EVALUATION OF ADVANCED COMPATIBILITY FRONTAL STRUCTURES USING THE PROGRESSIVE DEFORMABLE BARRIER (PDB)

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ABSTRACT

Vehicle compatibility combines aspects of both self and partner protection. Self protection involves a vehicle's compartment strength and occupant protection systems. Partner protection involves vehicle design attributes that work towards providing occupant crash protection of a vehicle's collision partner. Research has suggested that good engagement of the front structures and high compartment strength could be effective components for improving compatibility between passenger cars and other vehicles [1]. Studies have shown, however, that incompatible force distributions and greater relative front end stiffness are prevalent in the fleet. To research this issue, the Progressive Deformable Barrier (PDB) was evaluated for its ability to assess the compatibility between the front end force of vehicles equipped with and without compatibility countermeasures.

The paper investigates self protection and partner protection in the offset frontal crash test configuration using the data produced by a joint research program carried out at the Union Technique de l'Automobile du Motocycle et du Cycle (UTAC) in conjunction with the Directorate for Road Traffic and Safety (DSCR) in France and the National Highway Traffic Safety Administration (NHTSA) of the United States (U.S.). The program was initiated to investigate whether barrier deformation using the PDB, intrusion, and dummy injury measures could differentiate compatibility performances between vehicles with and without advanced frontal structures designed specifically to address vehicle compatibility.

INTRODUCTION

Safety researchers around the world, including the U.S. and France, have been concerned with vehicle compatibility in crashes for many years. NHTSA has conducted studies on vehicle aggressiveness (the injury risk vehicles pose to drivers of other vehicles in a collision) and methods for measuring it for over 25 years [2]. Examination of U.S. crash statistics shows a disparity in fatality risk for passenger car occupants in vehicle-to-vehicle collisions with light trucks and vans (LTVs). Past studies have shown that LTVs, as a class, were twice as aggressive toward their collision partners as passenger cars [2]. This mismatch in crash performance has considerable consequences for the traffic safety environment, as approximately half of all passenger vehicles sold in the U.S. are LTVs.

While LTVs are not nearly as widespread in Europe, vehicle compatibility has been a growing concern for its countries as well. Researchers have observed that European vehicles have generally been produced with greater mass, stiffer front ends, and higher compartment strengths to provide occupant crash protection in fixed offset barrier crash tests [1]. As vehicles get heavier and stiffer, however, the deformable barriers used for the evaluation of frontal offset crash protection begin bottoming out. As a consequence, the test becomes more severe for the stiffer, heavier vehicles, and they become more incompatible with smaller collision partners.

In 1996, European Enhanced Vehicle-Safety Committee Working Group 15 on vehicle compatibility was established in order to explore methodologies to assess vehicle compatibility, and develop test procedures to address it. In March 2002, vehicle compatibility was included as an area of focus for the exchange of information in the program of work adopted under the World Forum for the Harmonization of Vehicle Regulations (WP.29) 1998 Global Agreement. Both the U.S. and France are signatories to that agreement, and have concurrently undertaken international research collaborations.

DSCR has been researching the PDB test procedure approach for over 10 years as a means to address vehicle compatibility and recently proposed an

upgrade to United Nations Economic Commission for Europe (UNECE) Vehicle Safety Regulation 94 to incorporate the barrier [1][3]. The PDB progressively increases in stiffness horizontally at both the upper and lower load levels, thus earning its name, PDB, or Progressive Deformable Barrier. Its characteristics were designed to represent an actual vehicle structure with sufficient force level and energy absorption capacity to mitigate any occurrences of bottoming out. In doing so, the PDB may be better able to harmonize test severity among vehicles of different masses. The PDB test procedure aims to encourage lighter vehicles to be stronger without increasing the force levels of large vehicles [1]. By design, the PDB is also able to detect all frontal structures involved in a crash (i.e. cross members, subframes, blocker beams, and longitudinal frame rails). By detecting the impact deformations, the test procedure can encourage vehicle designs that incorporate structures to distribute homogeneous force levels over large surfaces.

In 2004, NHTSA and DSCR signed a bilateral agreement to enhance cooperation and increase the efficient use of resources. As a result, the two agencies elected to conduct joint analyses to promote the development of improved vehicle safety programs and related regulations. Vehicle compatibility was chosen as one focus area. The agencies initiated a joint research program to investigate the potential utility of the PDB in discerning levels of partner and self protection in full width and offset test configurations using heavy vehicles[4]. This research demonstrated that the PDB-XT was able to differentiate between vehicle frontal designs, such as unibody and body-on-frame construction. (*The PDB+ was renamed the PDB-XT and is the most recent configuration of the PDB.*) Based on these results, further research was initiated to determine if the PDB could identify structures designed for vehicle compatibility, such as Honda's Advanced Engineering Compatibility (ACE) body structure [5].

The paper investigates whether barrier deformation using the PDB, intrusion, and dummy injury measures could differentiate compatibility performances between vehicles without advanced frontal structures and those equipped with these structures designed specifically to address compatibility. It evaluates criteria of self protection and partner protection in the offset frontal crash test configuration. It also compares the results to car-to-car crash tests and real world crash analysis.

METHOD OF TEST EVALUATION

Test Severity

One approach toward evaluating both self protection and partner protection is to normalize the test severity for all vehicles—large and small—by using the PDB. Test velocity alone is not a good indication of the severity of the event because, unlike a rigid barrier test, a portion of the test energy is absorbed by the deformable element of the barrier. The energy absorbed by the barrier is a factor of the vehicle's mass, structural design, and stiffness. Therefore, the parameter used to equate the test severity for different vehicles at a common speed using the PDB is the Energy Equivalent Speed (EES) as defined in (Equation 1).

$$EES(km/h) = 3.6 \times \sqrt{\frac{2 \times Eabs}{M}} \qquad \text{(1a).}$$

Eabs = energy absorbed by the vehicle (J)
Eabs = Kinetic energy – Energy in the barrier
M = mass of the vehicle (kg)

$$Ebarrier = \int_{x_{min}}^{x_{max}} F dx \qquad F = P * S \qquad \text{(1b).}$$

P = barrier stiffness (MPa)
S = crushed surface (m^2)

