FIMCAR – INFLUENCE OF SEAS ON FRONTAL IMPACT COMPATIBILITY

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ABSTRACT

The aim of the FIMCAR project (Frontal Impact Compatibility and Assessment Research; co-funded by the European Commission within the 7th Framework Programme) was to develop and validate a frontal impact assessment approach that considers self and partner protection. Regarding the results of the FIMCAR accident analysis, one major issue of frontal impact compatibility is structural interaction. Not all car types have the potential to align their Primary Energy Absorbing Structures (PEAS) with the common interaction zone proposed by FIMCAR. Some cars use Secondary Energy Absorbing Structures (SEAS) to interact with external structures and thereby improve the structural interaction. There is a challenge to evaluate the different structural concepts, and in particular SEAS, in the possible variations of potential impact combinations.

The main objective of this study is the identification of characteristics of appropriate SEAS. Therefore this paper will give an overview about the investigations done within FICMAR to analyse parameters which improve the car-to-car crash performance. As part of the analysis physical test data as well as simulation results were used to study the interaction of the front end structures.

Within FIMCAR 10 car-to-car tests were conducted. The main outcome was that the alignment of the PEAS of both crash partners is crucial for the structural interaction. Furthermore the crash test showed that misaligned vehicles perform better if they are equipped with appropriate SEAS than vehicles without a lower load path. These investigations were supported by numerical simulations.

Within the FIMCAR project, amongst others, FEM vehicle models called Parametric Car Models (PCMs) were used for the assessment of car structures. For this study they were supplemented by the detailed FEM models provided by NCAC. For the SEAS analysis the PCMs were used to create several geometrical modifications. Due to the simplified design of the models the influence of the crash performance could be correlated well to the design of the SEAS.

The analysis of the simulations identified 3 geometrical parameters of the SEAS that had a positive influence in a car-to-car crash. The first parameter is the longitudinal position of the SEAS. A position of about 230mm behind the bumper beam (or further forward) improved the crash performance of both collision partners. The second parameter is the vertical connection between SEAS and PEAS. A robust connection located about 250mm behind the bumper beam was able to activate the penetrating structures of the striking vehicle and therefore to improve the structural interaction. The third geometrical parameter that was identified is the height of the cross section of the cross beam of the SEAS. An increase of the height by 50% to 60mm showed that the SEAS was able to support the penetrating structures better than the small SEAS.

According to the capabilities of assessment procedures to assess appropriate SEAS the OverRide Barrier (ORB), test configuration as well as the full width assessment metrics developed within FIMCAR were checked. The ORB test was not able to discriminate between appropriate and inappropriate SEAS. Regarding the full width test the Full Width Rigid Barrier (FWRB) configuration was not able to detect and assess the SEAS structures mainly due to the very short assessment interval, too. In contrast the Full Width Deformable Barrier (FWDB) was able to detect and correctly assess the SEAS that improved car-to-car crash performance due to their longer assessment period.

INTRODUCTION

Structural interaction was a high priority work item in the EC funded FIMCAR project (Frontal Impact Compatibility and Assessment Research). The project identified sub elements of structural interaction, i.e., structural alignment, horizontal load spreading and vertical load spreading. The latter is an issue that is in particular important to investigate the benefits of lower load paths. Secondary Energy Absorbing Structures (SEAS) have been identified in an earlier project [2], [7] relating to higher vehicles, like SUVs, to have a potential to address impact alignment in vehicles with a primary load path that is too high.

To further investigate vertical load spreading, three specific tasks were identified for this paper:

1) Report on recent international research related to evaluation and performance of lower load paths and SEAS
2) Identify the characteristics (geometrical parameters) of "appropriate" SEAS
3) Identify potential methods to assess or identify an appropriate SEAS

The benefits of vertical load spreading were identified in the VC-Compat project and confirmed in the FIMCAR car-to-car tests. Details of these tests will be presented in the following sections.

BACKGROUND

Within the last decade several relevant research activities were conducted to define requirements to address frontal impact compatibility requirements and to develop an assessment approach to address self and partner protection. Even though the vehicle fleets of different regions have specific compatibility requirements to fulfil, similar approaches to address compatibility issues like structural interaction can be found. A brief overview of the discussed test procedures is given in the following section.

Europe Amongst others, structural interaction has been detected as crucial to control the compatibility between passenger cars [1], [2], [7]]. To avoid car-to-car crash phenomena like over/underriding or fork effects, the focus was moved to the assessment of horizontal and vertical load spreading. Within VC-Compat different test procedures were evaluated regarding their potential to detect and correctly assess the height (and strength) of PEAS and SEAS [7]. Two test procedures were proposed to assess the structural interaction capabilities of a car: PDB and FWDB test [8]. However, no final metric for the PDB was evaluated and the proposed FWDB assessment still needed validation to show it could discriminate between good and poor performing cars.

USA A significant activity that was initiated by the automotive industry is the US voluntary commitment [6]. This was developed to ensure that Light Trucks and Vans (LTVs) have structures in alignment with a common interaction zone, also referred to as "Part 581 zone", measured vertically 16 to 20 inches (406mm – 508mm) from the ground to enable better interaction with cars. The US voluntary commitment states that all LTVs sold by participating manufacturers in the US must fulfil one of the two options below, see Figure 1:

OPTION 1
The light truck's PEAS shall overlap at least 50 percent of the Part 581 zone (Option 1a)
AND at least 50 percent of the light truck's PEAS shall overlap the Part 581 zone (Option 1b)

OPTION 2
If a light truck does not meet the criteria of Option 1, there must be a SEAS, connected to the primary structure, whose lower edge shall be not higher than the bottom of the Part 581 bumper zone.

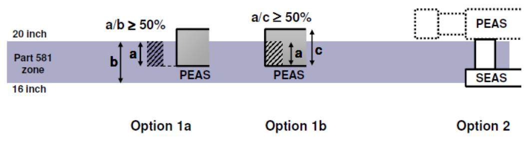

Figure 1. US voluntary commitment for improved compatibility of LTVs [18]

The assessment of the SEAS capabilities was evaluated with an additional test configuration, the OverRide Barrier (ORB) [12]. Thereby a rigid barrier equipped with Load Cells (LC) and positioned below the PEAS measures the forces applied by the SEAS during the test. The forces must reach 100kN within 400mm displacement measured from the most forward point of the vehicle structure, see Figure 2.

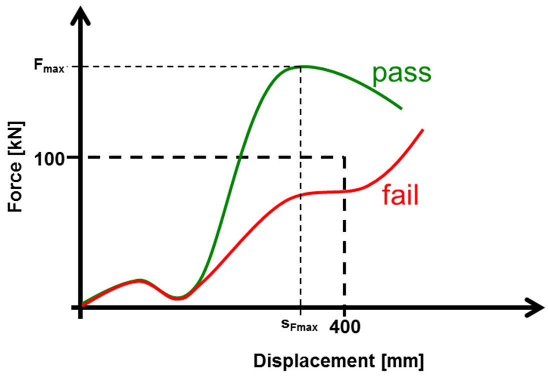

Figure 2. ORB test criterion

Japan The Japanese proposal to evaluate structural interaction consists of a combination of FWRB and ORB test [16]. The ORB test is used as a 2nd stage criterion, if the vehicle fails the proposed FWRB metric, see Figure 3. In contrast to the dynamic test configuration preferred by NHTSA the Japanese describe a static test, where an impactor loads the SEAS which has to withstand 100kN within 400mm displacement, too.

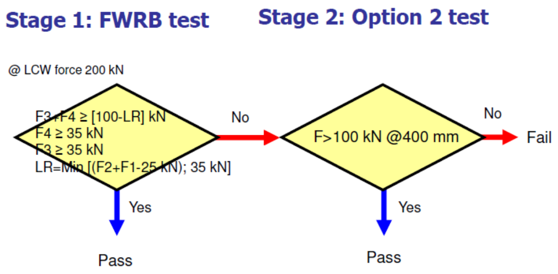

Figure 3. Japanese recommendation for full frontal test procedure [16]

FULL WIDTH ASSESSMENT PROCEDURES

Within FIMCAR two full width test procedures (FWRB and FWDB) were evaluated regarding their potential to address the defined priority items and are described in detail in [10]. Compatibility metrics were developed which should allow an assessment of the structural interaction capabilities of passenger cars. The final proposal for a frontal impact and compatibility assessment approach is to use the FWDB and its corresponding assessment metric in combination with the ODB (ECE R 94).

