

Comparison of the Dummy Response in two different Restraint System Crash Tests

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Abstract In the European Project FIMCAR, a proposal for a frontal impact test configuration was developed which included an additional full width deformable barrier (FWDB) test. Motivation for the deformable element was partly to measure structural forces as well as to produce a severe crash pulse different from that in the offset test.

The objective of this study was to analyse the safety performance of vehicles in the full width rigid barrier test (FWRB) and in the full width deformable barrier test (FWDB). In total, 12 vehicles were crashed in both configurations. Comparison of these tests to real world accident data was used to identify the crash barrier most representative of real world crashes.

For all vehicles, the airbag visible times¹ were later in the FWDB configuration. This was attributed to the attenuation of the initial acceleration peak, observed in FWRB tests, by the addition of the deformable element. These findings were in alignment with airbag triggering times seen in real world crash data. Also, the dummy loadings were slightly worse in FWDB compared to FWRB tests, which is possibly linked to the airbag firing and a more realistic loading of the vehicle crash structures in the FWDB configuration. Evaluations of the lower extremities have shown a general increasing of the tibia index with the crash pulse severity.

Keywords frontal impact, crash test, restraint system, accident data, simulation

I. INTRODUCTION

In the European Project FIMCAR [1], a proposal for a more complete evaluation of frontal impact protection was developed. The recommended test configuration consists of the existing offset deformable barrier (ODB) test and an additional full width deformable barrier (FWDB) test. Motivation for the deformable element for the full width test was partly to measure structural forces in a condition similar to a car-to-car crash while minimizing the influence of inertial loads from the drive train in a high deceleration test condition. The full width test produces a more severe crash pulse different from that in the ODB test. Previous analyses of airbag deployment (firing) times based on real world accident data also showed the field sample had much longer fire times than seen in standard rigid barrier crash tests with full overlap [2-3].

Recent European and Japanese accident analyses have shown that many injuries are attributed to high acceleration and a large proportion of accidents involve high frontal overlap which typically produce high acceleration levels. Additionally, classic compatibility problems are still found for occupants of smaller cars who have a greater injury risk in car-to-car accidents with high mass ratios. The chest is the body region most commonly injured with older occupants and females in particular at higher risk [4].

Figure 1 shows the distribution by injury causation of MAIS 2+ injured occupants in frontal impacts analysed in [5]. It can be seen that most injuries occur either due to contact with the restraint system or contact with interior parts without significant intrusions into the passenger compartment. In addition to acceleration, the cause of contact injuries without intrusion can be vehicle rotation, missing the airbag, bottoming out, too soft load limiters or multiple collisions after the airbag and the seat pretensioner were deployed.

¹ Time when airbag is first observed in crash test video, used when airbag firing signal data are not directly measured in the test

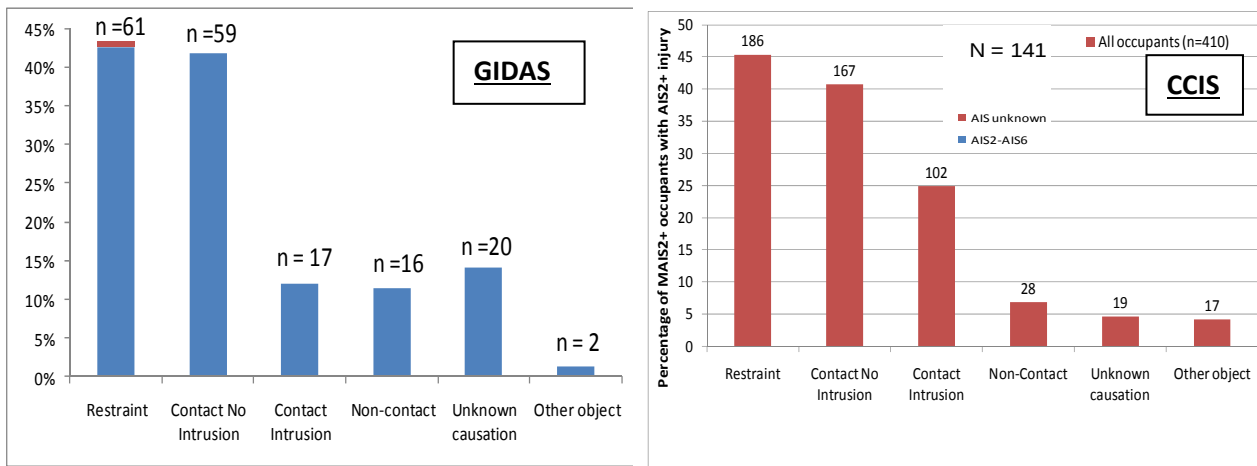


Figure 1 Percentage of belted MAIS 2+ injured occupants with AIS 2+ injuries grouped by injury causation category (left GIDAS, right CCIS data), [5]

