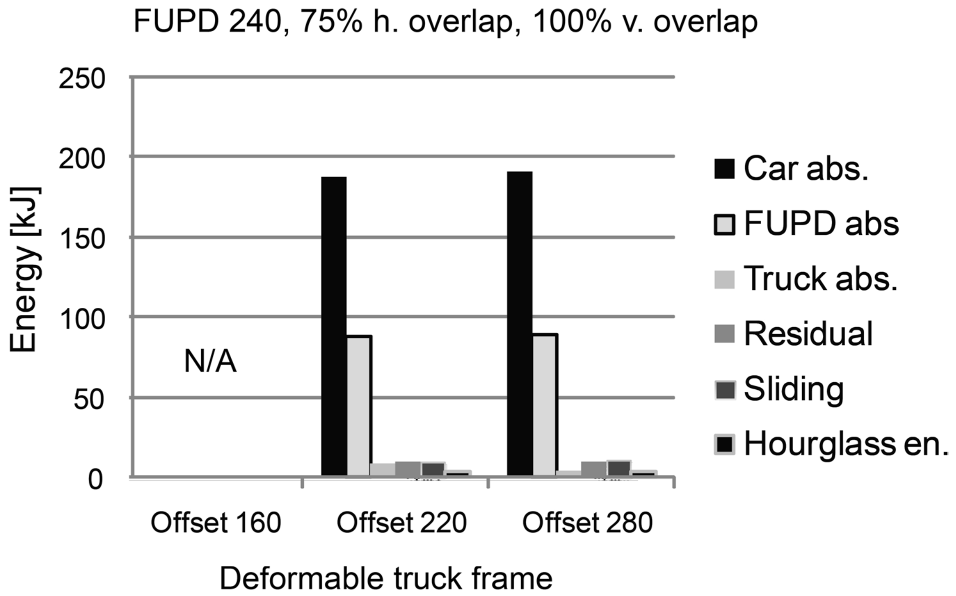

Figure 16: *Comparison of energy distributions for different offsets for the FUPD of 240 mm cross-beam and deformable truck rails*

The MPDB metrics encouraging the horizontal load spreading is also expected to improve structural interaction between the car front and FUPD. The trolley mass of 1500 kg for MPDB barrier implies increase in self-protection (stiffer front structure) of the smaller vehicles. Stiffer front structures and compartments are encouraged by the ODB test procedures and could lead to better performance of e.a. FUPD in small vehicle-to-HGVs impacts. Therefore, changes on the passenger car front structure expected from the FIMCAR test application are seen as beneficial car to HGVs impacts if HGVs are equipped with e.a. FUPD designed with recommendations from the study presented in the thesis.

4.2. Further understanding of the frontal crash compatibility

All parameters influencing compatibility have never been previously discussed together but rather their individual level of influence on crash performance was under investigation. In the following discussion, all previous parameters, together with some newly recognized parameters, are combined and their influence on each other and compatibility are presented in a diagram (Figure 17). The parameters influencing compatibility are divided into constraints, unpredictable factors, unpredictable but partially adjustable factors, and design variables. Constraints are parameters which have to be obeyed in designed process. Unpredictable factors force designers to find robust design solutions which will suit most of situations governed by unpredictable factors. Uncertainties related to unpredictable but partially adjustable factors can be limited by design. Design variables are those parameters freely available to be modified by designer.