Structural alignment metric [10]:

- Up to time of 40ms:
  - F4 + F3 ≥ [MIN(200, 0.4FT40) kN
  - F4 ≥ [MIN(100, 0.2FT40) kN
  - F3 ≥ [MIN((100-LR), (0.2FT40-LR))]
  - where:
    - FT40 = Maximum of total LCW force up to time of 40ms
    - Limit Reduction (LR) = [F2-70] kN and 0kN ≤ LR ≤ 50kN*
    - *Note values to be confirmed taking into account the new test velocity

Even though both full width test procedures have a lot of similarities there are also some important differences which mainly have an influence on the assessment metrics. The most important influence is the engine dump effect which makes the evaluation of forces contributed by Energy Absorbing Structures (EAS; PEAS & SEAS) in the LCW measurements impossible. Yonezawa et al. [18] showed that the engine typically starts to decelerate after 200mm displacement (depending on the vehicle - 10ms to 15ms) in the FWRB test. The disadvantage of a relatively short assessment period is overcome in the FWDB test configuration, due to the two honeycomb layers in front of the wall [2]. The crushable element ensures a longer assessment period because the honeycombs prevent the engine to directly impact the wall. Thus an assessment period of 40ms is possible, which offers the potential to assess the EAS of about 50% of the crash period. One further advantage is that a far rearward located SEAS which does not penetrate the second stiffer layer, does not apply relevant forces to the LCW. This was identified as a positive characteristic, because a far rearward placed SEAS will not contribute in car-to-car crashes and therefore will not be assessed as an appropriate SEAS.

CAR-TO-CAR TESTING

Within FIMCAR a large vehicle crash test program was envisaged. Car-to-barrier crashes were planned for the evaluation of the proposed test procedures and assessment approaches while car-to-car crashes were conducted to investigate the influence of structural misalignment.
The car-to-car crashes were classified into three test series. The main objective of all three test series was the evaluation of the SEAS in frontal and side impacts.

Table 1.
FIMCAR car-to-car test program [13]

Test series	Vehicle	Aim of the test	Test setup
1	Supermini 1 (PEAS) Supermini 2 (PEAS & SEAS)	The effect of structural alignment in vehicle equipped with lower load path compared to a case without a lower load path	Frontal car-car 56km/h 50% offset
2	Small family car 1 (PEAS & SEAS) SUV 1 (PEAS & SEAS)	The effect of structural alignment and lower load path in SUV type vehicles crashing against a small family car	Frontal car-car 56km/h 50% offset
3	Large family car 1 SUV 2 (PEAS & SEAS)	Investigate the importance of lower load paths for SUV type vehicles in side impact crash	Side impact car-car 50km/h

Table 1 gives an overview about the car-to-car crashes conducted within FIMCAR. A detailed summary about the results can be found in [13]. However the main findings will be described shortly in the following section.

Test series 1 – Super Mini vs. Super Mini

Regarding the decelerations, higher mean values for the first 300mm displacement and higher maximum values for Super Mini 2 (SM 2) could be observed for the aligned tests. Both misaligned configurations showed a delayed increase of the decelerations at the beginning of the crash compared to the aligned configurations, but the delay is longer for Super Mini 1 (SM 1; without SEAS).
The intrusions of the SM 2 were generally lower than for SM 1 in both configurations. Both configurations showed the same trend in the case of the misaligned structures in that the differences of intrusions for the two crash partners increased.
The dummy values showed no obvious trends. However some injury criteria were higher than the corresponding Euro NCAP criteria (a_{3ms} and HIC36 for SM 2 aligned).

Test series 2 – SUV vs. Small Family Car

The mean decelerations within the first 300mm displacement are again lower for the misaligned Small Family Car (SFC) compared to the aligned one. The maximum decelerations show hardly any differences. The deceleration measurement for the misaligned SUV failed, thus no comparison to the aligned configuration was possible.
Regarding the intrusions, the SFC had higher values in both configurations than the SUV. However, only the dashboard intrusions were lower in the aligned configuration. The aligned configuration led to less override of the SFC, but the structures were overloaded by the heavier SUV which resulted in higher intrusions in areas directly affected by the main load path.
No clear trends could be observed regarding the dummy measurements. With respect to the ECE R94 limits all measurements showed lower values.

Test series 3 – LFC vs. SUV

Comparing the deformation patterns of both crash configurations, the following observations could be made. The B-pillar intrusions of the LFC in the reference configurations were higher than those in the other configuration. Due to the loading of bumper beam and cross beam of the SEAS above the sill, the B-pillar displacement was higher. In the second configuration the bumper beam was the only structure that loads the B-pillar and the door intrusions increased due to the penetrating longitudinals of the SUV. Even though the door intrusions were higher in the modified configuration, the dummy measurements were lower because the longitudinals of the SUV penetrated the doors outside the contact area of dummy and inner door. It was expected that the dummy would be loaded more if the impact location moved rearwards. However the loads in the reference test were spread more homogenously than in the second configuration and demonstrate the importance of vertical load spreading.

Summary of car-to-car testing

Summarising the results of the car-to-car testing conducted within VC-Compat [7] and FIMCAR [13] the following observations were made:

- Cars with aligned PEAS show better results than misaligned.
- Vehicles with PEAS aligned in row 3 and row 4 were more stable when equipped with a lower path.
- Vehicles with PEAS in row 4 performed well if a SEAS was identified in FWDB metric in row 3 and/or row 2.

In addition to the car-to-car crashes, the test objects were also crashed against the FWDB. The FWDB metric assessment of well performing SEAS readings regarding car-to-car crash results was always positive.

FE MODEL APPROACHES

To support the development of frontal impact compatibility assessment metrics, an extensive virtual testing program was established within the FIMCAR project. For this purpose two different FE model approaches were used to create FE vehicle models. The first approach was based on the Generic Car Models (GCMs) already used within the APROSYS project [3]. The second modelling approach is the Parametric Car Models (PCMs). Supplementing the FIMCAR activities, a third FEM model type was used. The NCAC provides detailed FEM models of specific cars of different vehicle classes (e.g. Ford Taurus and Ford F250) [4]. The NCAC models used for the following investigations are comparable to the GCMs, except they represent a real vehicle and its corresponding crash performance. Table 2 summarises the main characteristics of the two modelling approaches. A more detailed description is given in [14].

Table 2.
Comparison of FE model approaches (information in brackets according to NCAC models)

	GCM (NCAC)	PCM
Number of elements	600,000 (750,000-1,000,000)	200,000
Level of detail	high	low
Computational effort	high	low
Number of models - modifications	5 – no modification (only minor modifications possible)	3 – theoretically unlimited number of modifications possible
Intended field of application	detailed analysis of structural interaction, representative crash behaviour	identification of influence of crash relevant parameters

Due to the high level of detail the GCMs/NCAC models offer the possibility for in-depth analysis of the crash performance of the corresponding structural concepts (SEAS designs) as well as a quantitative estimation of injury severity level controlling parameters like accelerations and intrusions. However, the detailed models did not allow structural modifications with acceptable efforts in the scope of this investigation. To overcome limitations w.r.t. modifications of detailed FE car models, PCMs were used for the investigation of different structural concepts and their influence in frontal impacts. An implicit parametric CAD model allowed fast modifications of the main crash relevant structures and a specific pre-defined simulation environment ensures that the simplified FE models could be computed directly without further pre-processing [15].

SEAS ANALYSIS

The study is subdivided into three parts. The first part is based on an NHTSA study analysing the capabilities of the ORB and their potential to assess SEAS properly. In part two and three, characteristics of SEAS are identified which bring benefits in car-to-car crashes. Furthermore the potential of the full width assessment candidates proposed by FIMCAR to detect SEAS is analysed.

Capability of ORB

The capability of the ORB was already investigated by Patel et al. [12]. As part of this study the influence of SEAS of Option 2 vehicles was investigated using car-to-car crashes as well as numerical simulations. The main conclusion was that the ORB test did not lead to a significant assessment of the SEAS with respect to the analysed SEAS designs. Even though the two investigated LTVs (Ford F250 and Chevrolet Silverado [4]) pass the ORB test, only the F250 showed an improved crash performance in car-to-car crashes compared to a modified F250 with removed SEAS.
Because the passenger car (1996 Dodge Neon) used for the study of Patel et al. [12] did not represent a modern car, the presented methodology was adopted and the passenger car was replaced by one of the PCMs developed within FIMCAR. Additionally both LTVs were crashed against the FWDB at 50km/h to analyse the Load Cell Wall (LCW) force distributions.

ORB simulations with and without SEAS Because the two LTV FEM models were not validated for the ORB, the performance of both vehicles was checked in ORB simulations. The SEAS of the F250 consists of a blocker beam which is attached about 250mm below and 55mm behind the PEAS. For the configuration without SEAS only this blocker beam was removed, while the attachment was kept. The SEAS of the Silverado consists of two separate brackets that are attached directly to the PEAS and are located about 280mm behind the bumper beam. For the Silverado without SEAS, these brackets were removed. Table 3 summarises the simulation results (s_{Fmax} and F_{max} are explained in Figure 2).

