NHTSA's Recent Test Program on Vehicle Compatibility

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Paper Number: 09-0416

ABSTRACT

The objective of this study was to understand the structural interaction in frontal collisions between a compact passenger car and different Option 2 light truck based vehicles (LTVs).

Vehicle-to-vehicle (VTV) crash tests were conducted to understand how these new concepts perform. Full frontal VTV crash tests into Model Year(MY) 2002 Ford Focus were conducted with the MY2006 Ford F-250 secondary energy absorbing structure (SEAS) attached and with the SEAS removed. Full frontal VTV crash tests into Focus were also conducted with the MY2006 Honda Ridgeline and MY2007 Chevrolet Silverado with the SEAS attached only. Ridgeline and Silverado SEAS are fixed below the rails and can not be removed like F-250. The results of these tests are presented and discussed in this paper. The largest LTVs are being equipped with new frontal structures to prevent override with passenger cars and it cannot be properly evaluated with the current full frontal barrier test. A new instrumented rigid override barrier (ORB) concept has been developed to evaluate the strength of SEAS and tested for this purpose. This paper summarizes and discusses the design and testing of the ORB.

Furthermore, Finite Element (FE) models of MY2006 Ford F-250 and MY2007 Chevrolet Silverado were developed by the National Crash Analysis Center at the George Washington University under a contract with National Highway Traffic Safety Administration (NHTSA) and Federal Highway Administration (FHWA). The structural interaction in frontal collisions between a compact passenger car and the two LTVs was investigated using computer simulations.

INTRODUCTION

In December 2003, a voluntary commitment was signed by 15 major members[1] of the Alliance in the USA to begin designing LTVs up to 10,000 pounds Gross Vehicle Weight Rating (GVWR) in accordance with one of the following two geometric alignment options no later than September 1st, 2009 [Alliance 2003, 2005, and 2006].

Alliance submitted an amendment to the agreement to the NHTSA on May 10th, 2006, which added a strength requirement for the SEAS. Alliance's research plan for further improving front-to-front compatibility also was refined to contemporaneously investigate potential dynamic geometric, stiffness, and other relevant front-end performance characteristics that would enhance partner protection without sacrificing self-protection in front crashes. This quasi-static test requirement states that the SEAS shall withstand a load of at least 100 kN exerted by a loading device, before this loading device travels 400 mm from the forward-most point of the significant vehicle structure.

Option 1: The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50% of the Part 581 zone (as defined in 49 CFR 571.3) AND at least 50% of the light truck's PEAS shall overlap the Part 581 zone (if the PEAS of the light truck is greater than 8 inches tall, then overlap of the entire Part 581 zone is required).

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

[1] BMW, DaimlerChrysler, Ford, GM, Honda, Hyundai, Isuzu, Kia, Mazda, Mitsubishi, Nissan, Subaru, Suzuki, Toyota, Volkswagen.

edge shall be no higher than the bottom of the Part 581 bumper zone.

The voluntary agreement was implemented in 2004 and, as of August 2008, 81% of MY2007 applicable vehicles were designed in accordance with the front-front criteria. With this voluntary agreement underway, it is useful to examine the light vehicle compatibility problem to see what vehicle structural changes have been made over years.

The emergence of SEAS in 2004 on large LTVs led to lack of consensus in developing a vehicle dynamic test, largely because the various fleet examples of SEAS were so different. One thing was clear however, to evaluate the performance of all the different types of SEAS frontal structures a new test was needed. The most promising evaluation concepts were either a deformable barrier test of some kind, or a low rigid ORB designed to engage and deform the SEAS to measure its strength in a dynamic test. While other organizations evaluated deformable barrier concepts, NHTSA focused on the ORB.

The objective of this study was to understand the structural interaction in frontal collisions between a compact passenger car and various Option 2 LTVs. The goal was to understand how these new concepts perform in ORB impacts and in VTV tests.

VTV crash tests were conducted to characterize the structural interaction between compact passenger cars and Option 2 LTVs. The results of these tests are presented and discussed in this paper. A new ORB concept was developed and tested for this purpose. This paper also summarizes and discusses the design and testing of the ORB.

In addition, Finite Element (FE) models of the 2006 Ford F250 and 2007 Chevrolet Silverado were developed by the National Crash Analysis Center at the George Washington University under a contract with NHTSA and the FHWA. The Ford F-250 has a cross member type SEAS while the Chevrolet Silverado had a non-cross member type SEAS. The structural interaction in frontal collisions between a compact passenger car and the two LTVs was investigated using computer simulations.

The FE models were validated against full frontal rigid barrier laboratory crash tests [http://www.ncac.gwu.edu/vml/models.html]. Full frontal impacts with a compact passenger car were performed with and without the SEAS to evaluate the change in structural interaction.

The ORB test procedure was expected to evaluate the strength and energy absorption characteristics of SEAS. The performance of SEAS in VTV tests was expected to show a benefit from using SEAS.

Updated ORB design

The initial full frontal tests and ORB design as shown in Figure 1 were described but the results were not included in ESV paper 07-0231 because the results were not completely analyzed at the time of writing that paper. As shown in Figure 1, lower one raw is ORB and upper four rows are not part of the ORB. During Honda Ridgeline SEAS test, its forces on ORB exceeded the Load Cell (LC) capacity (load cells were saturated). So after the initial test series, a redesigned ORB as shown in Figure 2, similar to first generation design except higher capacity LCs was designed and tested.

Figure 1. The initial ORB design.

Each load cell on the initial ORB was 250 x 250 mm in size; 222400 N (50,000 lbf) capacity (single axis). The ORB was 500 mm from the instrumented back-wall. The ORB is modular in design, with the width adjustable by adding or removing individual load cells and the supporting structure. The top of the ORB was infinitely adjustable to 16”–20” height (Part 581 zone) and was adjusted to be below the PEAS of the vehicle being tested.

Figure 2. The redesigned ORB

The redesigned ORB as shown in Figure 2 is similar to the first generation ORB except that each 250 x 250 mm load cell is now replaced by four 125 x 125 mm; 300,000 N (67,440 lbf) capacity single axis load cells.

VEHICLE CRASH TEST RESULTS

NHTSA conducted three ORB crash tests to evaluate the performance of vehicles with SEAS:

2006 Ford F-250 (Blocker Beam SEAS)
2006 Honda Ridgeline (PEAS Extension)
2007 Chevrolet Silverado (PEAS Extension)

These PEAS Extensions are basically SEAS with added structure at the bottom of the rails (PEAS) to bend rails downward.

The tests were subjected at vehicle speeds of 25 mph (40 kph), based on an estimate of the speeds required to generate a significant loading on the SEAS. The tests with the F-250 and Ridgeline were conducted with the 1st generation (initial) ORB, while the test with the Silverado was conducted with the redesigned ORB.

2006 Ford F-250 Results

The F-250 used a blocker-beam as SEAS. The SEAS can be easily removed for comparison tests without the SEAS.