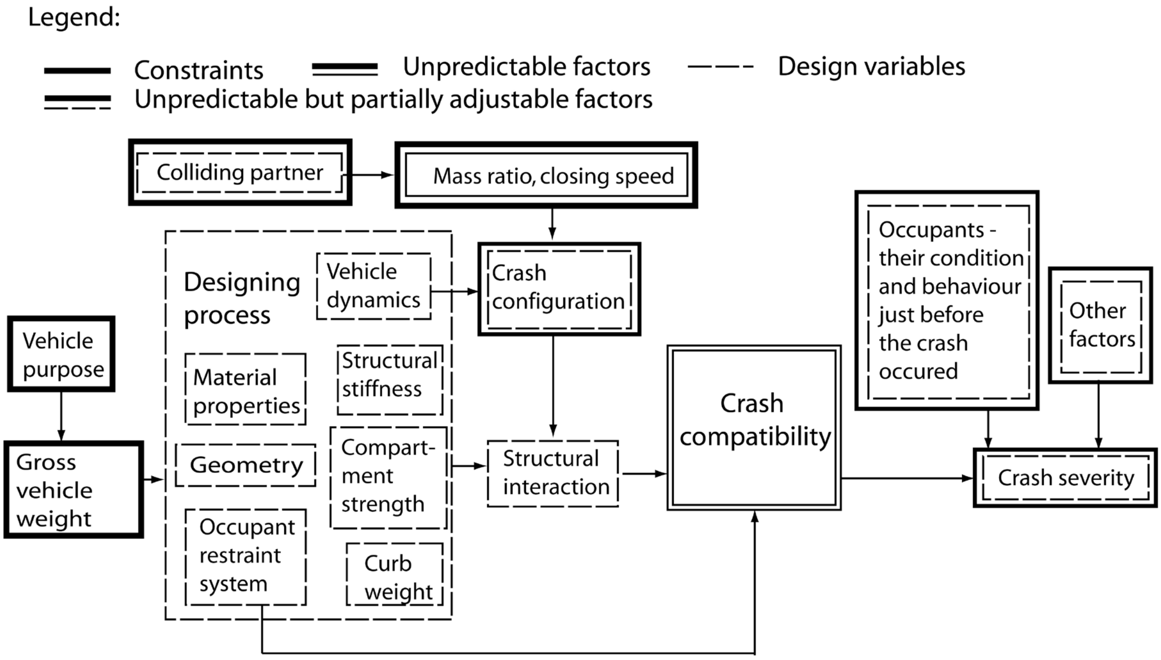

Figure 17: *Model of parameters and interactions influencing compatibility*

The first parameter appearing in Figure 17 is the purpose of the vehicle that governs the decision about future gross vehicle weight. For HGVs, the purpose is to have high gross weight and vehicle design is obviously governed by this factor. For other types of vehicle, the influence of the vehicle purpose is less obvious but it still influences the size and curb weight of the vehicle. For example, due to their purpose there is a difference in size and weight between a family and a sports car. Therefore, both, purpose and gross vehicle weight can be considered as constraints.

Vehicle design is governed by the purpose and by gross weight decisions which in their turn influence the structural stiffness of the vehicles. Here, the structural stiffness is defined as the combination of geometry and material properties of energy absorbing structures. In current legislative crash tests for passenger cars (Section 1.1) a car's front structure must manage the kinetic energy of the impact, which is proportional to the vehicle mass, when hitting a barrier and rigid wall. This results in higher stiffnesses for heavier vehicles. Structural stiffness is also influenced by compartment strength. The occupant restraint system is part of vehicle's self-protection and is influenced by structural stiffness of the vehicle. Obviously, there is a mutual interaction between all the factors included in design. Since there is certain freedom in material and geometry choice, all of the factors included in design can be considered as design variables.

From the simulations it was seen that structural interaction is not only dependent on the geometry of the vehicles involved in the crash. If pure geometric alignment of load paths of the two colliding vehicles is achieved, structural stiffness governs the deformation mode of the parts in contact and consequently the time when two parts are going to interact with each other. This was seen in car-to-car (complementary Paper 1) and in car-to-e.a. FUPD simulations (Paper II) (Figure 18). In both cases, the time when certain load paths start to deform was an important factor influencing the amount of energy absorbed but even the severity of the crash outcome. Therefore, structural stiffness can be seen as a factor influencing structural interaction. Because, the structural interaction is dependent on the whole design process, all those factors included in design can be also included in the factors influencing structural interaction.

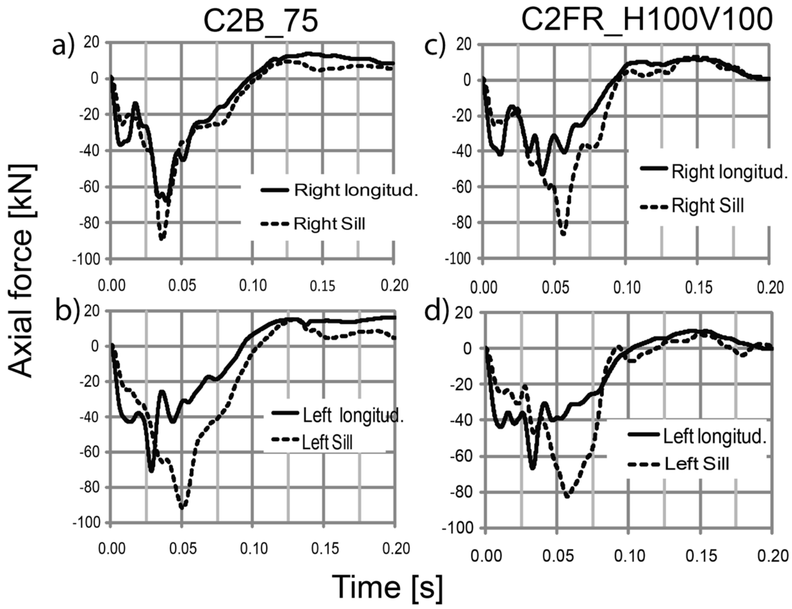

Figure 18: *Axial loads measured in the right [(a) and (c)] and left [(b) and (d)] longitudinal structures of the car when crashed against FWRB [(a) and (b)] and against e.a. FUPD (c)*

The crash configuration refers to vertical and horizontal overlap just before the crash occurred (Lindquist et al., 2004) and therefore directly influences structural interaction together with geometry of the colliding vehicles. It is the factor that was not discussed by previous researchers directly in connection to compatibility but rather in accident statistics. In general, the actual crash configuration is practically unpredictable. It depends on unpredictable factors such as driving history preceding the accident, road infrastructure, etc. There is also one design variable influencing crash configuration – vehicle dynamics. When one or both vehicles start to brake before the collision occurs, the braking vehicle pitches and changes the vertical placement of the loading paths in relation to the other vehicle. This is seen in real accidents even for identical cars (complementary Paper 3). It is not possible to predict whether the braking will be applied or not and how long it will last, but the vertical displacement due to pitch angle if braking is applied can be governed by design. Since design variable, vehicle dynamics, influences crash configuration, crash configuration can be considered as unpredictable but partially adjustable factor influencing structural interaction.