Table 3.
ORB results for LTV modifications

	Modification	s_{Fmax} [mm]	F_{max} [kN]
Ford F250	with SEAS	300	360
	without SEAS	330	340
Chevrolet Silverado	with SEAS	240	420
	without SEAS	400	0

The LTVs equipped with SEAS pass the test. Compared to the crash test data, the forces applied by the numerical models are much higher. This mainly depends on the ORB barrier type used for the F250 crash test where only the blocker beam impacted the ORB (3 LCs 250x250mm were used). The vertical connections between blocker beam and SEAS were not activated. In contrast to this, the ORB barrier used for the simulations overlapped the front of the trucks completely. Due to this the F250 with removed blocker beam was also able to pass the test. The higher loads computed for the Silverado resulted due to the fact, that no failure was defined in the FEM model. The SEAS remain connected for the whole impact and could apply much higher forces compared to the original SEAS which broke off. Due to numerical problems during the computation, the Silverado bumper had to be removed whereby no forces could be applied to the ORB in the configuration without SEAS.

Car-to-car simulations with and without SEAS A crash configuration for the car-to-car simulations similar to Patel et al. [12] was used but a PCM model replaced the Dodge Neon as the target vehicle. Both vehicles were crashed against each other with 100% horizontal overlap and a 100km/h closing speed for this study. An overview about of the structural alignment is given in Figure 4 and Figure 5.

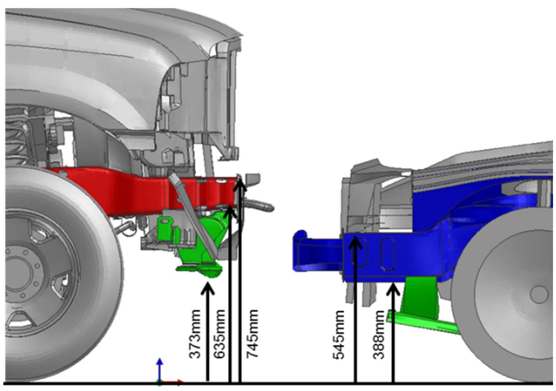

Figure 4. Vertical alignment of Ford F250 (left) and PCM LFC (right)

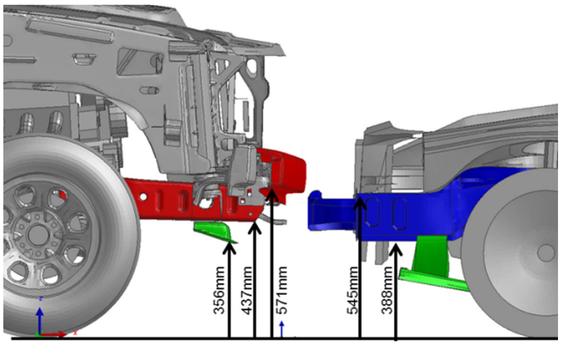

Figure 5. Vertical alignment of Chevrolet Silverado (left) and PCM LFC (right)

The PCMs were designed to meet the proposed assessment criteria within FIMCAR. Based on this the PEAS of the LFC are in alignment with row 4 and row 3 of the full width Load Cell Wall (LCW) and therefore within the Part 581 zone. The alignments of the Energy Absorbing Structures (EAS) of F250 and Silverado with the PEAS of the LFC are comparable to the original alignment used with the Dodge Neon. The PEAS of the LFC are aligned with the SEAS of the F250 only. However, the distance between the longitudinals of the F250 (980mm) is higher compared to the Silverado (800mm). Thus there is a vertical alignment of the PEAS of Silverado and LFC but there is a horizontal geometrical mismatch, see Figure 6.

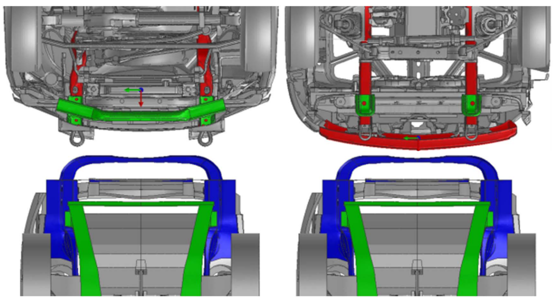

Figure 6. Horizontal alignment (top: left – Ford F250, right – Chevrolet Silverado; bottom: PCM LFC)

Figure 7 shows exemplarily the deceleration-displacement curves of the F250-to-PCM simulations. The solid graphs show the configuration where the LTV (red curves) was equipped with SEAS, the dotted graph without SEAS.

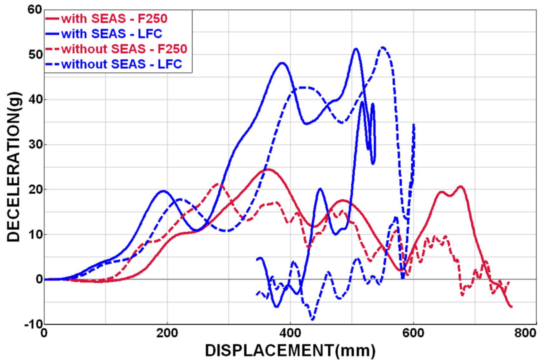

Figure 7. Deceleration-displacement curves F250 vs. LFC (solid lines – with SEAS, dotted lines – without SEAS)

The simulations show a reduction in the stopping distance by 50mm of the PCM (blue curves) and a slight increase of the deceleration of the F250, which can be related to improved structural interaction. Thus the trend to override the PCM was also reduced in the configuration with SEAS.
Regarding the results of the Silverado simulations no significant influence of the presence of the SEAS could be observed on the collision partner. The Silverado overrides the LFC in both configurations and no interaction of the brackets with the PEAS of the LFC was detected. The analysis of the intrusions showed also no differences.

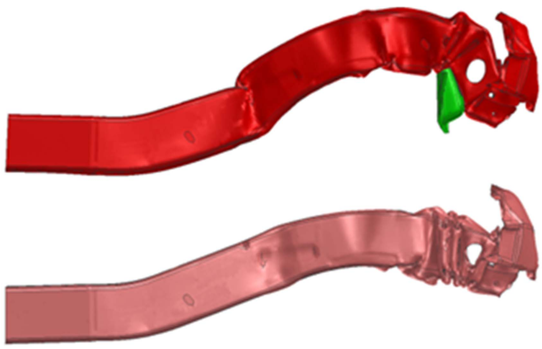

Figure 8. Change in deformation mode due to absence of SEAS (longitudinal of Silverado; top with SEAS, bottom without SEAS)

As Patel et al. [12] already mentioned, the deformation behaviour of the PEAS changed due to the removal of the SEAS. Without the SEAS, the PEAS have a better buckling behaviour which resulted in slightly higher decelerations and in a more efficient energy absorption mechanism, see Figure 8. Comparable observations were made in frame of another study conducted within FIMCAR, where the influence of the towing eye on the full width assessment metrics was analysed [5].

<u>FWDB simulations with and without SEAS</u> In the last step the LTVs were crashed against the FWDB at 50km/h. The main objective was to check if this assessment procedure is able to detect the SEAS and if these specific types of SEAS are able to load the barrier enough to pass the test. Especially for the F250, there was the question if the attachment and the blocker beam is stiff enough to load the barrier significantly, because the PEAS does not overlap row 4 (distance of lower edge of PEAS to the ground 635mm) and therefore does not contribute to the loads that have to be applied into the common interaction zone.

Table 4.
LCW forces (up to 40ms) of FWDB simulations with modified LTVs

	Ford F250		Chevrolet Silverado	
	w SEAS	w/o SEAS	w SEAS	w/o SEAS
F_{tot} [kN]	849	825	753	724
F4 [kN]	142	137	266	266
F3 [kN]	25	10	308	258
F2 [kN]	4	4	23	9
	fail	fail	pass	pass

Table 4 summarises the computed results of the FWDB simulations. Regarding the F250 the SEAS could not apply enough loads to row 3 to pass the test. Compared with the configuration without the blocker beam, the results show that the attachment is the only structures which applied loads to row 4 and row 3. The blocker beam itself had just a minor influence, even though it had a positive influence in the car-to-car crashes. Basically the same observations were made regarding the Silverado. However, due to the removed brackets the deformation behaviour of the PEAS changed and the forces decreased.