Figure 2 shows the body regions commonly injured in frontal collisions in Japan [6] and the predominance of chest injuries at all severity levels can be observed. Accompanying data in this study highlighted the high number of injured occupants over 65 as well as a high proportion of injured females in the front seat passenger position. The Quasi- ΔV shown in Figure 2 is not the actual delta-V determined in in-depth accident analysis, but is calculated from police data and vehicle specification data. The Quasi- ΔV of car 1 is calculated by vehicle mass (m_1 , m_2) and travelling velocity (V_1 , V_2) as: $m_2 \cdot (V_1 + V_2) / (m_1 + m_2)$.

Passenger compartment intrusions have been greatly reduced in recent years due to the requirements of offset crash tests. However, a test procedure is needed which promotes a better restraint system addressing a range of crash pulses. The recommendation of EEVC [7] and IHRA [8] working groups on compatibility was to combine the full width and the offset tests in order to address intrusion and deceleration-related injuries.

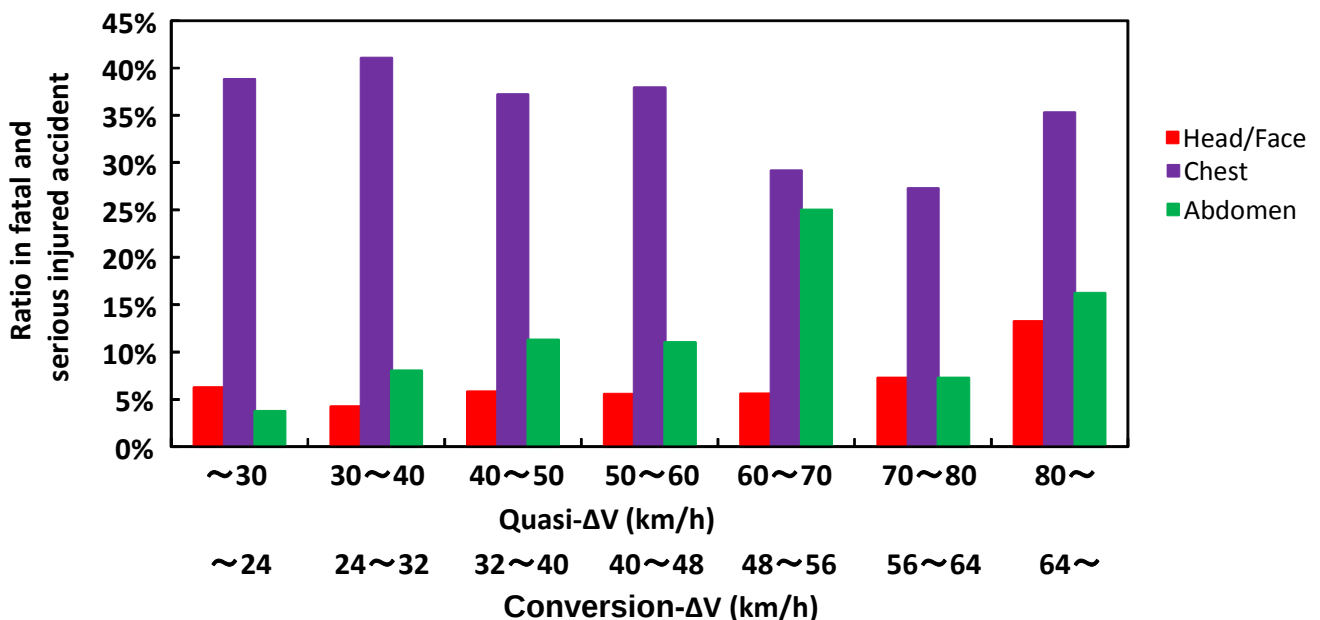


Figure 2 Distribution of injuries by body region and crash severity in Japan [6]

The aim of this study was to analyse the safety performance of European and Japanese vehicles in the standard full width rigid barrier test (FWRB) and to compare the crash test data against the full width deformable barrier test (FWDB). Comparison of these tests to available accident data was used to identify the crash barrier and restraint system evaluation most representative of real world crashes.