Self protection

Self protection is conceptualized as the ability of a vehicle to protect its own occupants in a vehicle-to-vehicle crash. Many of the crashworthiness regulations around the world are directed toward evaluating a vehicle's "self protection," or how the vehicle protects its own occupants. To achieve good self protection, front end design must limit intrusion and acceleration levels in the passenger compartment as well as limit occupant injury criteria. The following parameters were measured to evaluate the level of self protection the vehicles offered:

- Compartment intrusion
- Dummy injury criteria
- Vehicle acceleration

Partner protection

The concept of partner protection involves vehicle design attributes that function to maximize protection of the occupants within the collision partner. In order to take advantage of the potential energy absorption of a vehicle front end in a vehicle-to-vehicle crash, good engagement of the vehicle's energy absorbing structures must occur. To achieve this result, the deformation of the front

end must be distributed over a large surface. In this study, post-crash test barrier digitization is used to examine the different barrier engagement patterns. The study also compares the following barrier-based parameters that have been identified in previous research as influential in the evaluation of partner protection [4]:

- Average Height of Deformation (AHOD): height at which the median deformation occurs, (evaluates the frontal geometry of a vehicle)
- Average Depth of Deformation (ADOD): average deformation over the barrier, (evaluates the frontal stiffness of a vehicle)
- Maximum Deformation (Dmax): the maximum depth of deformation to the barrier, (evaluates the localized stiffness of a vehicle)

Calculation method

- Average Height of Deformation (AHOD) (Equation 2):

For a given rectangular investigation region, the "depth profile" is computed as a function of height:

$$\rho(z) = k \int_{y_{\min}}^{y_{\max}} X(y,z)dy \qquad (2a).$$

Where k is a normalization constant ensuring that:

$$\int \rho(z)dz = 1 \qquad (2b).$$

The AHOD is then obtained as a mean value:

$$AHOD = \int z\rho(z)dz \qquad (2c).$$

- Average Depth of Deformation (ADOD) (Equation 3):

For a given investigation region with an area S:

$$ADOD = \frac{1}{S}\int X(y,z)dydz \qquad (3).$$

In addition to these PDB barrier-based parameters, the vehicles were also compared based on parameters developed in prior full width rigid barrier testing of these vehicles: KW400 and AHOF [6].

- KW400:

The stiffness-related crush energy absorbed by a vehicle in the first 400 mm of crush (also called the work stiffness).

- Average Height of Force (AHOF):

The average height of force delivered by a vehicle in the first 400 mm of crush.

TEST CONFIGURATION

This test procedure is based on the current PDB test protocol (Figure 1 and Figure 2) [3]. The barrier used is the barrier defined in the current test protocol version "XT".

PDB-XT 50% Offset	
Barrier	PDB-XT
Speed	60km/h
Overlap	50%
Dummies	H3 50% male H3 50% male + Leg Lx

Figure 1: Vehicle in front of the offset PDB.

In these tests, a Hybrid III 50th percentile male dummy fitted with Thor-Lx legs was seated in the driver's seat and a Hybrid III 50th percentile male dummy was seated in the passenger position. The dummies were positioned using a seating procedure that mimics the procedures used by humans to position themselves in the vehicle [7].

This procedure ensured the feet were in neutral position. In the case of the driver position dummy, the right foot was placed on the accelerator pedal, which provided proper dummy interaction with the vehicle interior to predict lower leg injuries. This procedure was developed to achieve repeatable positioning of the Thor-Lx feet with respect to the pedals in some vehicles. The data from the driver dummy's ankle measurements were inconclusive because of data acquisition problems.

VEHICLE SELECTION

In a previous cooperative research effort between DSCR and NHTSA [4], it was shown the PDB test

configuration was able to discriminate between a body-on-frame vehicle structure in a Chevrolet Silverado pickup truck and the unibody construction of a Chrysler Town & Country minivan. At the time it was stated future research could include evaluating the PDB's ability to identify secondary energy absorbing structures or other novel designs and assess their partner protection performance for crash compatibility. Research could also be expanded to appraise how the PDB performs with vehicles that have similar frontal stiffness and force matching to identify additional design factors that may play a roll in crash compatibility.

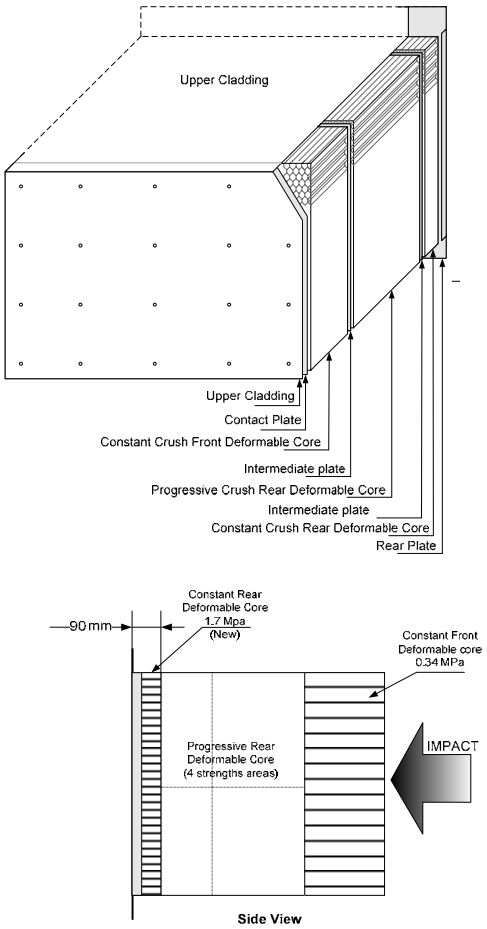


Figure 2 : PDB-XT barrier specification.

This series of tests evaluated the PDB's ability to differentiate the performance of vehicles with and without advanced frontal structures designed to improve self and partner protection when involved in a frontal crash with an incompatible vehicle. The 2005 Honda Odyssey minivan and 2006 Honda Civic compact car were selected because they were designed with Honda's Advanced Compatibility Engineering (ACE) body structure.