The factor "colliding partner" is considered as unpredictable but partially adjustable factor. It is partially adjustable because it includes all those factors presented in the diagram that contain even design factors. It is also unpredictable, because there is no way to predict which vehicle will be involved in collision. Mass ratio and closing speed are also unpredictable factors. It has been seen, from work done in Paper II, that structural interaction is not same for different speeds. The e.a. FUPD is designed for a higher speed and performs better in interaction to car front under speeds of 75km/h than under the impact speed of 56km/h due to its stiffness tuning to speed of 75 km/h. Mass ratio indicates possible difference in stiffness, geometry, etc. and even this factor then influence crash compatibility through structural interaction.

Even if demands for good geometrical alignment are accomplished, a severe crash (higher mass ratio, higher speed) is more likely to cause failure of the loading paths and their connections and significantly change the structural interaction. The failure is often seen in real crashes. Influence of the failure between car longitudinals and front sub-frame was one of the concerns in Paper II. It was found that the failure worsens the crash outcome from crash safety point of view. If a high closing speed is involved in the collision, the ability of at least one of the colliding vehicles to efficiently absorb the energy can be exhausted. In this case it is impossible to talk about compatibility because the vehicles are constructed in accordance to the safety tests under certain impact speed. It is unrealistic to expect that the vehicle will be able to protect its occupants for speeds higher than those the vehicle was constructed for.

Structural interaction is a complex issue. It depends on many factors already presented and also includes the factors related to the collision partner. It is not definite and evolves through the whole deformation process. Thomas (2005) and O'Brian (2010) equate the level of structural interaction to the level of compatibility in the collision. In this thesis, it is found as a crucial factor influencing compatibility. However, the level of structural interaction is not seen here as equivalent to the level of compatibility. There is interdependence between structural interaction and the occupant restraint system. The restraint system is developed in accordance to the car structure and its crash performance against barrier tests. During a crash the vehicle front structure is designed to deform in the way that will produce an acceleration curve of the vehicle which suits the occupant restraint system in the best way. Further, in the diagram (Figure 17) there is one more connection going directly from the factor "Occupant restraint system" to "Crash compatibility". The restraint system performance is influenced by structural interaction. Finally, it is structural interaction and the occupant restraint system that influence crash compatibility as a measure of self- and partner – protection. Further, crash severity is not only dependent on crash compatibility. There are more factors influencing final crash severity but they are out of the scope of research. One factor is identified as an example: "Occupants – their condition and behaviour just before crash occurred". The purpose of identifying particularly this factor is to differentiate the influence of compatibility achieved through structural interaction and the designed restraint system, and the influence of the restraint system on crash severity when other factors (occupants, seat position, loose cargo, etc.) affect proper usage of the restraint system are present.

4.3. The RED method for the compatibility rating and further discussion

Based on the presented view on compatibility factors, an objective method for evaluating compatibility has been developed - the RED method in the Paper VI. The main idea used in the method development is the fact that the only guideline for the design of the vehicle's front structure, from a safety point of view, is its behaviour in impacts against different barriers in accordance to accepted safety tests. Therefore, any deviation of the vehicle's structural performance in a crash against another vehicle from that showed during a corresponding barrier test can be considered as a deviation from compatible behaviour. It is assumed that the barrier test is accepted as an appropriate compatibility test for the crash configuration.

It is assumed that the deformation mode is directly connected to an amount of absorbed energy through pure deformation of a structure. The car load paths are mostly loaded in the axial direction. Therefore two modes, local and global buckling, are of special interest for an investigation. A bending mode is seen as a consequence (continuation) of global buckling or mode existing mostly at the end of car crash process, for example bending of A-Pillars towards the occupant compartment.

In Paper V the crash simulations of simple structures were used to derive an indicator for structural performance derived from the energy absorption and the impact force calculated during the crash. A new, artificial quantity, the Equivalent Energy Displacement increment has been established. The Equivalent Energy Displacement increment is calculated from the internal energy increment for calculated from stresses and strains developed in a time step. It represents the amount of possible deformation (in the direction of interest) developed in time step. This displacement can differ from the actual calculated displacement increment of the structure which is displacement of the unaffected (un-deformed vehicle) zone in time step. The difference was found to be connected to the deformation mode of the structure. A plot of RED increment versus displacement is a visual representation of the local and global buckling and bending modes, and their combination (Figure 13 and Figure 14)

The new method gives more insight into structural deformation behaviour and the transition between different deformation modes. This concept was further developed into the RED method in Paper VI where the RED value is used to judge the behaviour of the car in the crash against the FWRB. The behaviour of the car is observed through the transition between different deformation modes of the structure during the crash. Three phases in a vehicle's crash response associated to the deformation of three main sets of load paths could be clearly distinguish in the RED curve (Figure 15).

To judge the behaviour of the car in the crash, two values are used in the RED method: Structural Efficiency (SE) and Crash Stability. The Structural Efficiency relates to the ability of the car to behave in the way that is proposed by the designer (Paper VI). In an ideal case, the car structure would deform in the proposed way and Structural Efficiency would take value of "1". Practically it means that those three phases (Figure 15) starts and ends in accordance to designer's proposal.