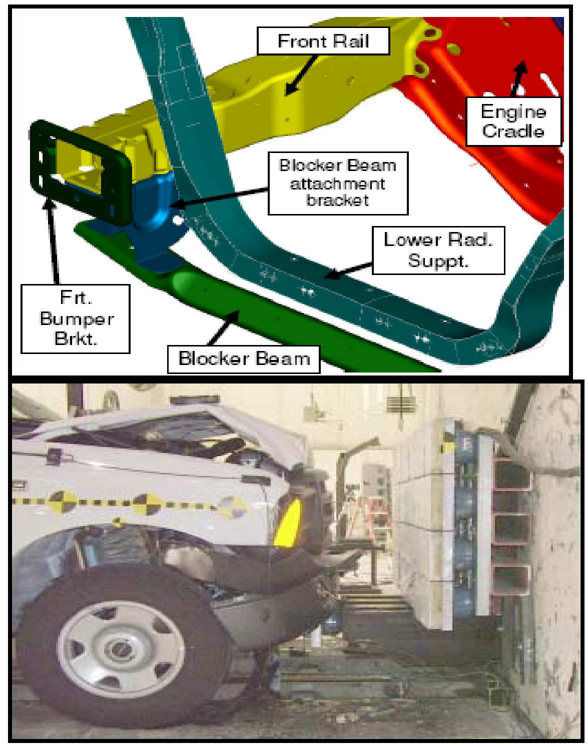
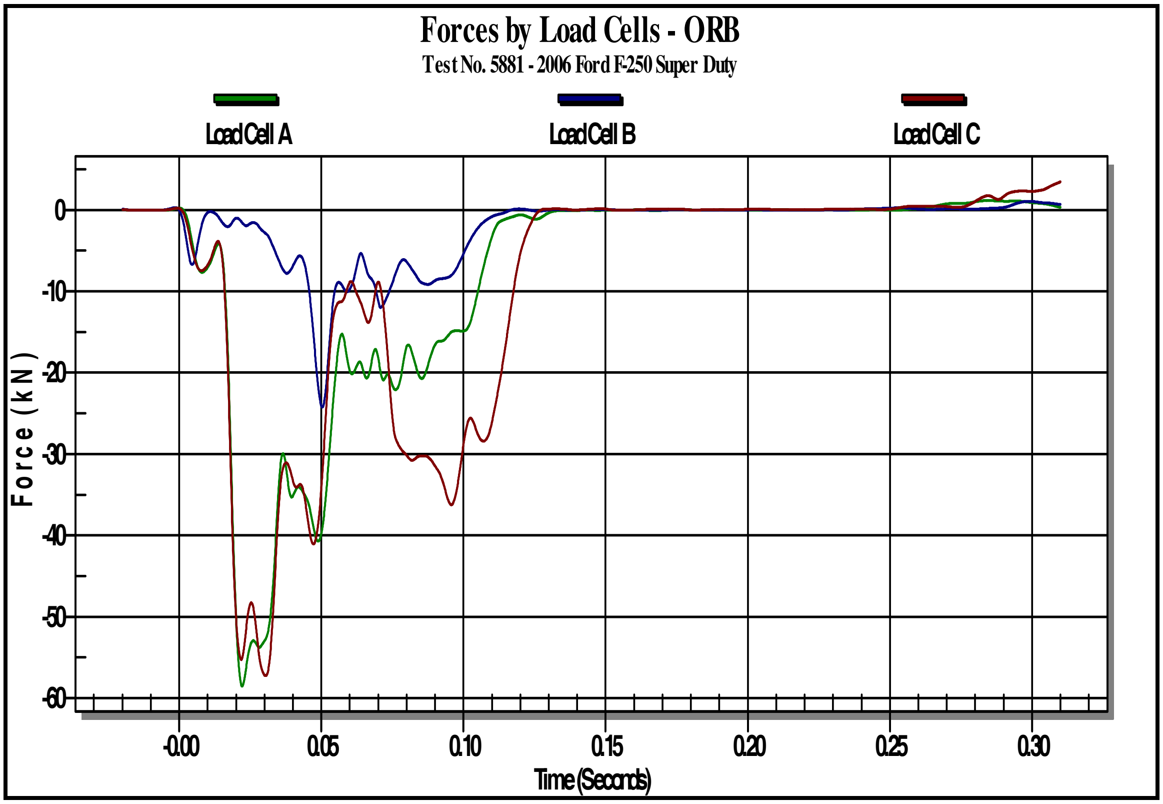


Figure 3. Ford F-250 SEAS design and test

Figure 3 shows the location of the PEAS and SEAS of the F-250.



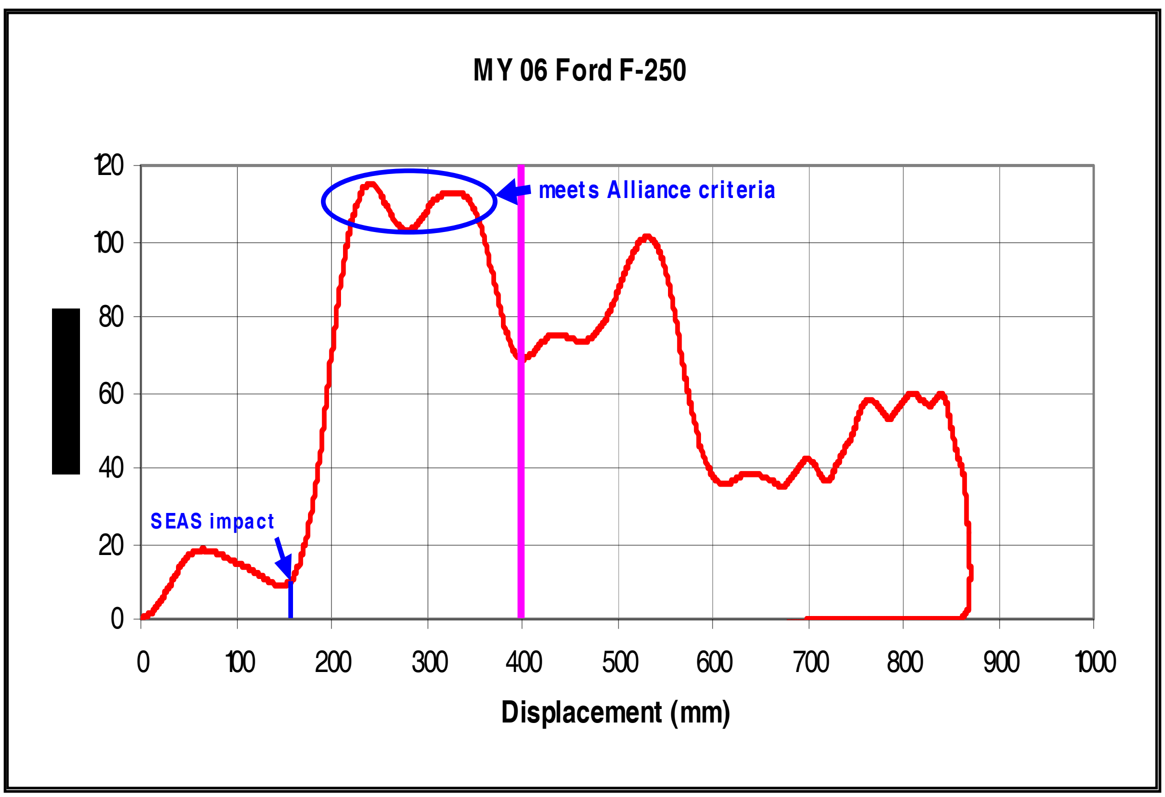


Figure 4. Ford F-250 forces recorded by the ORB load cells and Force-Deformation plot

Figure 4 shows that the vehicle met the Technical Working Group's (TWG) criteria of the SEAS withstanding a force of 100 kN within displacement of 400 mm from the forward-most point of the vehicle structure. It was noted that no load cells were overloaded as shown in the plot above but the vehicle's end brackets which are used to attach the SEAS to the rails generated higher forces.