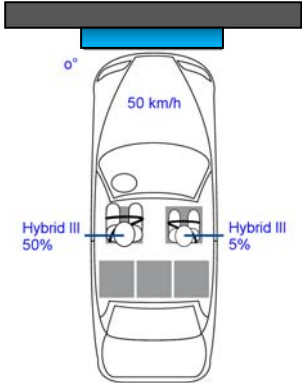
II. METHODS

In this paper several approaches are used to identify the differences between a full width test against the

rigid barrier (FWRB) and a full width test against the deformable barrier (FWDB). The deformable element used was developed in previous European research projects [9] and is 2000 mm wide, 300 mm thick and 750 mm tall. The height can also be 1000 mm depending on the vehicle size and height of the load cell wall. The deformable element has two layers, each 150 mm thick with different crush strengths. The first layer has 0.34 MPa axial crush strength and the second layer has 1.71 MPa crush strength honeycomb. A more detailed description of the barrier and the load cell wall to which it is mounted can be found in [10]. A series of crash tests with three European vehicle models, in total six tests, were conducted. In addition, a series of crash tests with three Japanese vehicle models (also six tests) were conducted as well but in a different test configuration (Table 1).

Table 1 Crash test matrix

		FWRB	FWDB
Driver HIII 50%ile / Passenger 5%ile	50 km/h	<i>Dacia Sandero</i>	<i>Dacia Sandero</i>
Driver HIII 50%ile / Passenger 5%ile	50 km/h	<i>Seat Ibiza</i>	<i>Seat Ibiza</i>
Driver HIII 50%ile / Passenger 5%ile	50 km/h	<i>VW Up!</i>	<i>VW Up!</i>
Driver HIII 50%ile / Passenger 50%ile	55 km/h	<i>Life</i>	<i>Life</i>
Driver HIII 50%ile / Passenger 50%ile	55 km/h	<i>Wagon R</i>	<i>Wagon R</i>
Driver HIII 50%ile / Passenger 50%ile	55 km/h	<i>Toyota Yaris</i>	<i>Toyota Yaris</i>



Results from these tests suggested that additional information was needed to completely understand the performance of the vehicle and its restraint system. Therefore, a comparison of airbag deployment and firing times with data from the crash tests and real world crashes was performed. Simulations with human body models were done with one Japanese vehicle model, which was also used for the crash test series, to analyze the thorax loading in more detail and to establish if the HIII dummies detect any loading differences between the barrier configurations. The Hybrid III AM50th dummy and the human FE model (THUMS version 3.0) were used in the simulations and were seated on the driver seat of a small car. The acceleration of the Toyota Yaris obtained in FWRB and FWDB tests was prescribed for the passenger compartment of a small car (the intrusion was not considered in the model). The airbag fire time was set based on the actual FWRB and FWDB tests.

To analyze and to compare the relevant IARVs (injury assessment reference values), the following limits (Table 2) were chosen in light of the current discussions in the UNECE Informal Working Group on Frontal Impact to modify the UNECE Regulation 94 [11]. The HIII 5th percentile dummy is not used in European regulation so IARVs were scaled in accordance with Mertz et al. [12].

Table 2 Injury assessment reference values selected for the Hybrid III 50th and 5th percentile dummies

	HIC [36ms]	Head acc 3ms	Neck moment	Thorax Deflection	Thorax Acceleration
HIII 50th	1000	80 g	57 Nm	42 mm	60 g
HIII 5th	1000	80 g	29 Nm	34 mm	60 g

To analyze the crash pulse of the different vehicles the acceleration of the B-pillar in the x-direction, filtered with CFC 60, was used. Based on that signal, the OLC (Occupant Load Criterion) was calculated in accordance with Kübler et al [13]. OLC predicts the relative motion of the dummy and vehicle and calculates the average acceleration experienced by the dummy when its position (relative to the vehicle) is in the interval between 65 mm and 235 mm. The OLC provides an indication of occupant loading without direct measurements from the dummy.