From the RED method point of view it means that a deformation length for each set of car structure components during the crash was equal to its calculated available deformation length. The Structural Efficiency is not a measure of occupant protection in the car. It is assumed that occupant protection is satisfactory in the test if the designer's proposal is correct, i.e. in accordance to occupant protection. As such, the Structural Efficiency can be used as guidance during vehicle design phase when simulation tools are used and dummies are still not included. Good Structural Efficiency is a prerequisite for having control over the behaviour of the structure to satisfy occupant protection. If there will be more than one compatibility (and/or self-protection) barrier test, good Structural Efficiency than has to be achieved for all the tests. The Crash Stability is another value derived from the RED curve. It shows how much the behaviour of each car in the crash against another car is close to the behaviour it showed in a compatibility test against barrier. The prerequisite is satisfactory results in the barrier test regarding occupant protection for the same crash configuration (Paper V and VI). In an ideal case there would be no difference in car structure deformation between these two cases, i.e. the Crash Stability would take a zero value implying that the car structure behaves as it behaved in a crash against barrier. In other words the RED curves for the two cases are the same. In this way, the stable (predictable) response against another vehicle of the structure is achieved, i.e. the car behaves in the way predicted by the barrier test.

The results from car to FWRB crash simulations showed that the car with an extended sub-frame showed best performance (SE) against the barrier compared to other two cars (Basic and ShSub). Actually, the results for ExSub and Basic are very similar. This was in accordance to intrusion values on the cars. In compatibility rating, the crash combination Basic to ExSub showed the worst results. In this case, the pattern of intrusion changed compared to the intrusion pattern when they were crashed against FWRB. The best result is obtained in the simulations of Basic to Basic crash. Even here, the intrusion values correspond to the ranking obtained by the RED method (Table 1). Discrepancy between the SE and compatibility rating for the two cars (ExSub and Basic) can be explained by the fact that FWRB test is not an appropriate compatibility test (Adolph et al., 2013). The FWRB is developed to assure self-protection while compatibility rating refers to both, self- and partner-protection.

From the results obtained from crash simulations of the car models against a fixed rigid barrier and against each other, it was seen that a vehicle can be robust but not have a stable (predictable) performance (ExSub). It makes the vehicle unpredictable and raises a question if the vehicle will show robustness against other vehicles that it was not crashed against. ShSub model shows an opposite behaviour. It showed the stable response but poor self-protection performance against other cars. These two cases suggest that both Structural Efficiency and Crash Stability have to be satisfied by both vehicles in order to each the vehicle from high compatibility ranked pair is to be considered as a candidate for a compatible vehicle.

The implementation steps of the RED method on the design phase are given by Figure 19. For the purpose of presentation it is assumed that there is one barrier test for each of the three different (horizontal) overlaps.

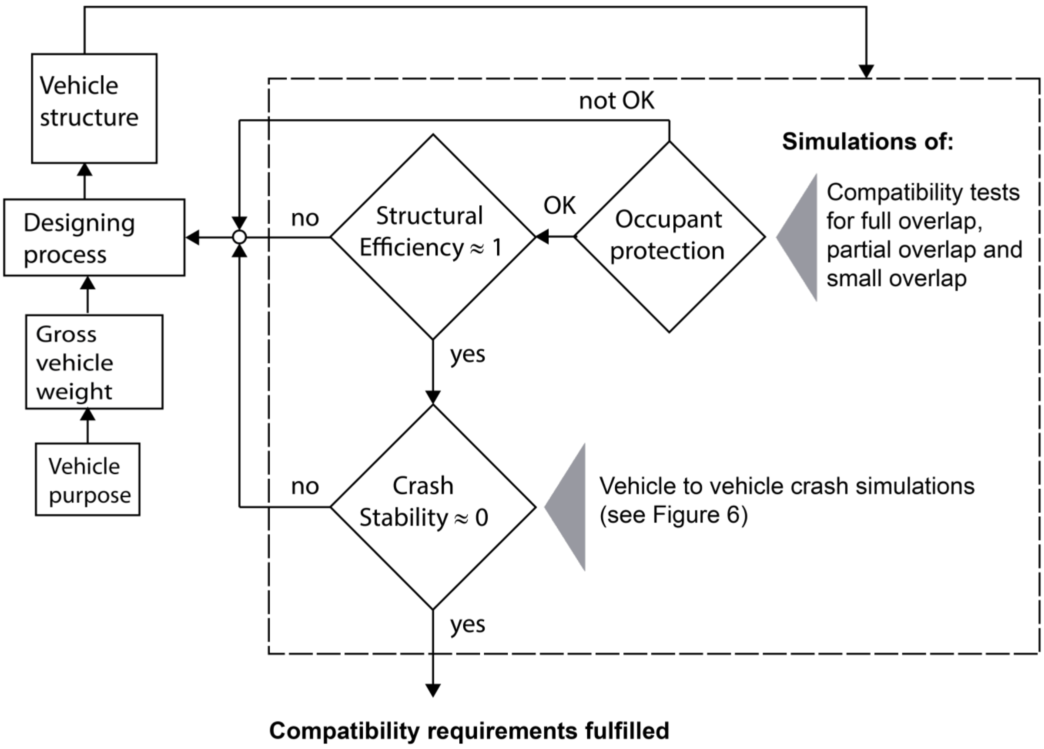

Figure 19: *Implementation steps of the RED method on design process: Steps leading to compatibility*