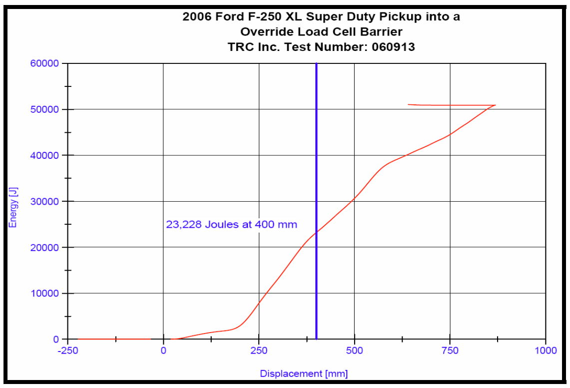
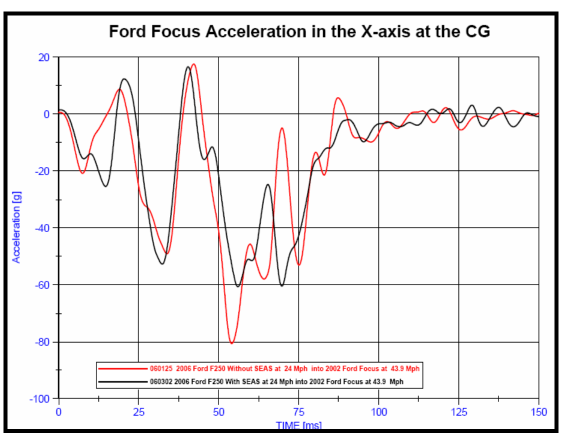


Figure 5. The energy absorbed by the SEAS

Total crash Energy = 181,237 J
% absorbed by SEAS in 400 mm = 12.8 %

VTV crash tests into the 2002 Ford Focus were conducted with the F-250 SEAS attached and with the SEAS removed. The crash pulses and dummy injury assessment values from the two tests are shown in Figure 6.



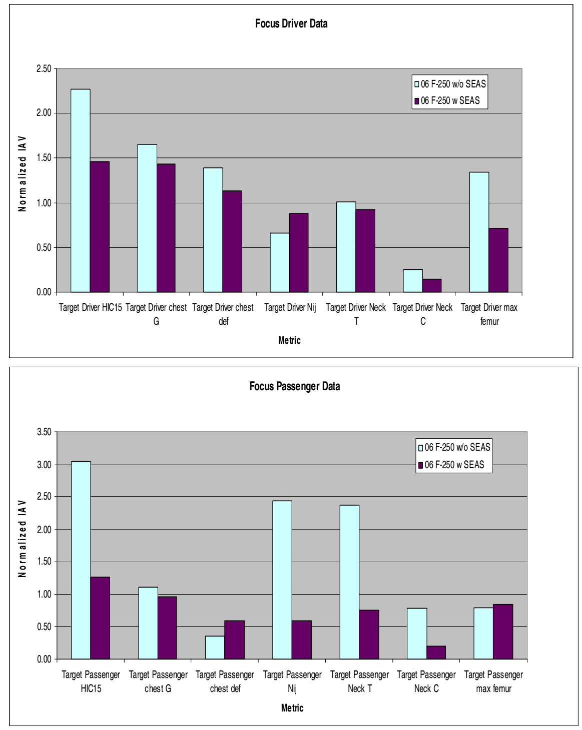


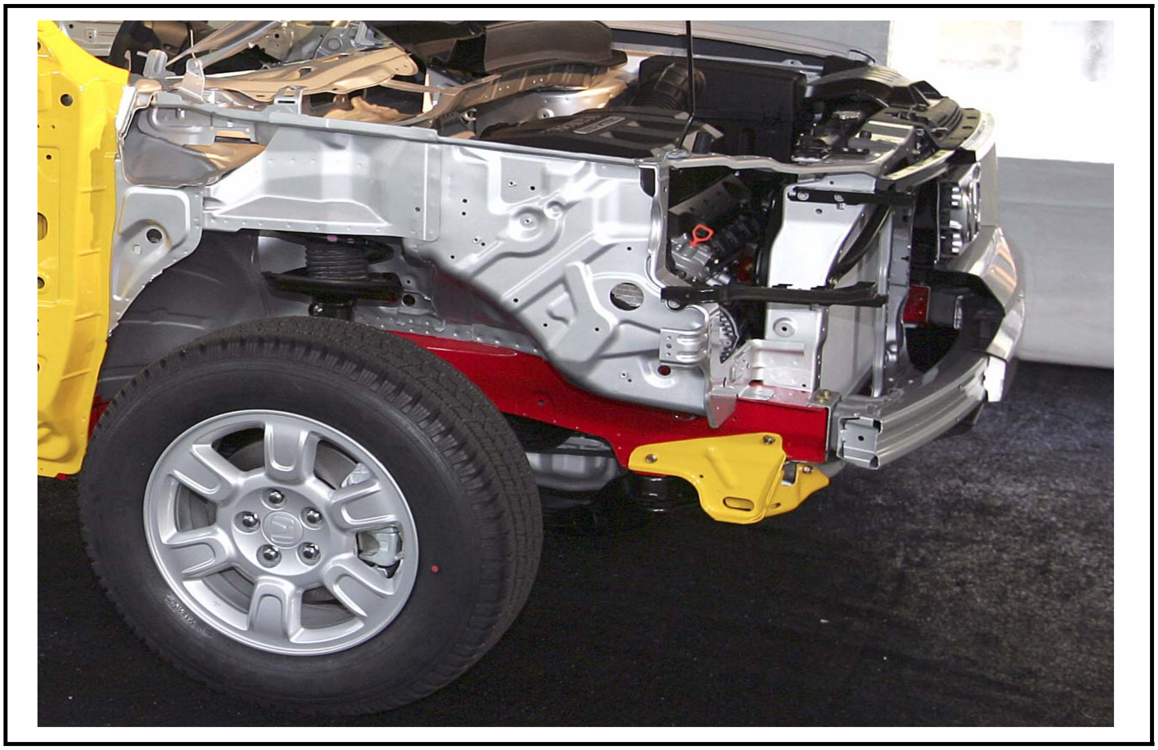
Figure 6. Ford Focus deceleration and dummy injury assessment values

In the comparison VTV test with Ford Focus, the SEAS on the F-250 appears to have improved compatibility by lowering the dummy assessment values and the peak g in the partner vehicle. Post test pictures show reduced crush (and more occupant compartment space) in the Focus in the impact with the F-250 with the SEAS attached.

2006 Honda Ridgeline Results

The location of the PEAS (red color) and SEAS (yellow color) in the Ridgeline is shown in Figure 7. The PEAS extended into the Part 581 zone. This overlap of the PEAS into the Part 581 Zone resulted in high loads on the ORB in this test.

Figure 8 shows the pre-test and post-test pictures of the ORB and SEAS alignment and the deformed PEAS and SEAS respectively.