According to Honda marketing literature [5], the ACE body design helps spread out the forces of a frontal collision to help avoid concentrated impact forces that cause injuries. The ACE body structure is further reported to be highly effective at absorbing the energy of a frontal crash. It is also reported to help minimize the potential for under-ride or over-ride during head-on or offset frontal collisions with a larger or smaller vehicle.

According to Honda, the ACE body structure also creates a network of fully integrated load-bearing elements that helps attenuate peak impact forces by more evenly distributing them across a relatively large area in the front of the vehicle.

Honda further stated that unlike most conventional designs that direct frontal crash energy only to the lower load-bearing structures in the front end, the ACE body structure actively channels frontal crash energy to both upper and lower structural elements, including the floor frame rails, side sills, and A-pillars. Honda suggested that by engineering specific pathways that help distribute these frontal impact forces throughout a greater percentage of the vehicle's overall structure, the ACE body structure can more effectively route them around and away from the passenger compartment to help limit cabin deformation and further improve occupant protection. Honda reported that its unique front main structure composed of polygonal frame members is integral to the ACE body structure concept.

In addition to the two vehicles with ACE the previous generation 2004 Honda Odyssey—without the ACE body structure—was selected as a baseline vehicle.

Load cell data collected to compute frontal stiffness and force matching height, drawn from the U.S. New Car Assessment Program (USNCAP), was available for the two Honda Odyssey vehicles. In this test program, vehicles equipped with belted 50th percentile male Hybrid III dummies are impacted into a full width rigid barrier at 56 km/h, and load cell data is collected from the test. Additionally, the selected vehicles were part of a series of vehicle-to-vehicle tests in which the bullet vehicles were crashed into a Ford Focus in a full frontal crash configuration. For the recent PDB-XT offset tests, the Honda Odysseys were ballasted to approximately the same weight as in the vehicle-to-vehicle test series to allow for a direct comparison of the results.

Figure 3: 2005 Honda Odyssey

2005 Honda Odyssey	
Test Mass	2,245 kg
Width	1,920 mm
Structure	ACE

Figure 4: 2005 Honda Odyssey Specifications

Figure 5: 2004 Honda Odyssey

2004 Honda Odyssey	
Test Mass	2,245 kg
Width	1,920 mm
Structure	Without ACE

Figure 6: 2004 Honda Odyssey Specifications

TEST RESULTS

The following sections describe the test results based on test severity, self protection, and PDB-XT partner protection. Three PDB-XT tests were performed, but this discussion is focused on the performance of the two Odyssey vehicles. The results from the 2006 Honda Civic with ACE test yielded consistent findings and are presented in Appendix A for information only.

2005 Honda Odyssey with ACE

Test severity - The amount of energy absorbed in the offset PDB-XT was 104 kJ for the 2005 Honda Odyssey test with ACE. The calculated EES for this test was 49.6 km/h, which is 10 km/h less than the test speed.

Self protection - In terms of self protection, the 2005 Honda Odyssey maintained its occupant compartment integrity (Figure 7). The front end crushed the barrier uniformly without any undeformed load paths. The subframe appeared strong and transferred loads in the test. Additionally, the left rear subframe attachment bolt broke off. It should be noted that the upper turret above the wheel that connects to the crossbar deformed down in front of the tire. After the test, the front left door was not able to close properly after it was opened.

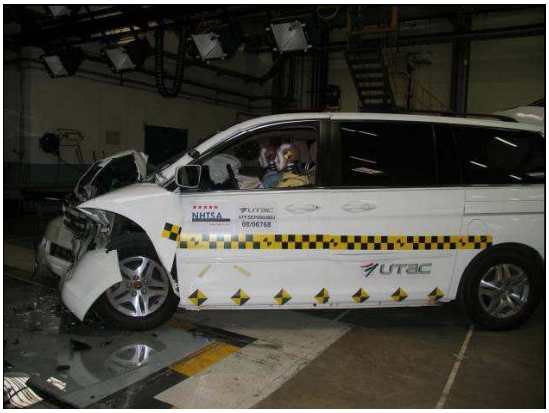


Figure 7: 2005 Honda Odyssey with ACE PDB-XT Offset.

The injury measures for the 50th percentile male driver and passenger dummies are reported in Figure 8.

	IARV*	Driver	Pass.
HIC36	1,000	290	284
Chest Def (mm)	50	26.6	26.5
Chest Gs	60	39.2	27.4
Left Femur (kN)	8	4.76	2.03
Right Femur (kN)	8	1.21	0.97
UL Tibia Index	1.3	0.46	0.76
UR Tibia Index	1.3	0.51	0.43
LL Tibia Index	1.3	0.39	0.34
LR Tibia Index	1.3	0.57	0.21

* As defined in UNECE R.94, except for Chest G's which is defined in U.S. FMVSS No. 208.

Figure 8: 2005 Honda Odyssey with ACE PDB-XT offset – Dummy Injury Measures

None of the occupant injury measures were elevated in this test. The calculated mean intrusion on the driver's side upper region (dashboard and A-pillar) was 30 mm and 87 mm in the lower region (pedal axle and footwell). Although the intrusion (Figure 9) was localized in the footwell area on the driver's side, the driver's side dummy lower leg injury measures were not significantly affected.

The maximum acceleration measured was 29 g at 86 ms, corresponding to 1.059 m of displacement (Figure 10). The average acceleration was 15.8 g.

Partner protection - A large deformation of the longitudinal and lower load path was observed in the PDB-XT offset test of the 2005 Honda Odyssey with the ACE body structure. Two levels of the load paths and the connection between them created a large reaction surface for engagement with a partner vehicle (Figure 11 and Figure 12). The vertical structural element protecting the left wheel was also imprinted on the barrier. There was no bottoming out of the barrier.

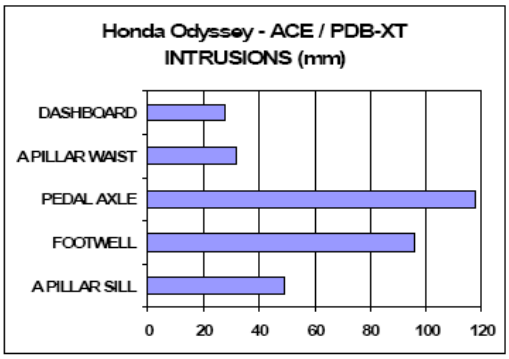


Figure 9: 2005 Honda Odyssey with ACE PDB-XT Offset – Driver Side Intrusions.