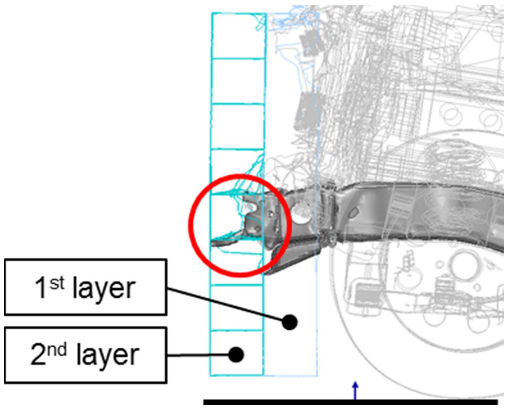

Figure 9. Towing eye contact in FWDB test (Chevrolet Silverado)

Even though the PEAS of the Silverado overlaps row 3 only with 14% the sum forces of row 3 are relative high. The reason for that is the towing eye in front of the PEAS, see Figure 9. Due to this very stiff part effects of the PEAS were covered and an assessment of crash relevant structures was not possible. Therefore the towing eye was removed and the simulations were repeated. Even with the overlap of the longitudinal with row 3 enough forces were applied and the vehicle passed the FWDB test again.

<u>Summary of LTV simulations</u> The conducted simulations confirm the results of Patel et al. [12] and also show that they can be transferred to modern cars.
The assessment of the SEAS with the ORB did not necessarily provide benefits in a car-to-car crash. The following main reasons could be identified:

1. The acceptance criteria are too generous. The requirement to meet a force threshold in the first 400mm of travel can result in significant interaction of a stiff PEAS before any contribution of a SEAS with the collision partner in car-to-car accidents.
2. The force measurement in a rigid load measurement system can overestimate the contribution of structures when a displacement based procedure is used to evaluate stiff structures like steel components.
3. The test method has no requirement for energy absorption of the structures and thus no demands are placed on the SEAS to maintain the threshold force.

Regarding the results of the Silverado simulations the assessment of the FWDB metric gives contradictory information (pass FWDB test but overrides PCM). The main reason for that is the design of the PEAS of the Silverado which has the bumper beam above its PEAS (typically in front of the PEAS). The bumper beam position resulted in a poor horizontal load spreading between the longitudinals which is not being assessed by the FWDB metric. Furthermore, heavy vehicles have less problems to apply 100kN in row 3 and row 4 due to their mass. Thus a relative small overlap of PEAS and row 3 is sufficient for the Silverado to pass the FWDB metric. Assessment metric improvements like a load distribution criterion (see proposed FWRB metrics in [9]) or an increased LCW resolution could lead to a more sensitive assessment.

Analysis of SEAS characteristics with PCMs

The goal of this study was to investigate the influence of the SEAS in car-to-car crashes and to identify characteristics of appropriate SEAS that are able to improve structural interaction. Therefore geometrical modifications in terms of varied stiffness and SEAS positions were simulated. In a first step the modified PCM models were crashed in an adapted ORB test to identify the force level of the SEAS. Furthermore it should be checked, if this test configuration is able to assess a SEAS in a correct manner (distinguish between SEAS that provide benefits in car-to car crashes and others). After that the PCMs were run against the FWRB and FWDB with 50km/h. The main objective was to check if the SEAS could be detected on the LCW.

First modifications Figure 10 shows the baseline configuration of the used PCM (Large Family Car – LFC). The PEAS are in alignment with row 3 and 4 and the SEAS are in alignment with row 2.

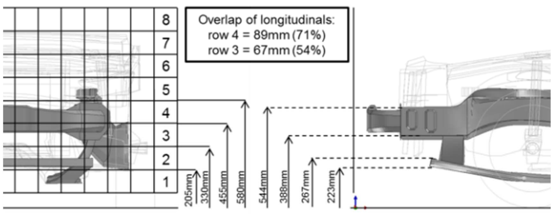

Figure 10. Baseline configuration of the PCM (LFC)

In a first step the position of the SEAS in longitudinal direction was modified, see Figure 11. These modifications only affected the longitudinals and the cross beam of the SEAS. The position of the vertical connection was not changed in this first step. Earlier simulations with a modified Ford Taurus model indicated that an appropriate SEAS will bring benefits if it is located between 180mm and 400mm behind the bumper beam [11].

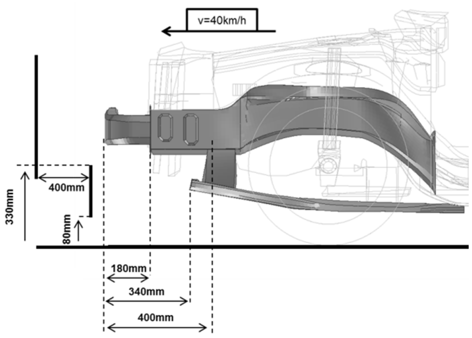

Figure 11. Adapted ORB crash configuration and geometry of PEAS and SEAS and lower boundary (400mm) for SEAS modification

In addition to the baseline configuration five modifications were created, see Table 5.

Table 5.
First modifications of SEAS

Modification	Distance between bumper beam and SEAS [mm]
D200	200
D250	250
D300	300
D350	350
D400	400

ORB simulations Regarding the stiffness level of the SEAS, other simulations within FIMCAR indicated that the sub frame of the baseline LFC was relative weak. For this purpose the stiffness of the sub frame was increased by factor 2. The results of the ORB simulations are summarised in Table 6 and Table 7.

Table 6.
ORB results for LFC SEAS modifications

Modification	s_{Fmax} [mm]	F_{max} [kN]
D200	288	203
D250	337	198
D300	387	186
Baseline	400	73
D350	400	68
D400	400	26

Table 7.
ORB results for LFC with reinforced SEAS (stiffness increased by factor 2) modifications

Modification	s_{Fmax} [mm]	F_{max} [kN]
D200	288	457
D250	338	468
D300	388	446
Baseline	400	257
D350	400	183
D400	331	25

The configurations with the standard SEAS pass the ORB test if the SEAS was located 200mm to 300mm behind the bumper beam. After the reinforcement of the SEAS the baseline LFC and the D350 modification pass the ORB test too.
Following the intention of the ORB test to assess SEAS on vehicles that do not meet the US volunteer commitment, it should be expected that all configuration that pass the metric (configurations that are highlighted in Table 6 and Table 7) should bring benefits in car-to-car crashes.

FWRB and FWDB simulations To address the vertical load spreading initially the PDB was the most promising crash configuration to detect and assess the capabilities of lower load paths [9]. However, the FW test procedures also offer the possibility to detect those structures. To define suitable thresholds for the assessment metrics force levels had to be specified which could be related to corresponding SEAS and their capability to improve car-to-car crashes. Furthermore both full width test candidates had to be evaluated regarding their potential to identify appropriate SEAS.
To compare the results of the ORB tests the six LFC configurations were crashed against the FWRB and FWDB with and impact velocity of 50km/h.
The row sum forces of the FWRB and FWDB crash simulations are shown in Figure 20 and Figure 21 in the appendix. Compared to the FWDB, the FWRB clearly detects the sub frame of all configurations except modification D400. For the three configurations with the far forward located sub frame (D200, D250 and D300) the maximum forces are higher than 100kN and were applied to the wall within 20ms to 40ms of the crash (red circles). The baseline model and the modification D350 apply also forces in row 2 to the LCW but after 40ms which is relative late in the crash (red dotted circles). The FWDB detects also loads in row 2 but below 100kN and the maximum was not reached within the first 40ms of the impact (blue cirlces). However, the forces start to increase after 20ms.
The results of the simulations with the reinforced sub frame showed for the FWRB configuration unrealistic high peak forces when the sub frame contacted the wall but at the same point in time compared to the simulations with the baseline sub frame. In the FWDB configuration the reinforced sub frame was able to apply significant loads to the wall. The forces were up to 150kN for the D200 configuration but the maximum was reached not until after 50ms. The further back the sub frame was located, the lower the load applied in row 2. Due to the load spreading of the deformable element a small proportion of the forces was also applied to row 1.

Table 8.
Differences in SEAS detection between FWRB and FWDB

	FWRB	**FWDB**
Detection of SEAS	yes	yes
Detected SEAS configurations	D200 to D350	D200 to D350
Clearly detected SEAS configurations	D200 to D350	D200 to D300
Force level of sum force in row 2 of clearly detected SEAS	>100kN	50kN <F2 <100kN
t_{maxF2} for configuration D200	23ms	45ms
Force progression in row 2	Relatively short peak (Δt = 10ms)	Continuously loading (Δt = 40ms)

Table 8 summarizes the results of the car-to-FWB simulations of the first SEAS modifications. Both FW tests were able to clearly detect the baseline sub frame located between 200mm and 300mm (350mm for FWRB) behind the bumper beam. Furthermore, both test procedures were able to detect the reinforced SEAS except the sub frame was located 400mm behind the bumper beam (D400). The forces in row 2 did not reach their maximum within the assessment periods of the corresponding test procedure. The main differences between FWRB and FWDB were, that the forces measured in row 2 were higher in the FWRB (>100kN) test than in the FWDB (50kN <F2 <100kN) test and the characteristic of the force progression in both configurations. The forces applied to the LCW in the FWRB test occurred only a relative short moment ($\Delta t \approx 10$ms) compared to the longer duration ($\Delta t \approx 40$ms) in the FWDB test. In comparison to the FWRB, the forces applied in row 2 started to increase within the first 40ms in the FWDB and reached about 75% of the maximum sum forces of row 2 within this period (modification D200). These results were not influenced due to engine dump because the simplified engine is located about 610mm behind the bumper and does not contribute to the load distribution in the FWB tests.