Figures 7. Honda Ridgeline SEAS design (PEAS in red and SEAS in yellow color)

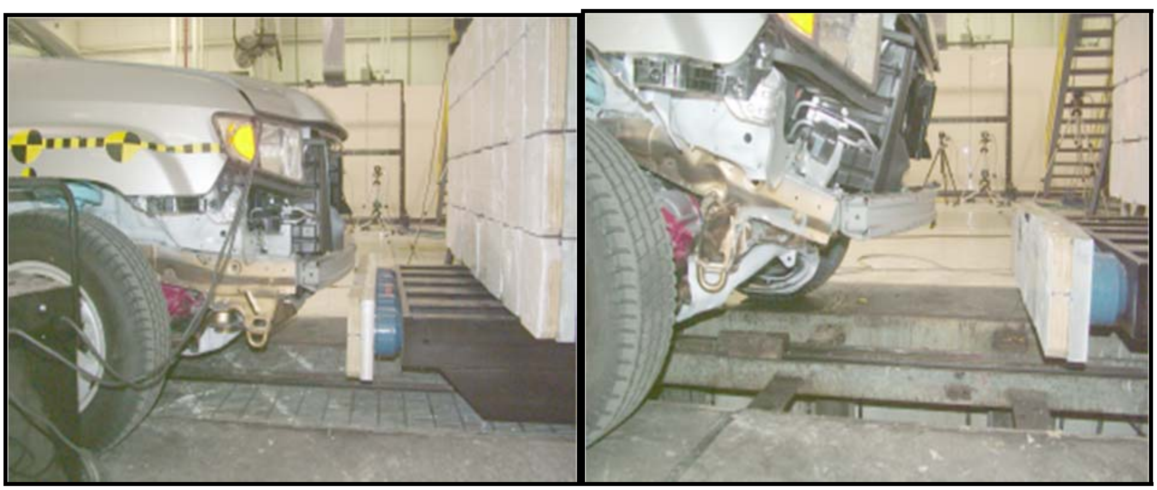
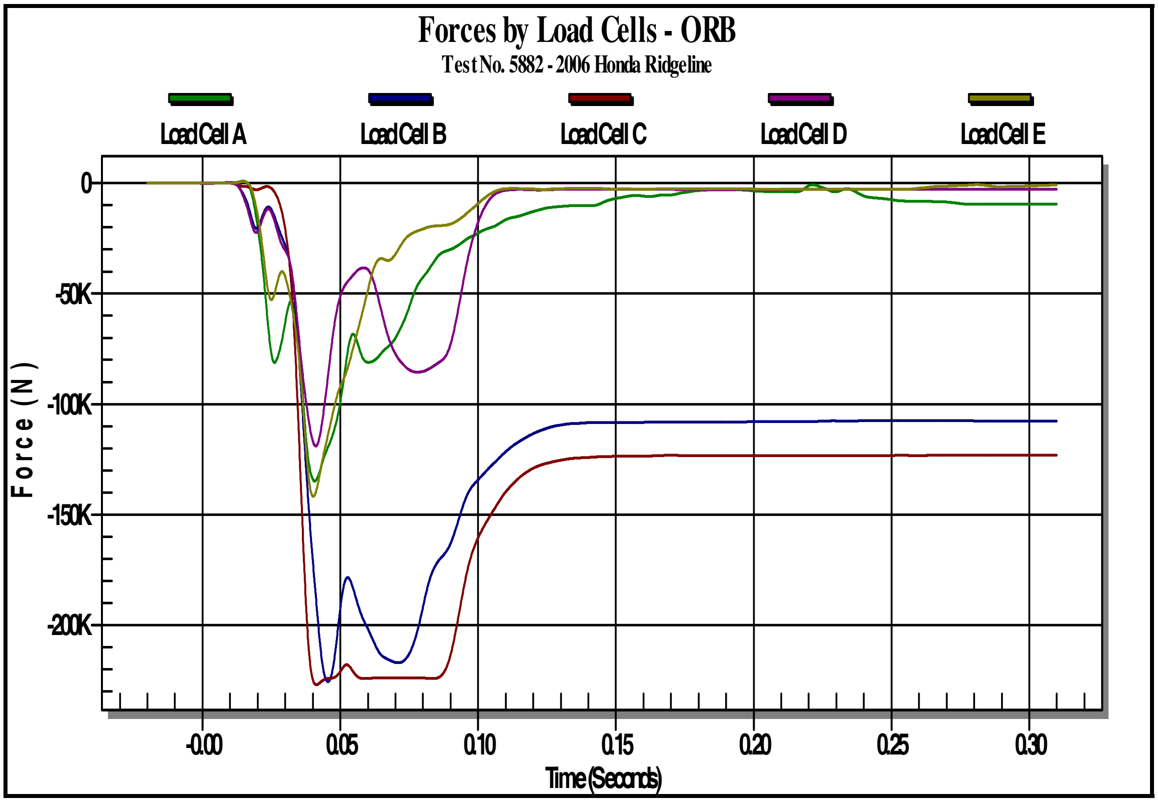
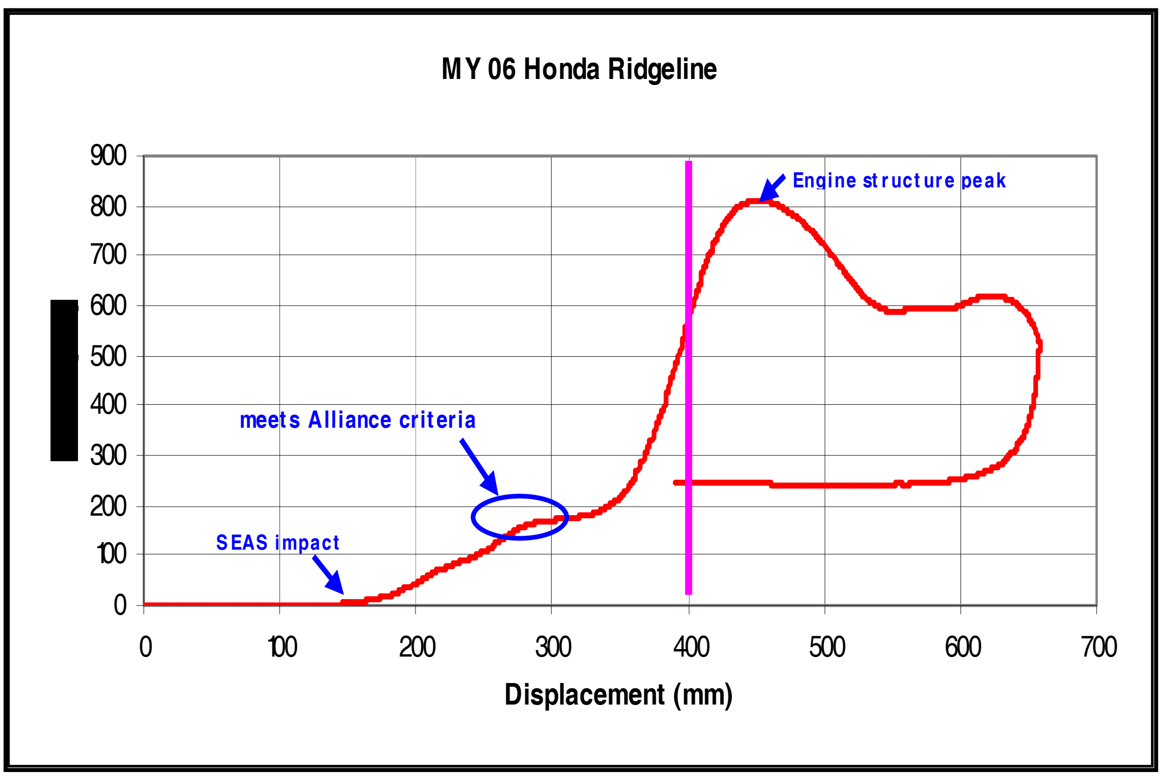


Figure 8. The pre and post-test pictures of the ORB with the align PEAS and deformed PEAS- SEAS respectively.