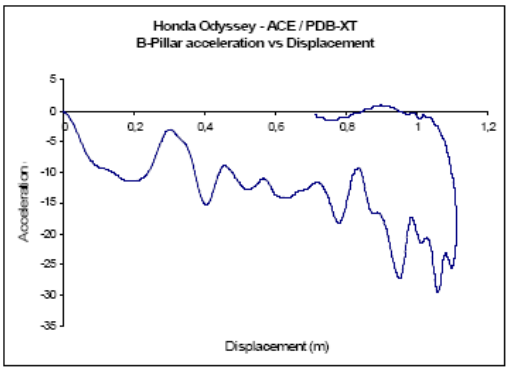


Figure 10: 2005 Honda Odyssey with ACE PDB-XT offset – Acceleration Pulse.

Figure 11: 2005 Honda Odyssey with ACE PDB-XT offset – front end deformation.

Figure 12: 2005 Honda Odyssey with ACE PDB-XT offset – barrier deformation.

In Figure 13, the barrier was able to detect the homogeneous frontal structure of the vehicle. The barrier did identify the deformation due to the crossbeam and the subframe in addition to the strong vertical connections between the load paths. The calculated partner protection parameters based on barrier digitization analysis are presented in Figure 14. The energy absorbed in the barrier was 104 kJ which represented 33 percent of the total kinetic energy.

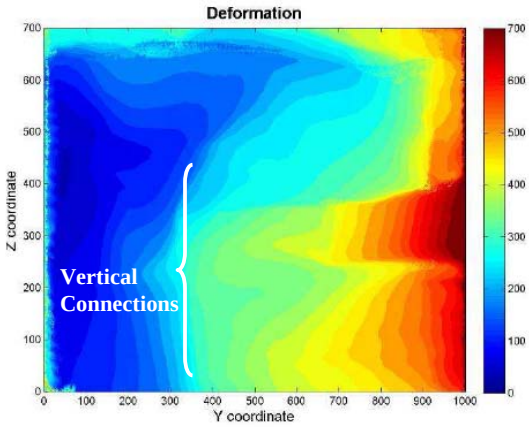


Figure 13: 2005 Honda Odyssey with ACE PDB-XT offset – barrier digitization.

Partner protection	
ADOD (X)	321 mm
AHOD (Z)	397 mm
Dmax	619 mm

Figure 14: Partner Protection Parameters for the 2005 Honda Odyssey with ACE PDB-XT offset test.

2004 Honda Odyssey without ACE

Test severity - The amount of energy absorbed in the offset PDB-XT test was 97 kJ for the 2004 Honda Odyssey without ACE. The calculated EES for this test was 50.6 km/h, which is approximately 9 km/h less than the test speed.

Self protection - In terms of self protection, the 2004 Honda Odyssey without ACE performed well. It resulted in good occupant compartment integrity, including the front left door maintaining its ability to open and close (Figure 15). The left longitudinal frame rail did not compress. Also the subframe detached at it rear attachment point to the floor pan.

Figure 15: 2004 Honda Odyssey without ACE PDB-XT offset.

The injury measures for the 50th percentile male driver and passenger dummies are reported in Figure 16. The head, chest and leg injury measurements of the dummies were low.

	IARV*	Driver	Pass.
HIC36	1,000	283	273
Chest Def (mm)	50	28.7	33.4
Chest Gs (3ms)	60	37.1	28.7
Left Femur (kN)	8	1.61	2.78
Right Femur (kN)	8	0.75	1.36
UL Tibia Index	1.3	0.28	0.45
UR Tibia Index	1.3	0.29	0.16
LL Tibia Index	1.3	0.22	0.27
LR Tibia Index	1.3	0.32	0.11

* As defined in UNECE R.94, except for Chest G's which is defined in U.S. FMVSS No. 208.

Figure 16: 2004 Honda Odyssey without ACE PDB-XT offset Dummy Injury Measures.

The calculated mean intrusion on the driver's side upper region (dashboard and A-pillar) was 59 mm and 155 mm for the lower region (pedal axle and footwell). The intrusion was highly localized in the footwell area (Figure 17). However, the driver's side lower leg injury measurements were not significantly affected.

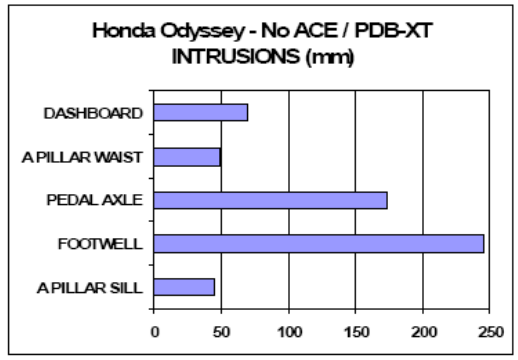


Figure 17: 2004 Honda Odyssey without ACE PDB-XT Offset – Driver side intrusions.

The maximum acceleration measured was 32 g at 93 ms, corresponding to 1.164 m of displacement (Figure 18). The average acceleration was 15.4 g.

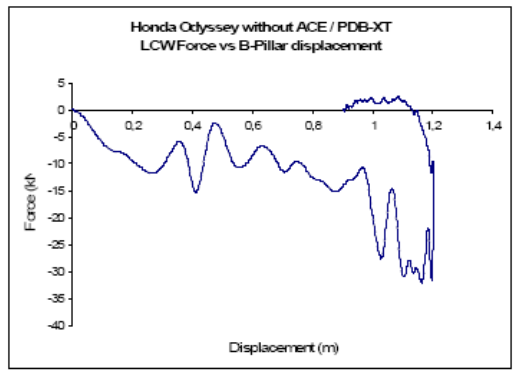


Figure 18: 2004 Honda Odyssey without ACE PDB-XT offset – Acceleration

Partner protection - There was good integrity and no bottoming out of the PDB-XT after the 2004 Honda Odyssey without ACE test. The deformation was not, however, homogeneous. The barrier detected the non-deforming left longitudinal frame rail and the horizontal crossbeam and lower subframe (Figure 19) in the test. The left wheel also engaged and deformed the barrier. The PDB-XT was able to detect the unique load paths of this vehicle (Figure 20).