It is supposed that two cars satisfying compatibility barrier tests should show high level of compatibility when they crash with each other under crash configurations that corresponds to the barrier tests. In complementary Paper 1 it was shown that the same car crashed to itself may show different results for different crash configurations showing special sensitivity to variation of vertical overlap. During the design process, when occupant protection and structural efficiency is achieved for certain vehicle, the next step is to assure that the vehicle is compatible at least with itself, i.e. the Crash Stability for the vehicle against itself has to converge to 0. Visualization of the steps leading to compatibility is given by Figure 20. Barrier compatibility tests are still in development, therefore, Figure 20 shows possible values of Crash Stability that might be obtained from simulations of a vehicle [vehicle(1)] when crashed against itself [vehicle(2)] and calculated in accordance to Table 2 in Paper VI (column 7). The change of vertical alignment due to dynamic behaviour of the car during braking should be taken into consideration by three different vertical overlaps in combination to the three horizontal overlaps. In Section 1.1., two definitions of compatibility that complement each other have been chosen. Applying them in the RED method with horizontal and vertical compatibility implies that the Crash Stability has to satisfy both vertical and horizontal compatibility. To achieve horizontal compatibility the set of results (Crash Stability) for each vehicle has to be more horizontally distributed implying small difference in Crash Stability for different horizontal overlaps (satisfaction of horizontal compatibility according to the first definition) as demonstrated in Figure 20b. To achieve vertical compatibility the set of results (Crash Stability) of each vehicle for different vertical overlaps have to be closer to each other in vertical direction (satisfaction of vertical compatibility according to the first definition) and finally they have to converge to 0 in order to satisfy even the second definition that comprises self- and partner-protection. Namely, it is not rigorous enough to achieve similar crash response (equal occupant loads) of the two colliding vehicles. Convergence to zero implies that the crash response is acceptable even from a severity point and from the compatibility rating point of view. For example, Column 5 in Table 1 gives a sum of Crash Stability values for the each car in one pair of different cars. Smaller values (close to zero) for each car gives better relative compatibility ranking for the pair of cars but also smaller value for each car limits the difference between the Crash Stability values for the two different vehicles. In this way both definitions of compatibility are satisfied, the first one requiring similar occupant load (similar crash response) if incompatibility is to not be present, and the second one requiring self- and partner-protection achieved. Two vehicles satisfying the Crash Stability criteria in the crash against itself are more likely to have higher compatibility rank than the pair of other vehicles satisfying only compatibility barrier tests.