Figures 9. Honda Ridgeline forces recorded by the ORB load cells and Force-Deformation plot

The forces on the ORB easily exceeded 100 kN in 400 mm displacement. However, forces in two of the five ORB exceeded the load cells capacity as shown in Figure 9 plot of individual ORB load cells. The results of this test beyond 400 mm displacement are of questionable quality.

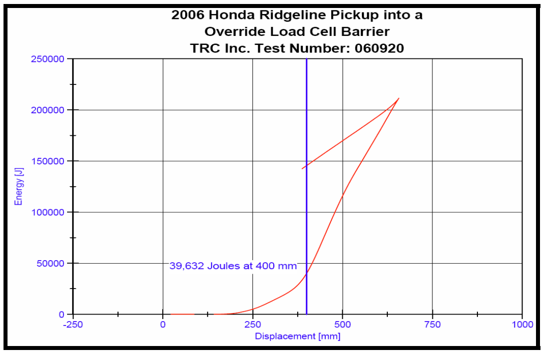


Figure 10. The energy absorbed by SEAS

Total crash Energy = 143,838 J
% absorbed by SEAS in 400 mm = 27.5 %

VTV crash test into the 2002 Ford Focus was conducted with the Ridgeline SEAS only, since SEAS can not be removed for this vehicle. The injury measures in this test were much higher. These high injury values suggest that the Ridgeline SEAS structure was stiff. This result calls for further research to evaluate SEAS structure and especially redesign the ORB to measure its strength.

2007 Chevrolet Silverado Results

The Silverado has brackets attached to PEAS as shown in Figure 11-12. These brackets are intended to bend the PEAS downwards in a frontal crash.

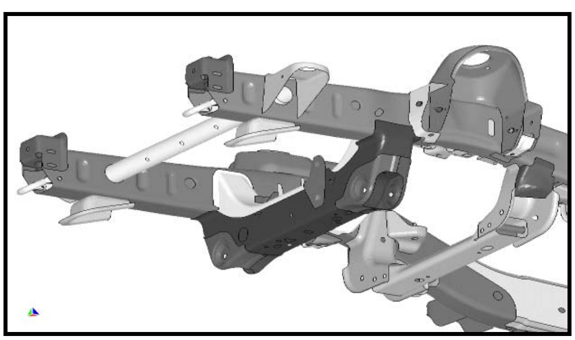
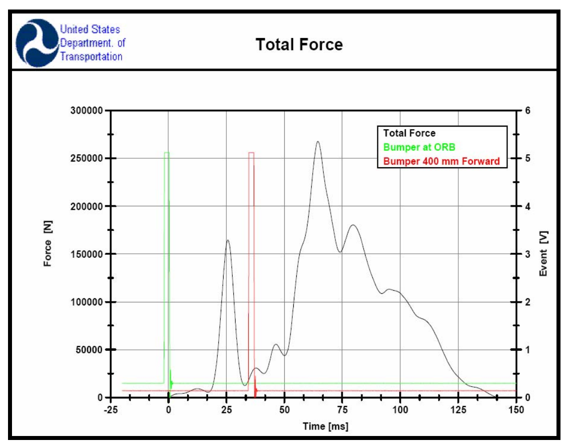


Figure 11. Silverado SEAS design

Figure 12. The pre-test picture of the alignment of the ORB and the SEAS

Figure 13. The post-test picture showing the deformed PEAS and SEAS



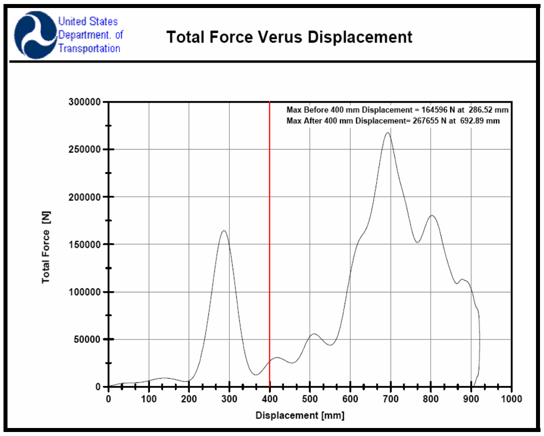


Figure 14. Chevrolet Silverado forces recorded by the ORB load cells (Force-Deformation plot)

The SEAS for this vehicle met the TWG criteria of 100 kN in 400 mm displacement and observed that forces were not exceeded the load cells capacity.

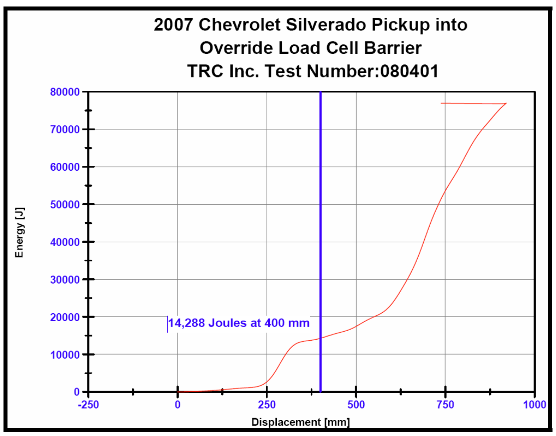


Figure 15. The energy absorbed by SEAS

Total crash Energy = 160,276 J
% absorbed by SEAS in 400 mm = 8.9 %

VTV crash test into the 2002 Ford Focus was conducted with the Silverado SEAS only. SEAS for this vehicle can not be removed. VTV test could be conducted with the SEAS brackets removed by cutting off the brackets at the attachment point with the PEAS. However, such a test has not been conducted. The results from the VTV test (with SEAS) with the Ford Focus had high injury assessment values for the Focus occupants.

COMPUTER SIMULATION RESULTS

The structural interaction between passenger cars and Option 2 LTVs in frontal crashes was investigated using computer simulations. The NCAC/GWU has developed a fleet of virtual vehicles which were used to evaluate the effectiveness of static geometric alignment on structural interaction. The vehicle models chosen for this study as shown in Figure 16, were based on the 1996 Dodge Neon, 2006 Ford F-250 and the 2007 Chevrolet Silverado. All of these FE models were validated to full frontal rigid barrier impact tests [http://www.ncac.gwu.edu/vml/models.html].