Car-to-car simulations For the identification of the benefit of a far forward located sub frame, the LFC configurations were crashed against the three available reference PCMs (Super Mini – SM, Large Family Car – LFC and Executive – Exe), henceforth referred to as bullet vehicles. The vehicles were crashed against each other with a horizontal overlap of 50%, with respect to the modified LFC, and a closing speed of 112km/h. The modified LFCs were raised by 70mm to simulate a vertical mismatch between the PEAS and to estimate the influence of the SEAS, see

Figure 12. This offset was identified in another study within FIMCAR as a configuration where the LFC failed the FWRB and FWDB criteria, because the forces applied to row 3 were too low. Baseline runs were simulated to compare the geometrical misalignment with a perfect match of the PEAS.
The most important differences between SM, LFC and Exe (beside dimension and mass) are the position of the sub frame (LFC and Executive are equipped with an SEAS which is located about 350mm behind the bumper beam) and the cross section of the SEAS (SM has the smallest cross sections compared to LFC and Exe).

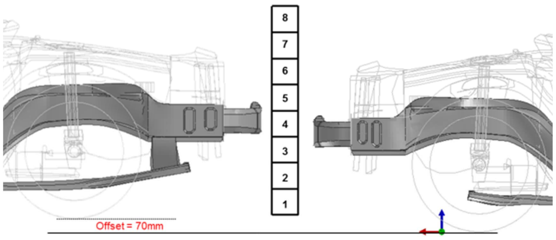

Figure 12. Car-to-car crash configuration (LFC (left) vs. SM (right))

In general the assessment of the occupant loading was done by calculation of simplified occupant load criteria (e.g. OLC) and comparison of the intrusions on the firewall. For the car-to-car simulations the assessment was done by analysing the deceleration-displacement curves and the intrusions of the colliding vehicles.
The analysis of the deceleration-displacement curves showed a reduction of the maximum decelerations for all cars in the misaligned configuration compared to the corresponding aligned configuration. The structural mismatch resulted in an under/overriding and the total displacement of the crash partners increased. For that reason the intrusions increased in both crash partners. However, no trend could be observed regarding the position of the sub frame and an improved car-to-car crash performance, neither in the baseline nor in the reinforced configuration. The analysis of the structural interaction of the PEAS/SEAS during the crash showed that the SEAS had a too small cross section to support penetrating structures properly. Thus the PEAS of the bullet vehicles slid between PEAS and SEAS of the modified and raised LFCs. But the vertical connection between PEAS and SEAS offered support, although the contact occurred relatively late in the impact due the large distance of this vertical link to the bumper beam (about 420mm, see Figure 11).

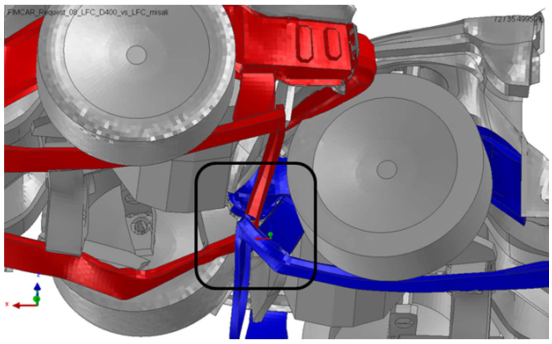

Figure 13. Contact between vertical connection and sub frame (D400 (red) vs. bullet vehicle (blue))

As highlighted in Figure 13 the results indicated that the vertical connection between the SEAS and the PEAS offered a good support to the penetrating structures. In almost every case the SEAS were not activated before they meet this part of the sub frame.

<u>Summary of results of first modifications</u> The simulations showed that the ORB test does not discriminated between appropriate (provides benefits in car-to-car crashes) and inappropriate SEAS. Thus the ORB test produces “false positives” which means that the test assesses a car structure as good while the car-to-car test showed no improvements in the structural interaction. Both full width tests showed their potential to detect a sub frame, especially SEAS which are located between 200mm and 300mm behind the bumper beam. However the FWRB clearly detected the SEAS although the forces were not measured within the first 15ms (before engine dump occurs) and although the SEAS modifications showed no benefit in car-to-car crashes. Thus the FWRB also produces false positives in terms of SEAS detection.
Because the main loads contributed by the SEAS in the FWRB tests occurred only in a relative short time ($\Delta t \approx 10$ms) an assessment of the SEAS performance is not possible compared to the FWDB tests ($\Delta t \approx 40$ms). In addition to an assessment of the forces within the first 40ms of the crash the FWDB also offers the potential to assess the energy absorbing capabilities of the SEAS over a significant period of the crash.
Because the results of the car-to-car simulations indicated that the vertical connection between PEAS and SEAS can bring benefits in car-to-car crashes additional modifications were done.

Second modifications In a second step the sub frame was modified as illustrated in Figure 14.

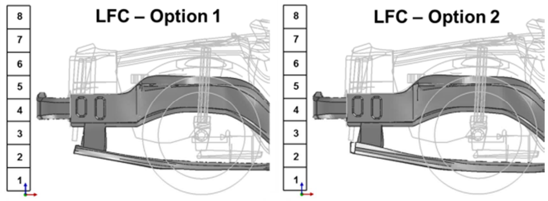

Figure 14. Second modifications of LFC SEAS

The second modifications were added to the D200 version (cross beam of the sub frame 200mm behind the bumper beam). The vertical connection was positioned 250mm behind the bumper beam (distance in the baseline configuration was about 420mm). Additionally the cross section of the cross beam was increased from 40mm to 60mm in vertical direction (LFC-Option 2). Both modification were also raised to align the PEAS with row 4.

Taking the results of the first modifications into account it was expected that the far forward located vertical conneting is able to catch the penetrating structures and that the increased cross section of the cross beam offers additional support to activate the EAS of the collision partner.

The LFC-Option 1 and Option 2 were based on the D200 modification so the ORB simulation was needless, because the D200 modification already passed the test.

FWDB simulations The FWRB simulation was not conducted, due to the relatively short assessment period. The LFCs were crashed against the FWDB with 50km/h.

Table 9.
LCW forces (up to 40ms) of FWDB simulations with raised LFC

	Baseline	Option 1	Option 2
F_{tot} [kN]	458	427	457
F4 [kN]	190	146	155
F3 [kN]	61	66	81
F2 [kN]	32	46	63
	fail	fail	fail

The results of the LCW forces of the FWDB simulations are summarized in Table 9, an overview about the force progression is given in the appendix. Compared to the baseline LFC the LFC-Option 2 was able to apply almost twice of the forces in row 2 within the first 40ms. The forces applied to row 3 also increased by 33% which could be related to the strong assembly of the far forward located vertical connection between PEAS and SEAS and the increased cross section of the cross beam of the sub frame.

Car-to-car simulations In the last step of this analysis the performance of the second modifications should be checked in car-to-car crash simulations. For this purpose the modified LFCs were raised by 70mm and crashed against the baseline LFC with 56km/h and a horizontal overlap of 50%, see Figure 15.

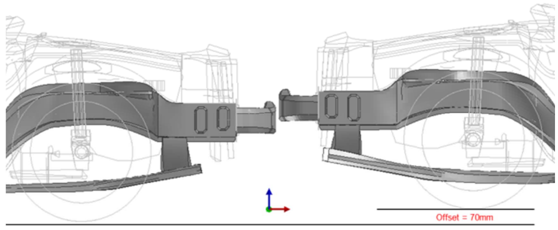

Figure 15. Car-to-car crash configuration with second modifications (baseline LFC - left and LFC-Option 2 - right)

As already described the analysis was performed regarding the deceleration-displacement curves and the intrusions. The results were compared to the car-to-car crash configuration LFC baseline vs. raised LFC baseline (misaligned).