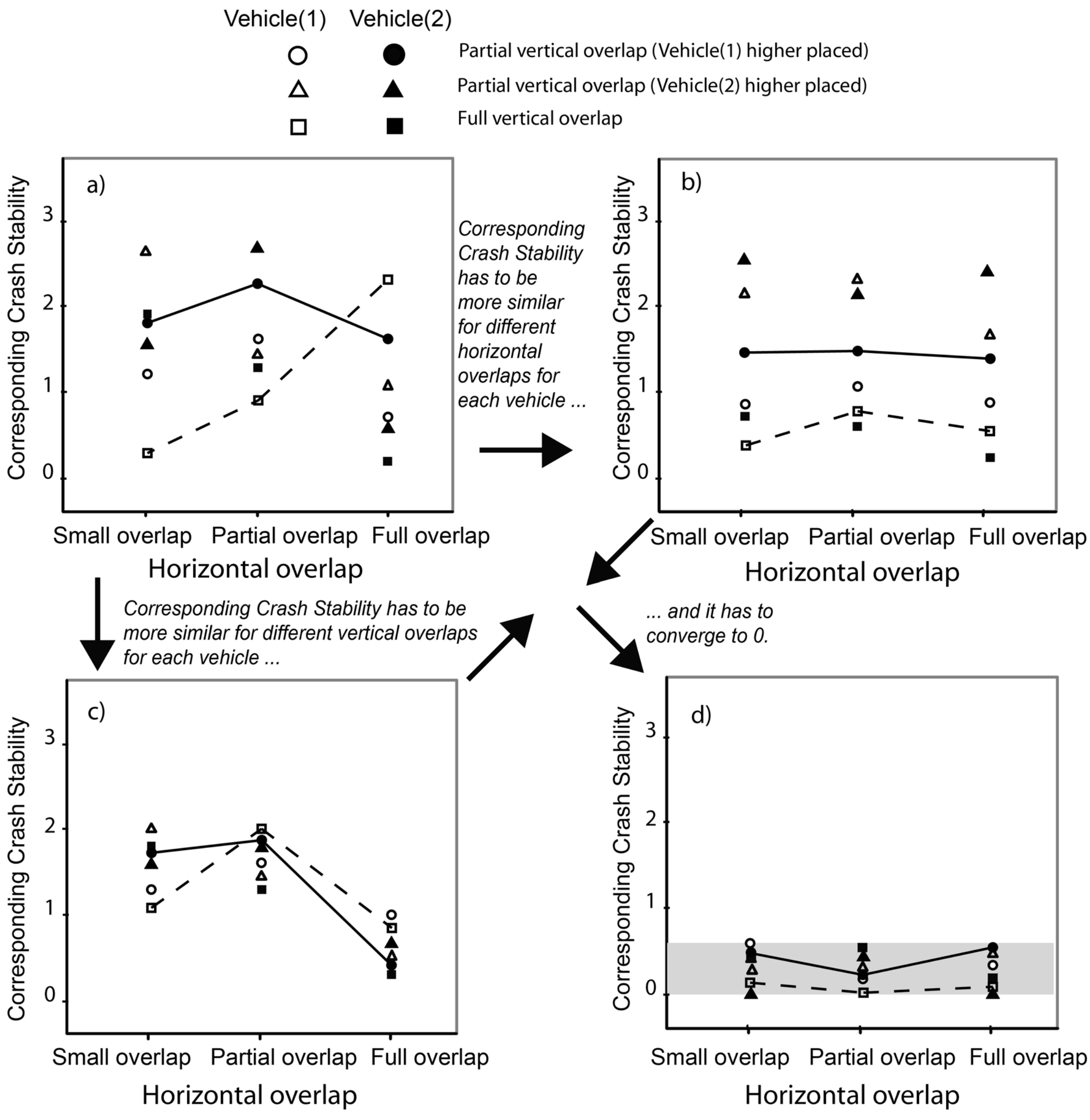

Figure 20: *Steps leading to Crash Stability d) starting from a) imaginary results from car crash against itself simulations through b) prerequisites for achievement of compatibility performances in horizontal and c) vertical direction*

When discussing compatibility between cars and HGVs, the two definitions of compatibility (Section 1.1.) cannot be considered as complementary. The first definition stating incompatibility as unequally distributed occupant loads between vehicles makes cars and HGVs compatibility unachievable. The second one comprising self-and partner protection is closer to what may be desired if compatibility between cars and HGVs is to be achieved

The in-depth accident analysis (Paper I) showed that the severe collision between car and HGV is only severe for the car occupants. Therefore, the object of concern is only the passenger car, i.e. its Crash Stability. Therefore, first step in the evaluation of the performance of e.a. FUPD is to ensure that it does not reduce the self-protection of the car. By this way the partner-protection from HGV's side is satisfied and compatibility is achieved. For the evaluation of an e.a. FUPD, the Crash Stability has to be calculated. In this case, only one value will be considered, the one referring to Crash Stability of the vehicle impacting the e.a. FUPD under the speed defined by the compatibility test for the same configuration. Again, the results closer to zero indicate higher compatibility between e.a. FUPD and the passenger car. It guaranties that the e.a. FUPD allows the passenger car to behave in the designed way (predictable behaviour). In the RED method, a zero value is obtained when the behaviour of the car during the crash does not differ from the behaviour that the car exhibited in the crash compatibility test (the barrier test) for the corresponding crash configuration.

An evaluation of compatibility between passenger car and other vehicles (SUVs, vans and pickups) may be done in the same way described for the evaluation of FUPD. In the model of the e.a. FUPD used for the parametric study, it was very convenient to use simplified spring model for representation of the e.a. supports that allows easy change of e. a. characteristics of the supports. While this model was satisfactory for its purpose it was not appropriate to use for detailed evaluation of e.a. FUPD by using the RED method since the method is based on distinguishing different deformation modes. Further, even if available, such a model should be evaluated against barrier compatibility tests that still are not available.

Because the RED method is based on FE crash simulations it can be used in the development as well as in the production phase of a vehicle crash structure or other kinds of structure where deformation modes are important. It is shown that the same method can be used in compatibility rating where new perspective on compatibility is introduced and applied. (see Figures 5 and 6).

The potential of the RED method has not been developed in Paper V and Paper VI. Because the method differentiates between deformation modes, a more thorough analysis of the scope and magnitude of the RED curve could give more information about the vehicles performance, in both, vehicle to FWRB and vehicle-to-vehicle simulations.

It is left to adapt the RED method to the cases when the colliding vehicles are of different masses or against deformable barriers. The examples used to assess the method are such that the reference displacements can be considered equivalent to vehicle deformations. There is no foreseen restriction of the RED to impacts where the contact interface is moving during the crash event and can be considered the next evolutionary step for the method.

The RED method directly refers to compatibility unlike quantities such as aggressivity, fatality risk (Fredette et al., 2008; Méndez et al. 2010; Huang et al. 2011) or secondary safety index (Newstead et al., 2011), etc. Neither does it need huge amount of data from traffic accidents. Other direct methods for evaluation of compatibility have been suggested by Thomas (2005) and O'Brian (2010). Thomas (2005) equates the level of structural interaction with compatibility. The level of structural interaction is evaluated through comparison of energy absorbed by the front-end of the vehicle in a vehicle to vehicle crash test and the one obtained in crash test against rigid barrier with the assumption that compartment integrity is preserved. This assumption is not necessary in the RED method. O'Brian proposed a definition of the compatible collision for two vehicles based on the comparison of injury risk for accidents with the same crash configuration as a corresponding barrier test. The collision is considered compatible if the injury risk calculated for the accidents is equal or lower than one calculated in the test, while the RED method is able to estimate the compatibility of the two vehicles in advance, before the accident happens. It can be used to evaluate FUPD and other incompatibility countermeasures, i.e. to estimate compatibility between passenger cars and any kind of its crash opponent.