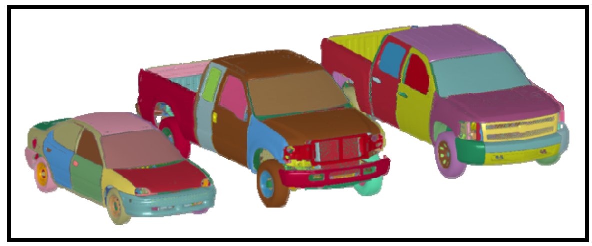


Figure 16. Finite Element Models of Neon, F-250 and Silverado

Frontal impacts between the following vehicle's pairs were analyzed in this study:

1996 Dodge Neon–2006 Ford F-250 (Option 2 LTV, cross-member type SEAS)
1996 Dodge Neon–2007 Chevy Silverado (Option 2 LTV, PEAS Extension)

The Force-Deformation (F-D) characteristic for the Neon, F-250 and Silverado in a full frontal fixed barrier impact is shown in Figure 17. From the F-D curves, it is evident that the frontal structure of the F-250 and the Silverado are much stronger than that of the Neon. True AHOF400 (average height of force delivered by a vehicle in the first 400 mm of crush), and the Kw400 (measure of stiffness based on crush energy absorbed by a vehicle in the first 400 mm of crush) [Mohan, 2008] were calculated for each of the vehicles. Table 1 summarizes the difference in mass, geometry and stiffness between the target vehicle (Neon) and the two bullet vehicles (F-250 and Silverado). The simulations were conducted such that the target vehicle (neon) experienced an impact severity similar to that of the frontal NCAP test condition.

Consequently, the energy required to crush 400 mm of the front end of the F-250 and the Silverado is much higher than the Neon, as reflected by their respective Kw400 measures. VTV full frontal simulations were conducted between Neon-F-250 and Neon-Silverado. The closing speed was chosen to match the impact severity of an NCAP test for the Neon.

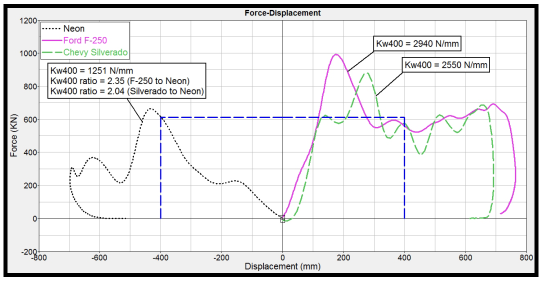


Figure 17. Force Deformation Comparison of Neon, F-250 and Silverado

Table 1. Mass, AHOF400 and Kw400 for Neon, F-250 and Silverado

		Target Veh.	Bullet 1	Bullet 2
		Neon	F-250	Silverado
Mass	kg	1335	2998	2622
Mass Ratio			2.25	1.96
True AHOF400	mm	448	704	584
AHOF Ratio			1.57	1.30
Kw400	N/mm	1251	2940	2550
Kw400 Ratio			2.35	2.04
Approach Veloci	mph	35	15.59	17.8
Closing Speed	mph		50.59	52.80

The front-end structural alignment between the Neon-F-250 and the Neon-Silverado is shown in Figure 18 and Figure 19. There is a significant vertical geometric mismatch between the PEAS of the Neon and F-250. The SEAS positioned below the PEAS of the F-250 overlaps 50% of the Neon PEAS as required by the Alliance voluntary commitment to improve compatibility in frontal impacts for Option 2 LTVs. Due to the presence of SEAS, the Silverado is classified as an Option 2 LTV in this study. Geometrically, the vertical mismatch of the PEAS is much lower between Neon-Silverado when compared to Neon-F-250.

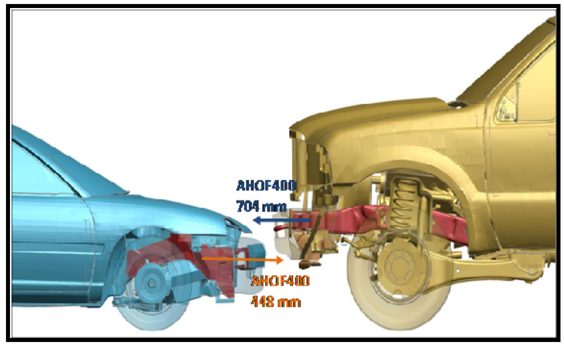


Figure 18. Geometric Alignment, Neon-F250

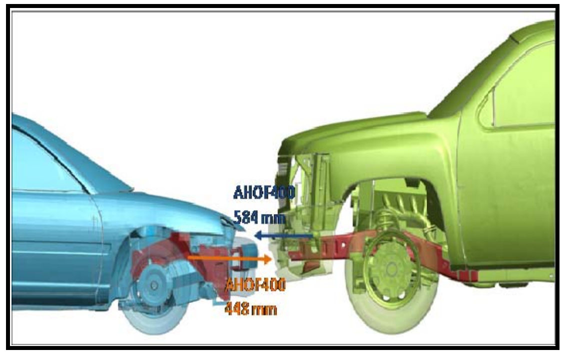


Figure 19. Geometric Alignment, Neon-Silverado

F-250-Neon Simulation Results

Full frontal simulations between the Neon and F-250 were conducted with and without the F-250 SEAS to evaluate the influence of SEAS on structural interaction between the two vehicles. The interaction between the PEAS of the Neon and the F-250 is illustrated in Figure 20 (with SEAS) and Figure 21 (without SEAS). The SEAS on the F-250 prevents the Neon from completely under riding the F-250. The front of the Neon PEAS interacts with the F-250 SEAS and crushes axially in the beginning, but as the SEAS starts to fail the Neon PEAS starts to bend towards the ground. Without the SEAS on the F-250, the structural interaction between the frontal structures is significantly reduced resulting in notable underriding of the Neon front end.

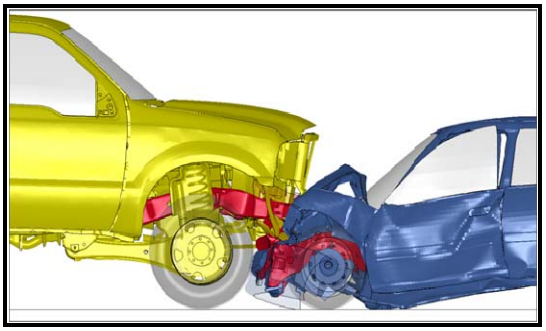


Figure 20. Structural Interaction between Neon and F-250 (with SEAS)

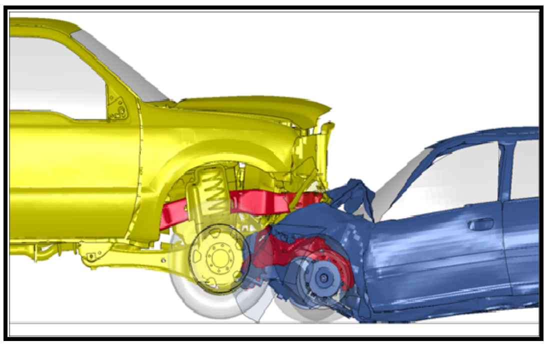


Figure 21. Structural Interaction between Neon and F-250 (without SEAS)

The change in structural interaction was primarily investigated based on the amount of crash energy absorbed by the vehicles involved in the crash. The amount of structural intrusion into the occupant compartment of the vulnerable vehicle was also compared.

The crash energy absorbed by the vulnerable vehicle (compact car, Neon in this study) is further divided into two groups:

- Front engine compartment energy
- Occupant compartment energy

The front engine compartment energy is the energy absorbed by the components that are designed to absorb the crash energy. The occupant compartment energy is the energy absorbed by the occupant compartment, which is primarily designed to prevent any structural collapse into the occupant compartment.