The calculated partner protection parameters based on barrier digitization analysis (Figure 21) are presented below (Figure 22). The energy absorbed in the barrier was 97 kJ which represented 30 percent of the total kinetic energy.

Figure 19: 2004 Honda Odyssey without ACE PDB-XT - front end deformation.

Figure 20: 2004 Honda Odyssey without ACE PDB-XT – barrier deformation.

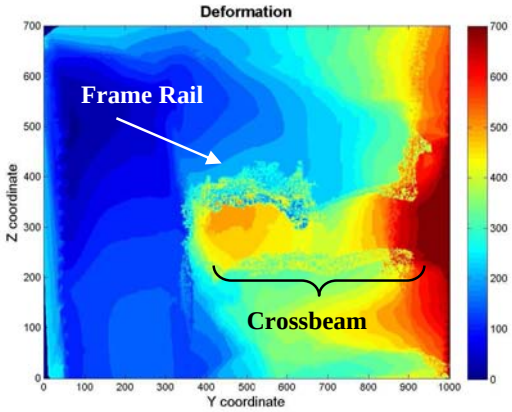


Figure 21: 2004 Honda Odyssey w/o ACE PDB-XT – barrier digitization.

Partner protection	
ADOD (X)	287 mm
AHOD (Z)	401 mm
Dmax	676 mm

Figure 22: Partner Protection Parameters for the 2004 Honda Odyssey without ACE PDB-XT offset test.

DISCUSSION

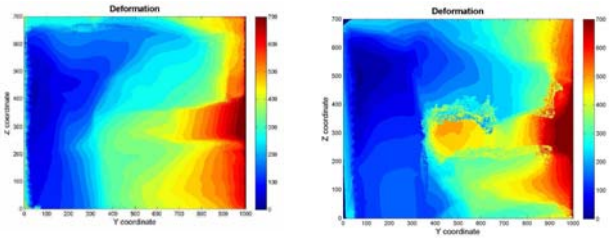
Self protection

The 2005 Honda Odyssey with ACE and 2004 Honda Odyssey without ACE had similar injury numbers for both the driver and passenger dummies. The vehicles demonstrated good performance in protecting the head, chest, and legs of the dummies in the PDB-XT offset test condition.

The Honda Odyssey with ACE had lower intrusion numbers than the Odyssey without ACE. The pedal axle intrusion values in the Odyssey without ACE were more than double that of the Odyssey with ACE. It is unknown why there was not an appreciable difference in the lower leg injury measurements.

Partner protection

The test results showed that structural differences between the two vehicles are detected by the PDB-XT in the offset test configuration (Figure 23). The 2004 Honda Odyssey without ACE barrier deformation was more localized and the left longitudinal frame rail (round yellow-orange coloration) and the vehicle's crossbeam are detected. In contrast, the deformation of the 2005 Honda Odyssey with ACE barrier was large and homogenous as identified by the graduated color change across its surface. The deformation was also wider and taller, protecting more of the front of the vehicle, and provided a broader reaction surface. The 2006 Honda Civic with ACE barrier deformation was consistent with the 2005 Honda Odyssey with ACE (Appendix A).



with ACE without ACE

Figure 23: Honda Odyssey Comparison of barrier deformation – Offset.

Figure 24 summarizes the partner protection parameters calculated for this test configuration. The AHOD values for the Honda Odyssey with and without ACE were within 1 percent of each other. This is consistent with USNCAP tests that similarly found the average height of force (AHOF400) values to be 450 mm, and 443 mm for the Odyssey with and without ACE, respectively [6]. The

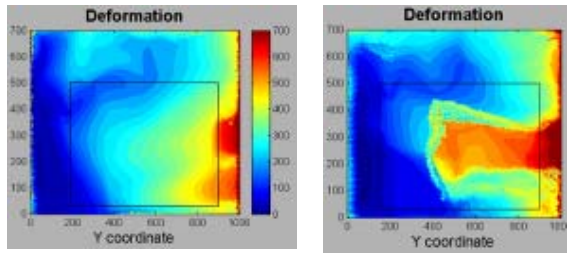
ADOD for the Odyssey with ACE was slightly higher but the Dmax was less. This is an indication the deformation was more uniform with the ACE structure.

Figure 24 also includes the results of earlier PDB offset tests with a 2005 Chrysler Town & Country unibody minivan and a 2003 Chevrolet Silverado body-on-frame pickup truck. For all four tests the AHOD values are similar. Of interest, Dmax was greatest in the 2004 Honda Odyssey without ACE and even greater than the Chevrolet Silverado. The Chevrolet Silverado was the stiffest vehicle in this series of tests as measured by KW400. It should be noted, the test weight for the Chevrolet Silverado and the two Honda Odyssey minivans were within about 50 kg. The Chysler Town & Country was almost 300 kg less than the Honda minivans.

	T&C	Silverado	Odyssey w/ACE	Odyssey w/o ACE
ADOD (X) (mm)	275	289	321	287
AHOD (Z) (mm)	404	414	397	401
Dmax (mm)	570	654	619	676

Figure 24: Comparison of Partner protection Parameters in the Offset Tests.

The barrier digitization showed the 2005 Honda Odyssey with ACE and the 2005 Chrysler Town & Country (Figure 25) produced a homogenous deformation in the barrier as indicated by the graduated color change across its surface and absence of abrupt color changes indicating increased penetration. The 2003 Chevrolet Silverado and 2004 Honda Odyssey without ACE produced more localized deformation at the location of the longitudinal frame rails. In prior series of tests, the 2003 Chevrolet Silverado and the 2003 Chrysler Town & Country were also crashed into a full width PDB-XT. The patterns of deformation between the full-width test and the offset test were also similar.



Town & Country Silverado

Figure 25: Comparison of barrier deformation – Offset.