Unlike the other compatibility assessments or metric described above, the RED method is able to feed more directly into the design process. The RED process identifies specific transitions in deformation modes during the crash while the methods described above only globally describe the system effectiveness without targeting specific structures, deformation modes, times, or displacements that may be useful for the designer.

Unlike the previous research on car-to-HGV compatibility (Subsection 1.1) the RED method can assign requirements for the passenger car (horizontal and vertical compatibility, Crash Efficiency and Crash Stability) which should assure more predictable behaviour of the passenger car when impacting a HGV.

5. Thesis contribution to the improvement of compatibility between HGVs and passenger cars

Investigations into the structural properties of FUPDs have been undertaken resulting in recommendations for compatibility improvements for both FUPD equipped HGVs and passenger cars. This thesis has contributed to the state of the art in terms of:

1. in-depth analysis of the accidents between cars and trucks equipped with FUPD;
2. parameter studies that identify desirable properties for FUPDS;
3. a better description of the interrelation of compatibility factors;
4. a new method to quantify the structural response of deforming structures;
5. a procedure to more readily achieve compatibility by separating vertical and horizontal crash performance; and
6. a new method to objectively rate the crash compatibility performance of vehicles.

The analysis of the accidents between cars and trucks equipped with FUPD was undertaken for the first time. While other papers have presented the injury outcome of crashes, no other study has conducted a detailed analysis of the structural interaction between vehicles. The method applied is recommended for future investigations of crash compatibility.

The different simulation series was important to identify the role of FUPD characteristics in isolation (Papers II and III) as well as when incorporated in the whole vehicle (Paper IV). This was needed to show how structural interaction and energy absorption work together.

For the first time, all the factors influencing compatibility are put together and their relation to all relevant parameters and variables are defined (Section 4.2.). The factors are divided into constraints, unpredictable factors, unpredictable but partially adjustable factors and design variables. Dividing the compatibility goals into two parts (compatibility performance in horizontal and compatibility performance in vertical direction) makes the goal of compatibility easier to understand and achieve

A new method (the RED method) for objective measurement of compatibility has been developed (Papers V and VI). This method is able to recognize and quantify deformation modes of a structure during a crash. Based on these abilities two new quantities are defined: Structural Efficiency and Crash Stability. The first quantity is a measure of how good the structure is really designed for the crash against the barrier. Crash Stability is used to evaluate the level of compatibility in vehicle to vehicle crashes, and the vehicle's ability to preserve its crash behaviour shown against the barrier. For the first time a method is presented to objectively evaluate FUPDs and other incompatibility countermeasures, i.e. to estimate compatibility between passenger cars and any kind of its crash opponent.

The main point of the RED method is to not only put requirements on HGV performance but also the collision partner which should provide more predictable behaviour in any type of frontal collision.

6. Limits of the study

The accident databases containing detailed information about passenger car accidents available to the author usually do not contain information about the HGVs involved in the accidents or the information is insufficient for an in-depth accident analysis. Consequently only a few accident reports were found suitable for the in-depth analysis.

The e.a. FUPD parametric study was based on frontal crash simulations. The influence of chosen parameters on other types of collisions such as HGV to car rear or car side has not been investigated. However, the proposed parameters are not to be expected to worsen those types of crash as long as the e.a. FUPD performs as rigid one, i.e. as long as e.a. supports are not activated. The highest test load force in the Regulation 93 concerning rigid FUPD is 160 kN is as same as proposed triggering force for FUPD e.a. elements. Further, the impact speeds are lower in HGVs to car side and rear accidents than those in frontal HGVs to car accidents. In Australia, 90% of all HGVs to car rear accidents occur under a speed less than 25 km/h, while 70% of all HGVs to car side accidents occur under a speed less than 30 km/h (Lambert and Rechnitzer, 2000). A B-pillar resistance bending force does not exceed 80 kN (Abe et al., 2005). Further research is needed to find out how the e.a. FUPD with proposed parameters interact with side and rear car structures in HGV front to cars side and to car rear impacts.

Most of the research has been based on FE simulations. Due to the lack of available FE models, heavy passenger cars were not considered while small cars were used only for detection of the lower limit of the compartment force necessary for successful application of e.a. FUPD against small vehicles. The models described in Papers II-V do not have full validation due to a lack of experimental data. The passenger car (Basic) model has been modified from a documented North American car model to better resemble a European car.

These modifications will not likely be validated in further work due to limitations in resources. To minimize this issue, simulations have been reviewed by a panel of industry experts to identify and minimize errors in the simulations. When the changes on the sub-frame were made on Ex-Sub and Sh-Sub models no other adjustments were made to resemble a European car.

The FE simulations were selected as the most appropriate method of systematically investigating several parameters controlling vehicle-vehicle crash response. The number of crash configurations investigated could not be accomplished with experimental methods due to limited resources and also the difficulty in conducting complex modifications to structures. The only other alternative method for studying vehicle interactions in a parametric study was the rigid body simulation models used by TNO in the VC-Compat project (Leneman et al., 2001). This approach to modelling was not chosen as rigid body models require an a priori definition of structural deformation and cannot fully capture the interaction of impacting structures.