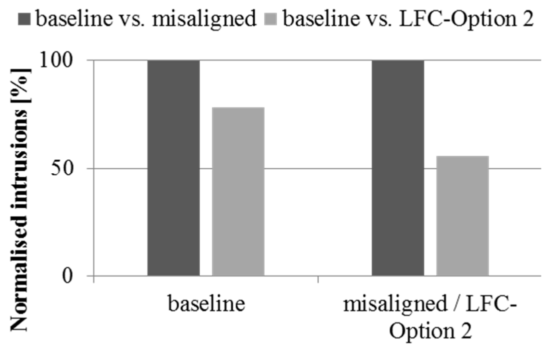

Figure 16. Normalised intrusions of car-to-car crash simulations (second modifications)

Figure 16 shows the improvement in the intrusion behavior. With respect to the baseline crash configuration the intrusions were reduced by almost 25% for the baseline LFC and by almost 50% for the LFC-Option 2. The reason for that is the improved structural interaction, see Figure 17, due to the activation of the sub frame.

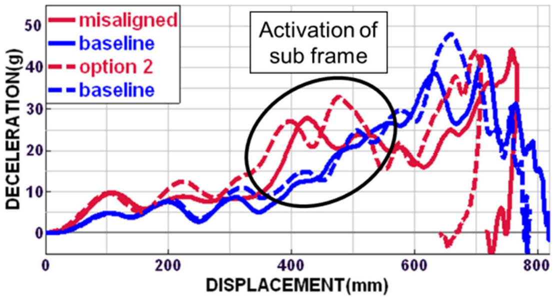

Figure 17. Deceleration-displacement curves (solid lines – baseline vs. misaligned, dotted lines baseline vs. LFC-Option 2)

A comparison of the red (modified) to blue (baseline) lines show that the decelerations increase earlier and reach a higher level (red dotted line) than in the misaligned configuration with the baseline SEAS (red solid line). The analyses of the crash performance of the LFC-Option 2 showed, that the SEAS modifications fulfilled their tasks to support the penetrating structures, which resulted in higher deceleration for the bullet vehicle too (blue dotted line at 650mm). Comparable trends could be observed for LFC-Option 1, however the benefit in the car-to-car crashes was higher due the increased cross section in option 2, which could be related to the increased stiffness of the sub frame.

<u>Summary of results of second modifications</u>

The second modifications of the SEAS were able to improve the car-to-car crash performance. The further forward vertical connection was able to catch the penetrating structures of the collision partner. In combination with an increased cross section of the SEAS cross beam, a relative large surface and high stiffness of the sub frame could be modelled which could partially compensate for the vertical misalignment between the PEAS. In addition the FWDB showed the potential to detect this type of SEAS. A clear trend could be observed showing the higher forces applied to the LCW due to the modified sub frame.

To promote SEAS structures and multiple load path designs, respectively, an assessment metric for the FWDB was developed within FIMCAR that should take into account forces applied in row 2. This should help cars to pass the test which were not able to bring down their PEAS into row 3 (e.g. SUVs). A limit reduction was introduced to reduce the minimum forces need to be applied to row 3 depending on the forces applied in row 2. But to reduce the limit at least 70kN needed to be applied in row 2 which was not the case for the simulations. The main reason for that was that the threshold of 70kN was identified in FW tests conducted with 56km/h. The finally proposed collision velocity was 50km/h which should lead to a lower criterion for the limit reduction. Therefore the forces applied by LFC-Option 2 could be enough to satisfy new minimum force requirements for row 3 and the vehicle may pass the test.

Crash simulations with other vehicle models

Chalmers and VTI had conducted an earlier study on the effect of sub frame on car-to-car impacts [11], [17]. These simulations indicated how modifications of the public available and detailed FE model of a Ford Taurus [4] affected the crash response.

In addition to the studies the modified Ford Taurus models were crashed against the FWDB. The objective was to check the correlation of the FWDB metrics to the car-to-car crash performance.

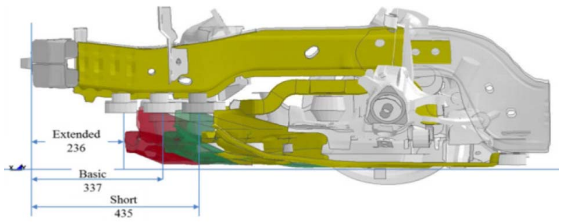

Figure 18. Sub frame modifications of Ford Taurus (based on [11])

The sub frame configurations investigated are shown in Figure 18. The basic sub frame is more than 300mm and the shortened sub frame is more than 400mm behind the bumper beam. The results of the car-to-car simulations were presented in [17]. What is significant to note is that the extended sub frame (Figure 18, red) tended to improve the vehicle performance while the shortened sub frame (Figure 18, yellow) tended to decrease the performance compared to the baseline vehicle.

<u>FWDB simulations</u> The FWDB tests were simulated with the Taurus in its raised conditions. (Based on the car-to-car simulations where the Taurus had a vertical offset of 25% - 25% of the vertical section height of the longitudinals were in contact.) The row loads calculated for the cases are shown in Figure 23 in the appendix. All three cases meet the FWDB metric. It can be seen that the shortened sub frame configuration case just meets the 100kN in row 3. The raised Taurus still has parts of its PEAS overlapping row 3 and this is enough to load this area of the barrier sufficiently for a positive evaluation. In contrast the row 2 loads show significant differences for the three Taurus configurations. Figure 19 shows a section cut of the three modifications at 40ms of the crash. Because the sub frame of the shortened sub frame (orange) did not contact the first layer of the crush element no significant forces were applied to the wall below row 3.

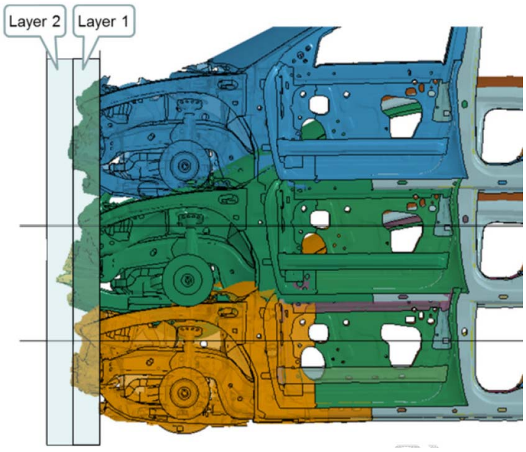

Figure 19. FWDB simulations with Ford Taurus modifications at 40ms (short sub frame – orange, baseline sub frame – green, extended sub frame - blue)

…..**Summary of results of Taurus modifications**
The results of the Taurus simulations showed that vehicles barely meeting the FWDB metric had poorer performance than those with higher loads in row 3 and 4. The results also showed that vehicles producing row 2 loads over 80kN were better than those with only 40kN in car-to-car crashes. The barrier was starting to detect sub frames 337mm behind the bumper beam and it was this region 300mm to 400mm that sub frames could be seen to introduce differences in car-to-car crash performance.

DISCUSSION

A general point that needs to be discussed is the limitation of the validity of the FEM models used for this study as well as the number and the type of the vehicles used for testing. However, in combination with test results of former research projects principle conclusions are possible.
Regarding the used FEM models two different types of model approaches can be distinguished with respect to the level of detail. On the one hand very detailed car models provided by NCAC were used to assess the specific design of crash structures and the corresponding crash performance in car-to-barrier and car-to-car crashes. Some simulations showed relevant differences between the original car and the corresponding model (e.g. brackets of Silverado) performance due to the fact that these models were not validated for these crash configurations. On the other hand there are the simplified PCMs which were used to investigate different structural concepts. The addition of a lower load path into an existing vehicle architecture will affect the stiffness level and therefore the force level of PEAS and SEAS should be adjusted. The modifications investigated in these studies did not take into account those effects. Another relevant issue is the simplified front end design of the PCMs. Regarding the FWB simulations, real cars often apply relevant loads into lower rows of the LCW even though they are not equipped with a SEAS. The PCMs only have energy absorbing structures (PEAS and SEAS) respectively load path creating structures (e.g. wheel-sill, engine-firewall). No other mechanisms that can create significant forces (such as radiator and battery support structures) loading the barrier or collision partner were included in detail. However, the conducted investigations show the influence and the potential of different SEAS designs as well as the presence of a lower load path.

CONCLUSIONS

The main objectives of this study were to analyse the influence of SEAS in car-to-car crashes and to identify characteristics of a SEAS that contribute positively in a car-to-car crash. Furthermore the capability of different test procedures was investigated regarding their potential to assess appropriate SEAS correctly.
Based on the test series conducted within VC Compat and FIMCAR the improvement of structural interaction due to the presence of SEAS in case of vertical misaligned PEAS was verified. In almost every case an improved interaction of the EAS resulted in an increase of the compartment decelerations and in a reduction of the intrusions (in particular for the overriden car), except the case if the compartment was overloaded due to a disadvantageous mass ratio of the crash partners. Simultaneously improved structural interaction also means that a transfer of injury causalities from “contact by intrusions” to occupant protection systems or “contact without intrusions” may occur. Furthermore in car-to-car crashes with different mass ratios the stiffness level of the front end structures become more relevant if the EAS are in alignment and will be activated in the crash. Finally the following priorities for structural interaction were made:

1) Cars with aligned PEAS show better results than misaligned.
2) Vehicles with PEAS aligned in row 3 and row 4 were more stable when equipped with a lower path.
3) Vehicles with PEAS in row 4 performed well if a SEAS was identified in FWDB metric in row 3 and/or row 2.
4) FWDB metric assessment of well performing SEAS readings regarding car-to-car crash results was always positive.