NHTSA had also been evaluating the merits of a stiffness metric, KW400, in its compatibility research program [6]. As part of this research, NHTSA conducted four full frontal vehicle-to-vehicle crash tests using a 2005 Chrysler Town & Country, a 2003 Chevrolet Silverado, a 2003 Honda Odyssey without ACE and a 2005 Honda Odyssey with ACE. Each vehicle impacted a standard collision partner, the 2002 Ford Focus. In this series of tests all the striking vehicle's were ballasted to a test weight of 2,273 kg and struck the target vehicle with an impact speed of 71.8 km/h. A review of the KW400 metric obtained from full frontal USNCAP barrier tests for these vehicles would suggest that the Chevrolet Silverado is the stiffest vehicle, the two Odysseys are less stiff, and the Chrysler Town & Country is the least stiff vehicle. When looking at the acceleration at the center of gravity (CG) from the vehicle-to-vehicle crash test with the Ford Focus, however, the data suggests that the 2005 Honda Odyssey with ACE is the stiffest vehicle and the Chevrolet Silverado is the least stiff of the bullet vehicles (Figure 26).

	KW400 N/mm	Accel. At CG in Focus (m^2/s)	Accel. At CG in Striking Vehicle (m^2/s)
2002 Ford Focus	934		
Bullet Vehicles			
2005 Chrysler Town & Country	1,137	90.5	47.6
2003 Honda Odyssey w/o ACE	1,448	108	32.1
2005 Honda Odyssey w/ACE	1,456	113.5	40.3
2003 Chevrolet Silverado	1,619	86.2	32.9

Figure 26: Vehicle-to Vehicle Full Frontal Test Results Including USNCAP Computed Stiffness [8].

An examination of the post crash photos for these tests shows that the Chevrolet Silverado did not fully engage the frame rails of the Focus and actually pushed the frame rails outward (Figure 27). Photos from the Chrysler Town & Country test exemplified homogeneous loading on the Focus (Figure 28). In the photos of the Ford Focus crashed by the Honda Odyssey without ACE, it is evident that the Honda Odyssey overrode the Ford Focus frame rails (Figure 29) but the Honda Odyssey with ACE, provided homogeneous loading (Figure 30). A review of the barrier digitization of the four vehicles shows similar deformation patterns as the Focus.

Figure 27: 2002 Ford Focus Post Crash with 2003 Chevrolet Silverado.

Figure 28: 2002 Ford Focus Post Crash with 2005 Chrysler Town & Country.

Figure 29: 2002 Ford Focus Post Crash with 2003 Honda Odyssey without ACE.

Figure 30: 2002 Ford Focus Post Crash with 2005 Honda Odyssey with ACE.

The frontal crush profile of the Focus measured after the vehicle-to-vehicle tests is an indicator of the level of structural engagement between the vehicles (Figure 31). The 2005 Chrysler Town & Country test resulted in uniform deformation of the bumper on the 2002 Ford Focus. This was consistent with the results of the offset and full width barrier digitization analysis showing homogenous deformation in the barrier. The 2003 Honda Odyssey without ACE did not fully engage the 2002 Ford Focus and produced non-uniform crush. The 2005 Honda Odyssey with ACE produced more crush and uniform deformation when compared to the non-ACE test. This was also consistent with the offset barrier analysis. The crush profile of the 2002 Ford Focus after the 2003 Chevrolet Silverado test could not be measured.

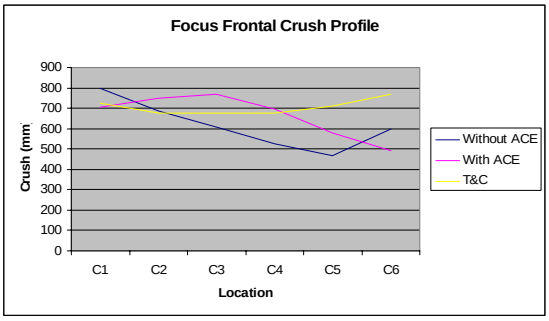


Figure 31: Focus Frontal Crush Profile at Bumper.

The higher stiffness of the Honda Odyssey and a more robust engagement with the 2002 Ford Focus appears to explain the higher acceleration at the CG in the 2002 Ford Focus when compared with the 2005 Chrysler Town & Country (the test weights for the striking vehicles were the same). In this same series of tests the 2005 Chrysler Town & Country experienced a higher acceleration at its CG compared to the stiffer 2005 Honda Odyssey with ACE. It also should be noted that 2003 Chevrolet Silverado and 2003 Honda Odyssey without ACE, which did not have good engagement with the 2002 Ford Focus, experienced the lowest acceleration at

the CG compared to the vehicles that showed good engagement. For all tests, the injury measurements were low for the striking vehicle. Furthermore, the accelerations at the CG provided a better indication of the interaction between the vehicles than relying on the dummy injury measures because it decoupled the occupant performance, which is subject to tuning of the restraint system from the forces the vehicle experienced.

Real-World Performance of ACE

The 2005 Honda Odyssey was the first vehicle released in the U.S. with ACE. Since that time Honda has been incorporating the ACE attributes into its vehicles as they undergo major designs. As of the 2009 model year, almost all Honda vehicles sold in the U.S. incorporate this new body structure philosophy.

A query of the 2005 through 2008 National Automotive Sampling System - Crashworthiness Data System (NASS-CDS) identified approximately 70 frontal crashes involving Honda vehicles with ACE. Almost all of the frontal cases identified were minor low delta-v crashes and did not significantly engage and crush the ACE structure. Also, at the time of the review, pictures for many of the 2008 cases were not published and the performance of the vehicle's structure could not be assessed. However a few cases shed some light on the real-world performance of the ACE design in the field.

For example, NASS-CDS Case No. 2007-04-0137 involved a 2006 Ford Escape and a 2005 Honda Odyssey with ACE. This was a relatively minor severity crash between two vehicles with a weight disparity. The 2006 Ford Escape weighted 1,545 kg compared to the 2,102 kg 2005 Honda Odyssey.

According to the case summary, the 2006 Ford Escape was traveling eastbound negotiating a left curve. The 2005 Honda Odyssey was traveling westbound negotiating a right curve. The front of the 2006 Ford Escape impacted the front of the 2005 Honda Odyssey with a CDC code of 01FYEW02. The principle direction of force with respect to the 2005 Honda Odyssey was 20 degrees. In this frontal oblique impact the total delta-v for the 2005 Honda Odyssey was estimated to be 15 kp/h. The frontal air bag in the 2006 Ford Escape did not deploy but deployed in the 2005 Honda Odyssey.