An additional analysis was done to investigate the differences on the loading of the dummy legs between the offset and full width test configurations. Therefore, crash test data from FWRB and ODB tests conducted in JNCAP from 2008 to 2012 were collected. The tibia index was calculated according to the JNCAP test protocol (FWRB test procedure FY2013 and ODB test procedure FY2013). In the JNCAP FWRB and ODB test protocols, the

intrusion is measured at three points (right, left and center) along the cross line² of the driver-side firewall and toeboard. In this study, the average of the three-point measurements was used to represent the intrusion into the passenger compartment.

Crash tests with European Vehicles (FWDB and FWRB)

For the crash tests with European vehicles, three “European” small vehicle models were selected: a budget vehicle (Dacia Sandero), a popular vehicle (Seat Ibiza) and a small vehicle with a new structure (VW Up!). All vehicles had generally the same standard safety equipment (seat belt pretensioner, load limiter, front airbags), but the Dacia Sandero was not equipped with a seat belt pretensioner. The test speed was 50 km/h with a HIII 50th percentile dummy on the driver seat in the mid position and a HIII 5th percentile dummy on the front passenger seat in the 25% longitudinal position³. The test weight was set according to UN-R 94 protocol.

Table 3 Details for the European vehicles

	Model	Test weight	Date of Registration	Engine	Gear box
Dacia Sandero	Essentiell	1171 kg	2012	1.2 l, 55 kW (front)	Manual
Seat Ibiza	“Reference” SC	1181 kg	2011	1.2 l, 44 kW (front)	Manual
VW Up!	“take up!”	1060 kg	2012	1.0 l, 44 kW (front)	Manual

Crash tests with Japanese Vehicles (JNCAP and FWDB)

The FWRB tests were introduced in Japanese regulations as of 1994 (test speed 50 km/h) and JNCAP tests as of 1996 (test speed 55 km/h). The Hybrid III 50th percentile dummies are seated in the driver and front passenger seats and the chest acceleration (3ms) is included in the regulation (≤ 60 g) and in JNCAP (linear rating scale: lower limit 38 and upper limit 60 g). Since ODB tests are also included in the regulation and in JNCAP, Japanese cars must meet both the chest acceleration and deflection in the FWRB and ODB tests. FWDB tests of some Japanese cars were conducted for research purposes. For the comparison of the Japanese vehicles in the FWDB and FWRB, data of two minicars⁴ and one small car were examined. The Honda Life (model year 2004) and Suzuki Wagon R (model year 2003) are Japanese minicars with curb masses of 880 kg and 840 kg, respectively. The Toyota Yaris (model year 2003) is a small car with curb mass of 920 kg. The test speed was 55 km/h and Hybrid III 50th percentile dummies were seated in the driver and front passenger seats.

Table 4 Details for the Japanese vehicles

	Model	Test weight	Date of Registration	Engine	Gear box
Honda Life	F	1052 kg	2004	0.659 l (front)	Automatic
Suzuki Wagon R	FX	1041 kg	2003	0.658 l (front)	Automatic
Toyota Yaris	F L Package	1091 kg	2003	0.997 l (front)	Automatic

Simulation study with human body models

The kinematic behavior of the occupants was further analysed using simulation models of the Toyota Yaris. A FE Model of the passenger compartment and the restraint system was available. The crash pulse and the trigger times for the FWRB and FWDB tests were taken from the actual crash tests. The Hybrid III 50th percentile dummy and the THUMS model (Version 3) were used as occupants.

Analyses of airbag fire times from real world crash data

As previous research had indicated differences between the real world triggering of restraint systems and the trigger times observed in crash tests [3], real world data were collected from the Event Data Recorder (EDR) data available from the NASS⁵ program. EDRs are standard on many North American vehicles and these

² The cross line is the intersection line and this is the boundary between the floor plane and the firewall plane.

³ The longitudinal seat position was set between the middle and most forward positions.

⁴ Japanese Minicars are also known as Kei cars in Japan and have limitations in regard to size (length ≤ 3.4 m, width ≤ 1.48 m, height ≤ 2.0 m) and engine displacement (≤ 0.66 l)

⁵ National Automotive Sampling System administered by the National Highway Traffic Safety Administration in the US

electronic recording systems record, among other variables, vehicle velocity changes and airbag firing times. Vehicles of model year 2003 and later experiencing frontal impacts (PDOF -330 to 30 degrees) and delta Vs greater than 30 km/h were collected from the NASS website. OLCs were also estimated from the data and used to compare the supplemental restraint (airbags and seatbelt pretensioners) deployment/visible times for the crash tests and real world crashes.