The simulations identified some geometrical characteristics of SEAS that help to improve the car-to-car crash performance. The main factor that

had a positive influence was the distance between SEAS and bumper beam. The simulations with the modified Ford Taurus showed that the contribution of the SEAS in car-to-car crashes is positive if it is located no more than 230mm behind the bumper beam. A distance of about 400mm resulted in negative effects. However, the PCM simulations showed that not only the position in longitudinal direction was crucial for a good crash performance. Other important factors were the height of the cross section of the SEAS cross beam and the position of the vertical connection to the PEAS. A connection positioned about 250mm behind the bumper beam was able to activate penetrating structures which resulted in an improved car-to-car crash performance.
To assess appropriate SEAS three different test procedures were evaluated. The ORB test proposed by NHTSA to evaluate the performance of Option 2 vehicles seems not to be suitable to discriminate between appropriate and inappropriate SEAS. Previous studies and the conducted simulations showed that the assessment of the ORB does not correlate with a good car-to-car crash performance. Within FIMCAR two full width tests were proposed to assess structural alignment. Both candidates were also evaluated regarding their potential to assess SEAS that bring benefits in car-to-car crashes. Due to the very short time window for the assessment of EAS (FWRB: 10ms to 15ms; FWDB: 40ms) the FWRB is not suitable for the assessment of SEAS, because the simulations showed that the SEAS starts to load the barrier after 20ms even in the case where the SEAS was in the most forward position. Furthermore the progression of the loads applied by the SEAS is a relative short peak, which makes the assessment of the performance difficult. In contrast the FWDB was able to detect and correctly assess the SEAS that improved car-to-car crash performance due to their longer assessment period. In addition the SEAS loaded the barrier for a longer period and maintained a relative high level.

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Further information is available at the FIMCAR web site www.fimcar.eu.

REFERENCES

[1] "*Developments of Criteria and Standards for Vehilce Compatibility (EUCAR - Final Technical Report)"*. 2000.

[2] "*EEVC WG 15 Final Report to EEVC Steering Committee"*. www.eevc.org.

[3] "*Generic car (FE) models for categories super minis, small family cars, large family / executive cars, MPV, heavy vehicle (APROSYS Deliverable D7.1.4 A)"*.

[4] "*NCAC - Finite Element Model Archive"*. http://www.ncac.gwu.edu/vml/models.html.

[5] Adolph, T. Wisch, M.; Edwards, M.; Thomson, R.; Stein, M.; Puppini, R.:"*D3.1 - Report analysis performed to develop assessment criteria and associated performance limits for full width test"*.

[6] Barbat, S.: "*Status of Enhanced Front-to-Front Vehicle Compatibility Technical Working Group Research and Commitments"*. 19th Enhanced Safety Vehicle Conference 2005. Paper Number: 05-463. Washington D.C. 2005.

[7] Edwards, M. Coo, P. de; van der Zweep, C.; Thomson, R.; Damm, R. M. T.; Delannoy, P.; Davis, H.; Wrige, A.; Malczyk, A.; Jongerius, C.; Stubenböck, H.; Knight, I.; Sjoberg, M.; Ait-Salem Duque, O.; Hashemi, R.:"*Improvement of Vehicle Crash Compatibility through the Development of Crash Test Procedures (VC-Compat - Final Technical Report)"*. 2007.

[8] Faerber, E.: "*EEVC Approach to Develop Test Procedures for the Improvement of Crash Compatibility between Passenger Cars"*. 20th Enhanced Safety Vehicle Conference 2007. Paper Number: 07-0331. Lyon. 2007.

[9] Johannsen, H. Adolph, T.; Thomson, R.; Edwards, M.; Lazaro, I.; Versmissen, T.: "*FIMCAR - Frontal Impact and Compatibility Assessment Research - Strategy and first results for future frontal impact assessment"*. 22nd Enhanced Safety Vehicle Conference 2011. Paper Number: 11-0286. Washington D.C. 2011.

[10] Johannsen, H. Adolph, T.; Edwards, M.; Lazaro, I.; Versmissen, T.; Thomson, R.:

"*Proposal for a Frontal Impact and Compatibility Assessment Approach based on the European FIMCAR Project"*. 23rd Enhanced Safety Vehicle Conference. Paper Number: 13-0104. Seoul. 2013.

[11] Park, C.-K. Thomson, R.; Krusper, A.; Kan, C.-D.: "*The Influence of Sub-Frame Geometry on a Vehicle's Frontal Crash Response"*. 21st Enhanced Safety Vehicle Conference 2009. Paper Number: 09-0403. Stuttgart. 2009.

[12] Patel, S. Prasad, A.; Mohan, P.: "*NHTSA's Recent Test Program on Vehicle Compatibility"*. 21st Enhanced Safety Vehicle Conference 2009. Paper Number: 09-0416. Stuttgart. 2009.

[13] Sandqvist, P. Thomson, R.; Kling, A.; Wågtröm, L.; Delannoy, P.; Vie, N.; Lazaro, I.; Candellero, S.; Nicaise, J.-L.; Duboc, F.:"*D6.1 - Report on car2car test results"*.

[14] Stein, M. Johannsen, H.; Puppini, R.: "*FIMCAR Models for the Assessment of Frontal Impact Compatibility"*. ICrash Conference 2012. Mailand. 2012.

[15] Stein, M. Friedemann, D.; Eisenach, A.; Zimmer, H.; Johannsen, H.: "*Parametric Modelling of Simplified Car Models for Assessment of Frontal Impact Compatibility"*. 8th LS Dyna User Conference. Strasbourg. 2011.

[16] Tanaka, Y.:"*Japanese Test Plan for Full Frontal Impact"*. 16th meeting of the GRSP Informal Group on Frontal Impact. Paris. 10.11.2012. https://www2.unece.org/wiki/download/attachments/4064596/FI-16-04e.pdf.

[17] Thomson, R. Krusper, A.; Avramov, N.; Rachid, K.: "*The Role of Vehicle Design on Structural Interaction"*. ICrash Conference 2008. Kyoto. 2008.

[18] Yonezawa, H. Mizuno, K.; Hirasawa, T.; Kanoshima, H.; Ichikawa, H.; Yamada, S.; Koga, H.; Yamaguchi, A.; Arai, Y.; Kikuchi, A.: "*Summary Activities Compatibility Group Japan"*. 21st Enhanced Safety Vehicle Conference 2009. Paper Number: 09-0203. Stuttgart. 2009. http://www-nrd.nhtsa.dot.gov/departments/esv/21st/.

APPENDICES

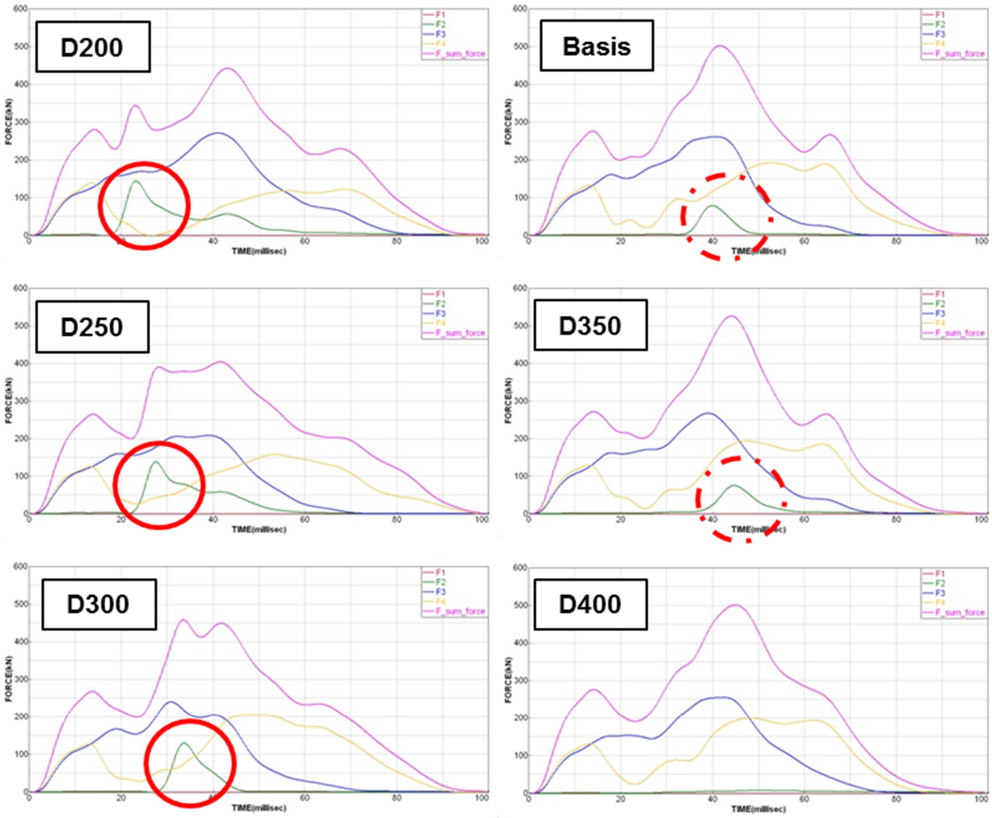

Figure 20. LCW sum forces of FWRB simulations (first modifications)