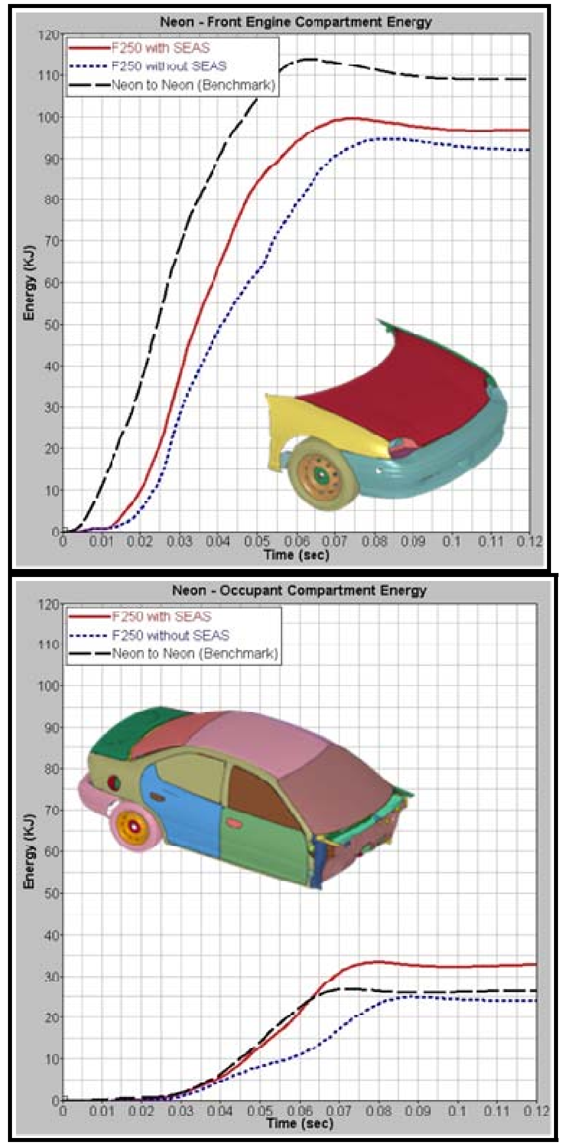


Figure 22. Energy Distribution (Neon-F-250)

The benchmark for energy comparison is a full frontal simulation between identical Neon's at the same impact severity. The mass, the AHOF400 and the Kw400 are all equal. The energy distribution for the Neon front engine compartment and occupant compartment for full frontal impact between Neon-F-250 (with SEAS), Neon-F-250 (without SEAS) and Neon-Neon is shown in Figure 22. Due to significant mismatch between the Neon PEAS and the F-250 PEAS, the Neon frontal structures do not deform ideally (as design optimized for frontal impact into fixed barrier). Consequently, the energy absorbed by the Neon front engine compartment is lower compared to the benchmark simulation between identical Neon's.

The presence of SEAS shows that the occupant compartment energy initially follows the benchmark simulation, but due to the taller, stiffer and heavier F-250, the Neon occupant compartment continues to crush and absorb more energy to satisfy the conservation of energy principle. On the other hand, without the SEAS, there is significant underride of the Neon frontal structures and the energy absorbed by the Neon occupant compartment converges to the benchmark simulation. Based on past crash testing, NHTSA has found that structural mismatch may reduce compartment acceleration on the partner vehicle; however, it is never desired.

The energy comparison would not be conclusive without evaluating the resulting intrusions into the occupant compartment of the vulnerable vehicle. The intrusion into the Neon occupant compartment in full frontal impact with F-250 (with and without SEAS) and Neon is shown in Figure 23. The structural underride between the Neon and F-250 without SEAS resulted in lower toe pan intrusions compared to the impact between Neon and F-250 with SEAS. This is expected as the lower load path is not utilized due to the geometrical mismatch of the structures without the SEAS on the F-250. The toe pan intrusions in the case of the Neon to F-250 with SEAS are very similar to the benchmark impact between identical Neons. However, in both cases (Neon to F-250 with SEAS and without SEAS) the driver side A-pillar intrusions are nearly twice (160mm) that of the benchmark impact between identical Neons. This intrusion is highly undesirable as the dash, steering column and the air bag modules are moving rearward and are compromising the survival space of the occupant. This may also result in lowering the effectiveness of the driver air bag in reducing risk of serious injuries.

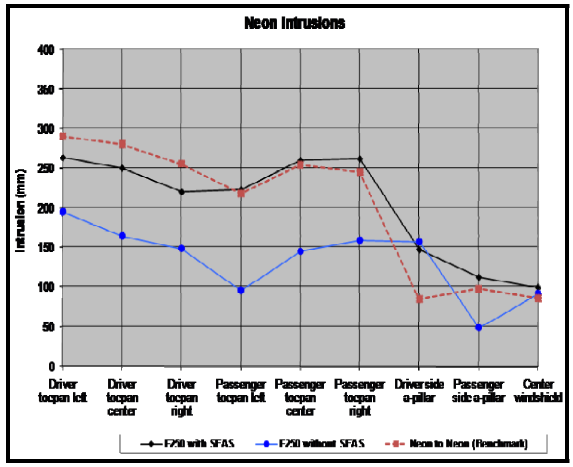


Figure 23. Neon Intrusions (Neon-F-250)

Silverado-Neon Simulation Results

The structural interaction between the PEAS of the Neon and the Silverado is illustrated in Figure 24 (with SEAS) and Figure 25 (without SEAS). The presence or absence of SEAS on the Silverado has negligible effect in the overall crush kinematics of the Neon frontal structures.

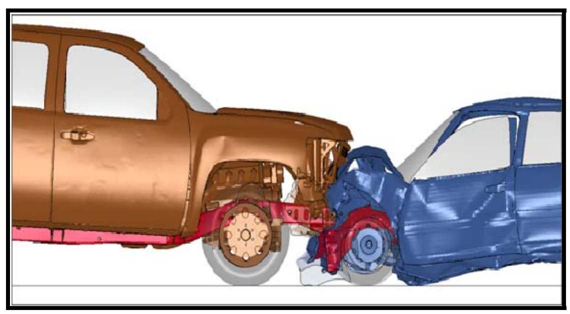


Figure 24. Structural Interaction between Neon and Silverado (with SEAS)

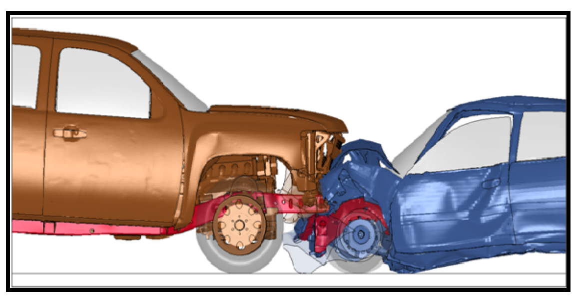


Figure 25. Structural Interaction between Neon and Silverado (without SEAS)

The energy distribution between the front engine compartment and occupant compartment of the

Neon for full frontal impact between Neon-Silverado (with SEAS), Neon-Silverado (without SEAS) and Neon-Neon is shown in Figure 26. The energy absorbed by the Neon frontal structures in a frontal impact between Neon-Silverado is similar to the benchmark simulation between identical Neons. The Neon frontal structures deform ideally (as design optimized for frontal impact into fixed barrier) absorbing the crash energy. However, the energy absorbed by the occupant compartment is significantly higher when compared to the benchmark simulation. Since, the Silverado is much heavier and stiffer than the Neon; the Neon structure has to absorb the remainder of the crash energy to satisfy the conservation of energy principle.