III. RESULTS

Crash tests with European Vehicles (FWDB and FWRB)

In Figure 3 the fronts of the three European vehicles are shown after the crash tests. The crash structures are loaded in a different way in the FWDB test procedure compared to the FWRB. The cross beam was bent at mid span while the low speed crash cans and the longitudinal members were not fully loaded. The deformation pattern produced from these, and other FWDB tests, is similar to car-to-car crash tests [14] as opposed to the flat and even damage distribution in a FWRB test.

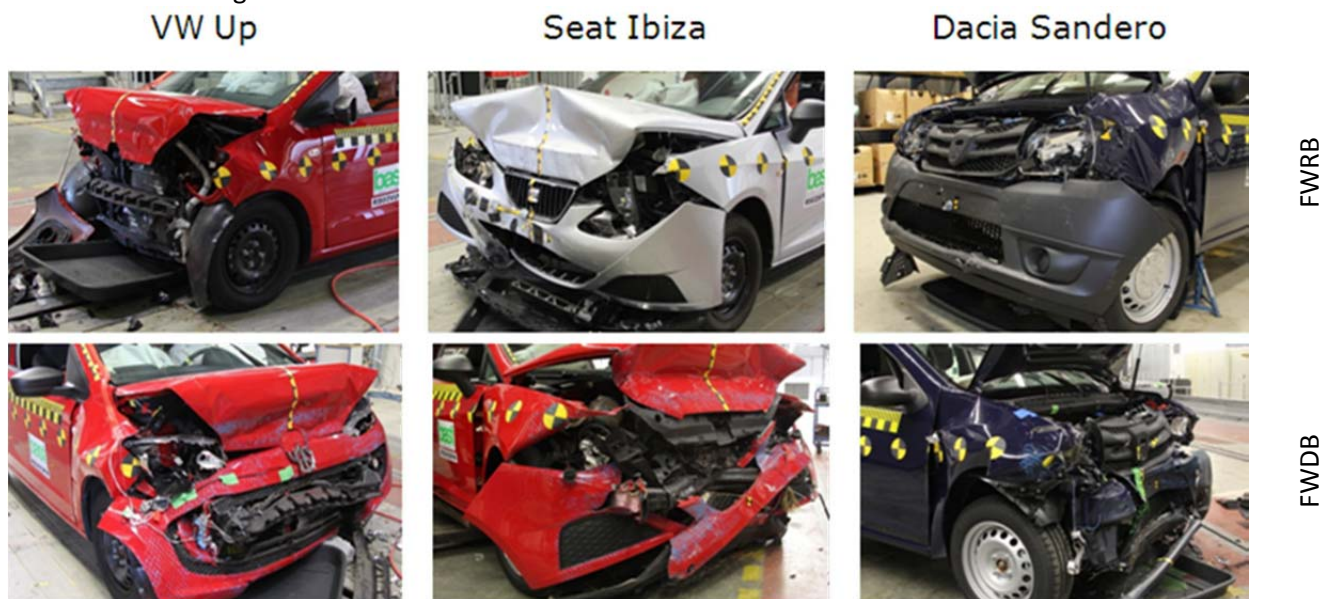


Figure 3 ¾ view of the front of the European vehicles tested in FWRB (top) and FWDB (bottom)

In Figure 4 the vehicle acceleration, velocity and OLC calculated are shown for the three European vehicles. The vehicle acceleration was highest for the VW Up! with a maximum value of 55 g and relatively low for the Dacia Sandero (30 g). In regard to the pulse shape, all three vehicles had higher initial accelerations at the beginning of a FWRB crash than in the FWDB test. It is interesting that the Dacia Sandero did not have a pronounced initial peak at the beginning of the crash, compared to the Seat Ibiza and VW Up!, and the accelerations remained relatively constant for the whole crash event. It could be assumed that the Dacia Sandero was not developed for the full width test but rather only for the ODB test. Both the Seat Ibiza and the VW Up! exhibited noticeable acceleration peaks at the beginning of the crash in the FWRB configuration followed by a second peak, containing the maximum crash accelerations, approximately 20 to 30 milliseconds later. That initial peak is not observed in the FWDB configuration. The OLC was lowest for the Dacia Sandero and much higher for the VW Up!, consistent with the peak accelerations observed in both cars.