The 43 year old female drive of the 2006 Ford Escape and the 68 year old driver of the 2005 Honda Odyssey sustained minor injuries from the event. It was not known if the drivers were restrained.

Based upon the photos, the ACE structure appeared to have engaged the 2006 Ford Escape in a consistent pattern to what was observed in the PDB-XT tests (Figure 32). The upper corner ACE structural element that connects to the crossbeam crushed downward at the left tire and absorbed the energy of the Escape. This is similar to what was observed in Figure 16.

Given the weight difference between the two vehicles, the lighter 2006 Ford Escape did not experience significant damage (Figure 33). For this case the intrusion values were not measured by the NASS-CDS researchers, however, based upon an examination of the interior photos, any intrusion was likely insignificant.

Figure 32: NASS-CDS No. 2007-04-0137 – 2005 Honda Odyssey.

Figure 33: NASS-CDS No. 2007-04-0137 – 2006 Ford Escape.

Future considerations

The DSCR is developing a parameter to assess the homogeneity of the vehicle crush pattern using the barrier digitization analysis. It will be based on the shape of the deformation, discriminating between localized deformation and homogeneous deformation. This parameter has the potential to be

very useful in differentiating the crash characteristics between two vehicles.

In this testing, a load cell wall was installed behind the PDB-XT to measure the global front end force. The PDB-XT procedure is able to measure this force with a high level of accuracy. With further research, it could be used for evaluating self and partner protection. (See test results in Appendix B).

With regard to the real world analysis, due to the limited data available at the time, there were an insufficient number of NASS-CDS cases to fully explore the performance of the ACE structure in vehicle-to-vehicle crashes. NHTSA will continue to monitor NASS-CDS for new cases.

CONCLUSIONS

This paper is an extension of PDB research that was presented at the 2007 Enhanced Safety of Vehicles Conference held in Lyon, France [4]. It investigated whether barrier deformation using the PDB, intrusion, and dummy injury measures could differentiate compatibility performances between vehicles equipped with and without advanced frontal structures, designed specifically to address compatibility. It also evaluated criteria of self protection and partner protection in the offset frontal crash test configurations and then compared these results to those of vehicle-to-vehicle crash tests and real world crash analysis.

The barriers performed as expected and no bottoming out with these vehicles occurred. With respect to self protection, both Honda Odysseys had similar dummy injury numbers, but the 2004 Honda Odyssey without ACE produced higher intrusion results. The testing also demonstrated the ability to assess partner protection. The PDB-XT digitization analysis was able to differentiate between the homogeneous crush of the 2005 Honda Odyssey with ACE and the localized crush of the 2004 Honda Odyssey without ACE.

The ACE produced a homogeneous deformation to the PDB-XT barrier suggesting it would provide good horizontal and vertical engagement with a partner vehicle throughout the crash event. This was verified through the analysis of vehicle-to-vehicle crash tests and preliminary real-world crash investigations. An analysis of various compatibility metrics indicated that stiffness alone may not indicate aggressivity. Similarly, AHOD and/or AHOF values among vehicles may not insure a proper engagement of the front structure over the full course of the crash. This was particularly apparent in the 2003 Chevrolet Silverado and 2002 Ford Focus tests.

In this test series, broader and less localized PDB-XT barrier deformation indicated better structural engagement with a partner vehicle. It was found, however, that when a stiffness disparity occurs with better engagement, it can result in the partner vehicle unequally sharing the crash energy. The homogeneity of the barrier deformations also provides an indicator of the degree of uniformity of the vehicle's frontal stiffness. The analysis in this paper suggests that further evaluation is needed to address both the stiffness of a vehicle as well as the homogeneity of that stiffness.

ACKNOWLEGDEMENTS

Under the bilateral agreement between NHTSA and DSCR, resources were leveraged to carry out a joint research program on vehicle compatibility. Results and knowledge gained from this test procedure evaluation proved to be useful to both countries.

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APPENDIX A

2006 Honda Civic with ACE

Figure 34: 2006 Honda Civic.

2006 Honda Civic	
Test Mass	1,487 kg
Width	1,572 mm
Structure	With ACE

Figure 35: 2006 Honda Civic Specifications

Test severity - The amount of energy absorbed in the offset PDB-XT test was 59.3 kJ for the 2006 Honda Civic with ACE. The calculated EES for this test was 51.3 km/h, which is 9 km/h less than the test speed.

Self protection - In terms of self protection, the 2006 Honda Civic maintained good integrity of the occupant compartment space (Figure 36). There was a large amount of deformation of the longitudinal and lower load paths. Overall the front end crushed uniformly without any undeformed load paths. It should also be noted that the upper turret above the wheel that connects to the crossbar deformed down in front of the tire.

Figure 36: 2006 Honda Civic with ACE PDB-XT offset.

The injury measures for the 50th percentile male driver and passenger dummies are reported in Figure 37. The occupant injury measures were low.

	IARV*	Driver	Pass.
HIC36	1,000	428	263
Chest Def (mm)	50	30.8	36.4
Chest Gs	60	34.6	31.5
Left Femur (kN)	8	1.46	2.8
Right Femur (kN)	8	1.26	0.74
UL Tibia Index	1.3	0.31	0.43
UR Tibia Index	1.3	0.68	0.34
LL Tibia Index	1.3	0.30	0.30
LR Tibia Index	1.3	0.63	0.23

* As defined in UNECE R.94, except for Chest G's which is defined in U.S. FMVSS No. 208.

Figure 37: 2006 Honda Civic with ACE PDB-XT offset – Dummy Injury Measures

The calculated mean intrusion on the driver's side upper region (dashboard and A-pillar) was 27 mm and 57 mm for the lower region (pedal axle and footwell). The intrusion was localized in the footwell area (Figure 38). However, the driver's side dummy lower leg injury measures were not significantly affected.