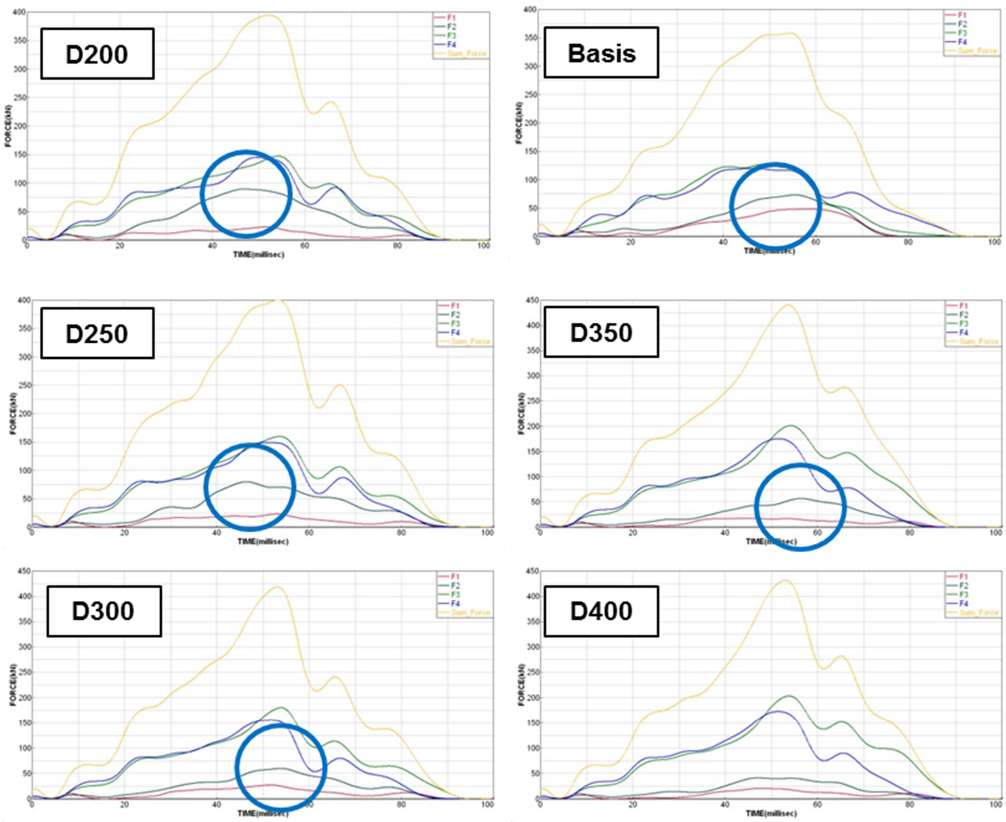

Figure 21. LCW sum forces of FWDB simulations (first modifications)

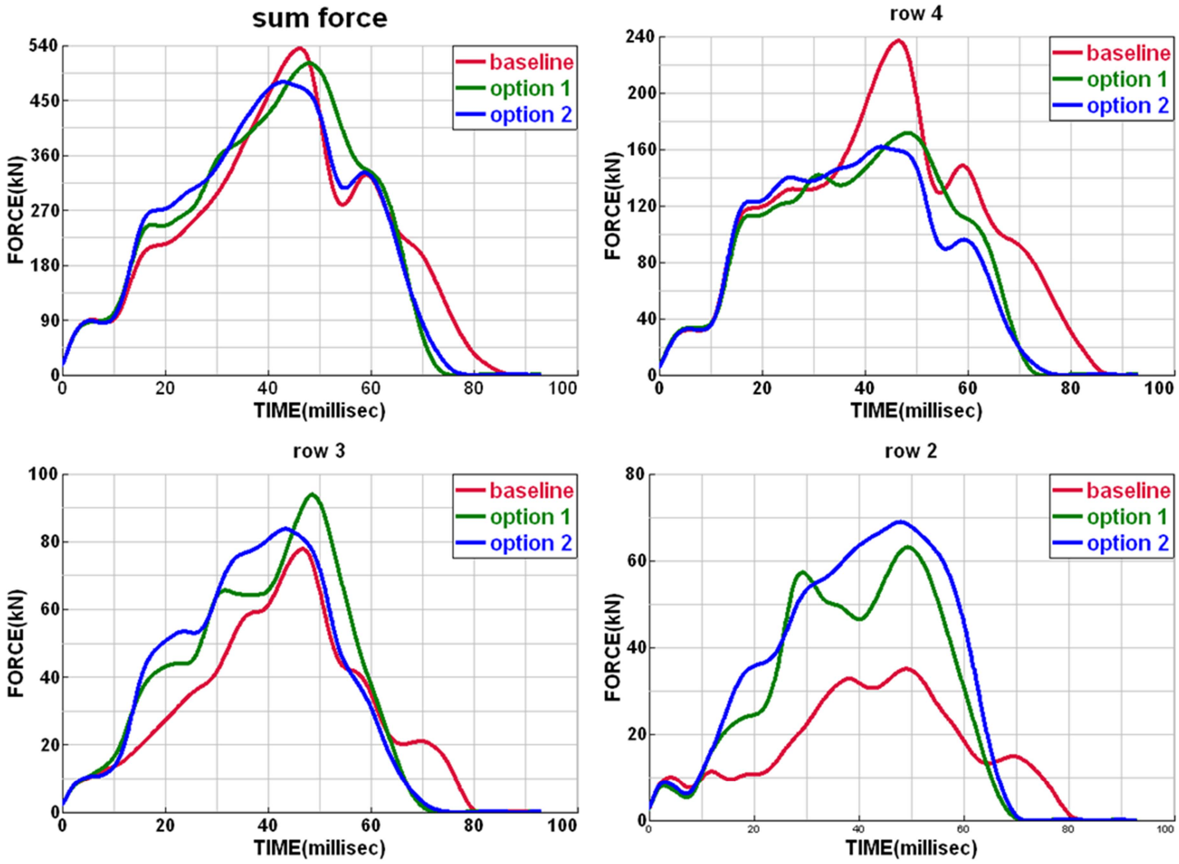

Figure 22. LCW sum forces of FWDB simulations with raised LFCs (second modifications)

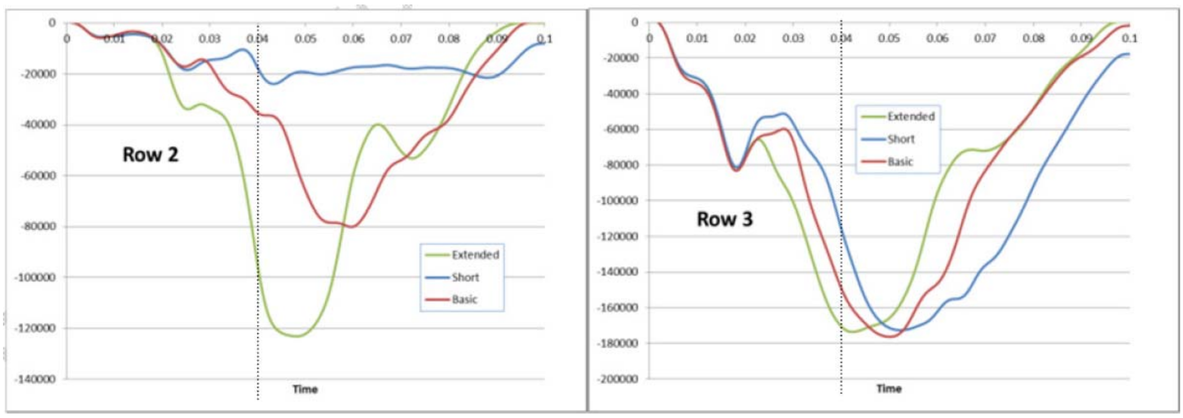

Figure 23. LCW row forces in FWDB Ford Taurus simulations