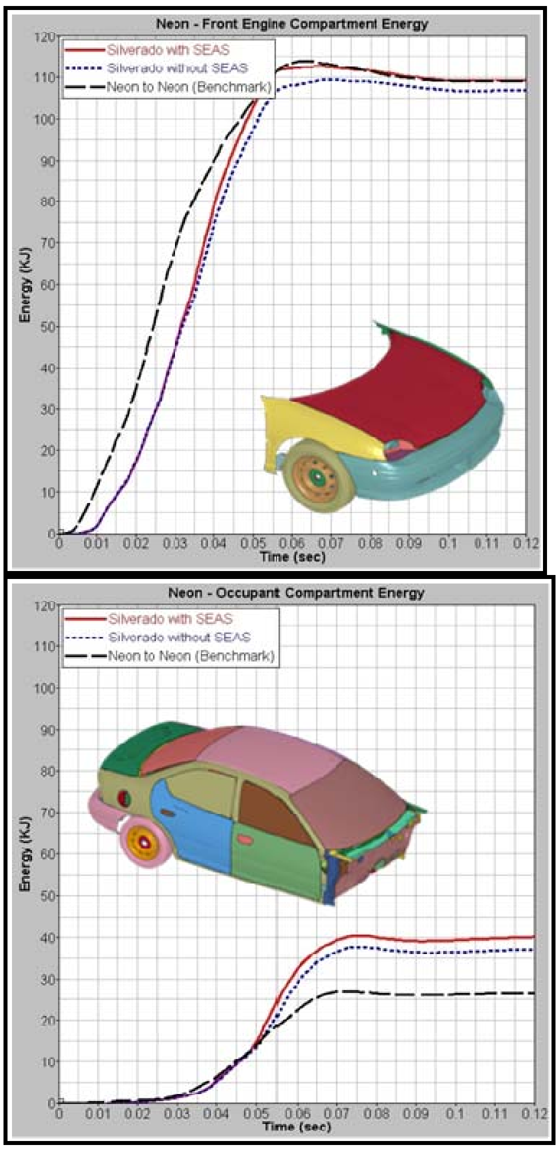


Figure 26. Energy Distribution (Neon-Silverado)

One interesting observation is that both the front engine compartment and occupant compartment energies of the Neon are marginally lower when impacted by the Silverado without the SEAS. The design and placement of the SEAS makes the Silverado PEAS stiffer and reduces its contribution to energy absorption in a frontal impact with the Neon. When the SEAS is removed, there is slightly higher energy absorption by the Silverado PEAS which lowers the amount of energy to be absorbed by the Neon frontal structure.

The resulting Neon compartment intrusions complement the observation above on energy distribution. The resulting toe pan and A-pillar intrusions are notably higher for the Neon-Silverado (with and without SEAS) simulation compared to the benchmark simulation Figure 27. Without the SEAS, the intrusions at the toe pan are slightly lower as some of the crash energy is absorbed by the Silverado PEAS.

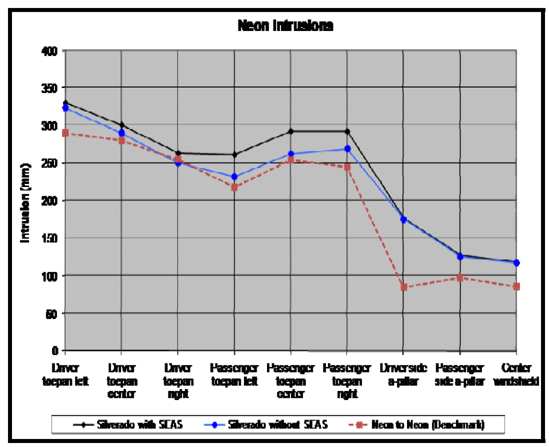


Figure 27. Neon Intrusions (Neon-Silverado)

SUMMARY OF COMPUTER SIMULATIONS

The observations from the Neon-F-250 simulations demonstrate that the cross-member type SEAS design helps prevent underriding of the Neon frontal structures. However, the SEAS in the Silverado was a non-contributing factor in the overall crush kinematics of the Neon frontal structures, mainly because of the vertical overlap of the PEAS structures of the Neon and Silverado. In fact, the Silverado without SEAS showed slight improvement in both intrusions and energy absorption of the Neon. Improvement in geometric compatibility is essentially a step in the right direction. Further improvement in structural interaction is possible by lowering the aggressiveness of the LTV's.

This preliminary analysis was limited to understanding the structural interaction in full frontal impacts. Other frontal and oblique impact conditions and impact locations and their effect on structural interaction were not considered in this preliminary analysis.

CONCLUSIONS

The industry voluntary test for the SEAS is a quasi-static push test that requires the SEAS structure to withstand a minimum of 100 kN of force before 400 mm deflection from the front of the primary structure (e.g., the rails on which it is mounted). Such a test may guarantee a minimum strength, but it does not prohibit the structure from being designed too strong for good car compatibility. An energy absorption evaluation could optimize the SEAS for compatibility.

The ORB dynamic tests showed that the vehicles tested meet the proposed SEAS performance criteria suggested by the Alliance's TWG.

The full frontal simulations between a compact passenger car (Neon) and the Ford F-250 without the SEAS showed reduced intrusions in the Neon toepan area. However, there was significant underride of the Neon which resulted in increased intrusions near the driver side A-pillar. In the case of F-250 with SEAS, there was increased structural interaction between the SEAS and the Neon PEAS which prevents frontal structures from underriding each other. As a consequence there is more intrusion into the occupant compartment when compared to the frontal impact without the SEAS. This observation was based on the simulation results with FE model of the 1996 model year Neon. In recent years, the structural design and self-protection levels of compact passenger cars have significantly improved (based on frontal NCAP and IIHS front offset test results) and the observation may be different in frontal impacts between these newer compact cars and the Ford F-250 with and without the SEAS. The presence or absence of SEAS on the Chevrolt Silverado had negligible effect in the overall crush kinematics of the Neon frontal structures. This is primarily attributed to the SEAS design and its location.

Further study is needed to determine the effective performance requirements for SEAS. This study was limited to the three SEAS designs that were available in production vehicles at the time of testing. Other SEAS designs and their performance may need to be considered before an appropriate ORB test procedure is identified. The difference in the design of the PEAS confounds the study of the effects of SEAS in VTV tests. In the case of the Ford F-250, where the SEAS could be removed, the VTV tests show a benefit from SEAS. However, the SEAS on the F-250 had the lowest strength. Additional criteria for the SEAS, like energy absorbed, may be considered in the future.

Like most programs using crash tests, this study is subject to limitations in the number of vehicles studied. Additional SEAS designs will need to be studied, along with their effect in mitigating injuries in the partner vehicle, before any conclusions can be made about the effectiveness of the proposed TWG performance criteria.

Option 2 LTV's reward the added SEAS to reduce override of passenger cars. These structures will require a new test procedure for evaluation. This paper shares the designs of the ORB, and results from tests of Option 2 vehicles equipped with and without SEAS.

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