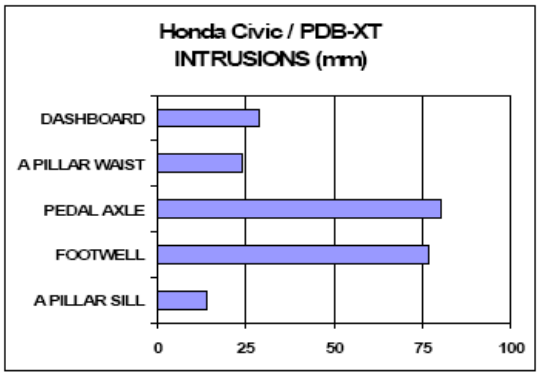

Figure 38: 2006 Honda Civic with ACE PDB-XT Offset – Driver Side Intrusions.

The maximum acceleration measured was 44 g at 77 ms, corresponding to 0.978 m of displacement (Figure 39). The average acceleration was 18.4 g.

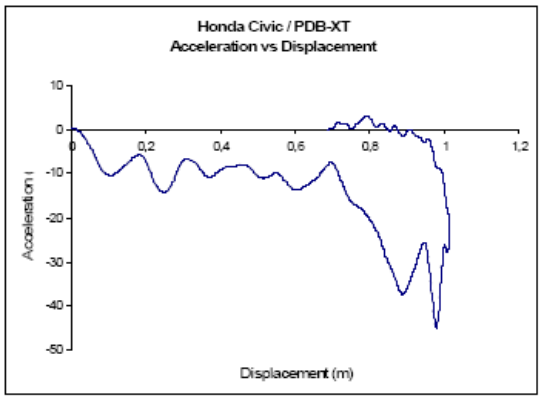

Figure 39: 2006 Honda Civic with ACE PDB-XT offset – Acceleration Pulse.

Partner protection - In the PDB-XT offset test, the forces generated by the longitudinal and lower load paths of the 2006 Honda Civic with ACE were distributed and crushed uniformly, resulting in homogeneous deformation of the barrier (Figure 40 and Figure 41). The two levels of load paths and connections between them created a large reaction surface for engagement with a partner vehicle. There was good engagement between the front of the vehicle and the barrier. No bottoming out of the barrier was observed.

Figure 40: 2006 Honda Civic with ACE PDB-XT offset – front end deformation.

Figure 41: 2006 Honda Civic with ACE PDB-XT offset – barrier deformation.

In Figure 42, the barrier was able to detect the lower load path of the vehicle. The calculated partner protection parameters based on barrier digitization analysis are presented in Figure 43. The energy absorbed in the barrier is 59 kJ that represented 28 percent of the total kinetic energy.

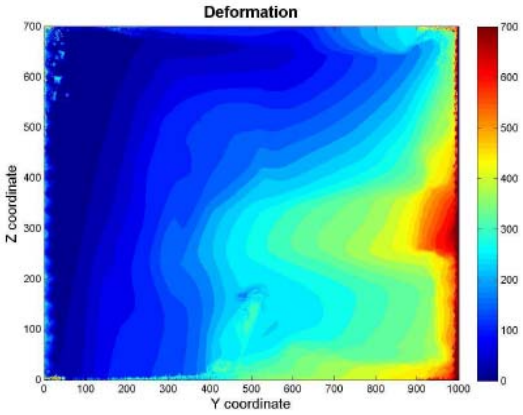

Figure 42: 2006 Honda Civic with ACE PDB-XT offset – barrier digitization.

Partner protection	
ADOD (X)	262 mm
AHOD (Z)	402 mm
Dmax	488 mm

Figure 43: Partner Protection Parameters for the Civic with ACE PDB-XT offset test.

APPENDIX B

Global force

PDB-XT Offset test (2005 Honda Odyssey with ACE) - The maximum global force was 463 kN at 1.078 meter displacement of the B-Pillar (Figure 44).

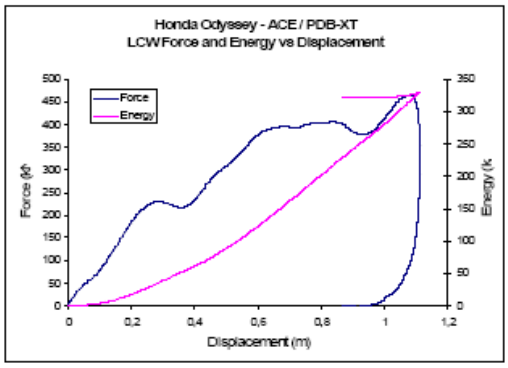

Figure 44: 2005 Honda Odyssey with ACE PDB-XT offset – Global force.

PDB-XT Offset test (2004 Honda Odyssey without ACE) - The maximum force was 476 kN at 1.183 m displacement of B-Pillar (Figure 45).

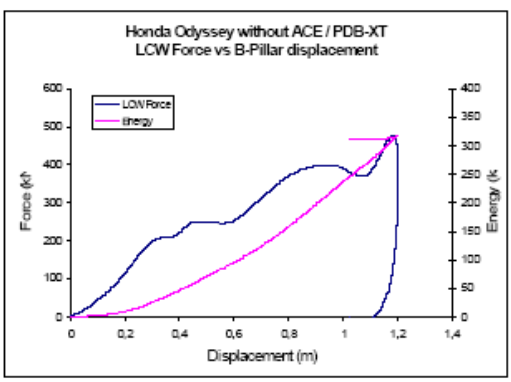

Figure 45: 2004 Honda Odyssey without ACE PDB-XT offset – Global force.

PDB-XT Offset test (2006 Honda Civic with ACE) - The maximum force was 363 kN at 1.002 m displacement of B-Pillar (Figure 46)

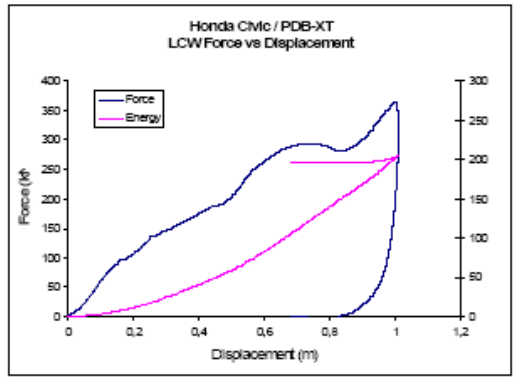

Figure 46: 2006 Honda Civic with ACE PDB-XT offset – Global force.