No dummy and restraint systems seat belt and airbag, were used in the simulations. This is not unusual in car structure studies (Barbat et al., 2003; O'Brien, 2010, Wågström, 2013). Measurements taken from dummies are results of the mutual action of car structural performance and its restraint systems. Therefore, parametric studies of e.a. FUPD is strictly based on comparison of intrusions and acceleration peaks, where any decrease of intrusions and/or acceleration has been seen as directly connected to decrease in occupant injuries (Hobbs, 1993; Thomas, 2005; Delannoy et al., 2005).

7. Conclusions

All the parameters influencing compatibility were put together and relationships between the parameters were clarified in this thesis. Based on the work, new parameters (crash configuration and passenger restraint system) influencing occupant safety as a consequence of crash compatibility were recognized. The parameters were divided into constraints, unpredictable factors, unpredictable but partially adjustable factors and design variables. The division of the parameters opens new opportunities for research on compatibility by enabling an easier overview of possible fields of action. The clear relationships between the parameters may help to identify the influence of a vehicle's structure in mitigating crash severity and allow for earlier optimizations in the design process. A more effective way of achieving the overall goal of compatibility is proposed by dividing compatibility goals into two parts - horizontal and vertical compatibility performance.

It was found that the ECE Regulation 93 is not sufficient to ensure a Front Underrun Protection Device serves its purpose for real crash conditions and the suggestions for improvement of the regulation were given. The upper limit for the FUPD clearance in the regulation should account for the clearance of fully laden trucks. The regulation should contain a lower limit for the FUPD ground clearance. Both upper and lower limits are necessary in order to ensure at least static geometric alignment is achieved between FUPD cross-beams and the front load paths of most passenger cars in the European fleet. This is also in accordance to the vertical position of car main load paths proposed by the compatibility test (FWDB) proposed within the FIMCAR project. This criterion is also compatible with the Auto Alliance initiative in the U.S.A.

From in-depth accident analysis and the simulations it was concluded that bending stiffness of a FUPD cross-beam is an important characteristic of its structural interaction with front-end of passenger car. Sufficient bending stiffness is necessary to overcome fork-effect in frontal collisions with passenger cars. The e.a. FUPD with the sufficiently stiff cross-beam could absorb up to 34% of collision's total kinetic energy. A bending strength characterized by the 7 mm thick steel cross-beam presented in Paper II was appropriate for the crash configurations investigated.

The right choice of triggering force and bending stiffness of the e.a. FUPD cross-beam led to better horizontal compatibility between e.a. FUPD and passenger car in the study. Results of the presented research indicate that 160 kN is an appropriate lower limit triggering force for the FUPD. In the simulations of frontal crash under different horizontal overlaps, the car showed better behaviour (more predictable distribution of intrusions) when it was run against e.a. FUPD (with 7 mm thick cross-beam and triggering force of 160kN) than when it was run against itself. It was shown that the theoretic potential (in car to e.a. FUPD crash simulations) for mitigating crash severity are promising but are limited when incorporating the FUPD in the HGV due to interactions with the surrounding HGV front structures. However, the situation improves if deformable truck frames are used and the offset between frame rails and the upper surface of the FUPD increases (at least 220 mm is needed). It was shown that the proposed changes of the truck's front will allow more deformation of the FUPD and consequently higher energy absorption by e.a. elements. Even with these modifications the 300 mm stroke available on FUPD could not be fully utilized as it was seen in car to (only) e.a. FUPD crash simulations. This implies that further changes on truck front are unavoidable if e.a. FUPD abilities are to be used to their full potential.

A unique method (the RED method) which is able to differentiate deformation modes of impacting structure has been developed. The method integrates impact force, internal energy and displacement of the structure resulting in the RED curve. An investigation of the RED curve, gives deeper insight into the deformation process of structures than any other known method. As such, the method can be a useful tool in design process. It can be applied on simple as well as complicated structures. When applied on a car structure during a crash it clearly distinguishes three phases in vehicle front structure deformation. This ability has been used for further developed of the RED method to a tool for compatibility measurement and rating. It can be used to evaluate FUPD and other incompatibility countermeasures, i.e. to estimate compatibility between passenger cars and any kind of its crash opponent. It uses simulation data that allows detection of eventual compatibility problems before the production phase of a vehicle.

8. Suggestions for Future Work

This study provided a more comprehensive understanding of vehicle crash compatibility parameters. The results are applied on compatibility between passenger cars and HGVs. Even a method (the RED method) for measuring the compatibility has been developed. The author of the thesis would suggest the following areas for future studies in the field:

- Further develop of the RED method to cover vehicle-to-vehicle crashes with vehicle of different masses;
- Investigate other analyses from information available in the RED curve form;
- Evaluate the Crash Stability based on other barrier compatibility tests. Different verified car models in the evaluation are desired;

- Apply the compatibility assessment developed in this thesis to the design of a new FUPD and benchmark it with existing designs;

The concepts and methods developed in this thesis have the potential to be further developed to enhance the design process and improve the post-production assessment of vehicle safety

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