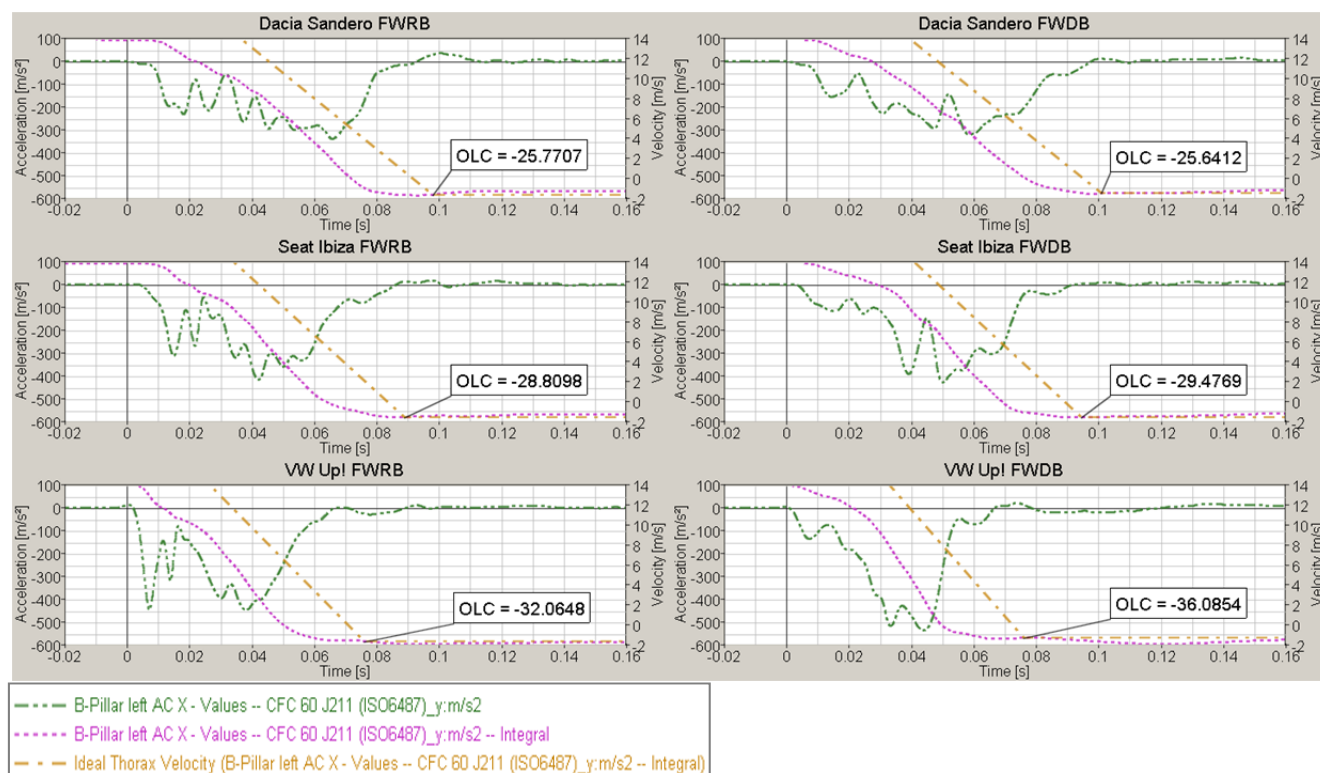


Figure 4 Vehicle acceleration (b-pillar, x-direction, driver side), velocity and OLC for Dacia Sandero, Seat Ibiza and VW Up

Airbag visible times were later for all vehicles in the FWDB configuration than for the FWRB, see Table 5, as there was no acceleration peak in the beginning of the crash to encourage deployment. The difference in firing times was greatest for the VW Up!, less noticeable for the Seat Ibiza and minimal for the Dacia Sandero. This can be observed in Figure 4 by noting the differences between the pulse shapes for the FWRB test (left) and FWDB test (right). The airbag firing times are dependent on the pulse characteristics at the start (first 20 ms) of the crash.

Table 5 Airbag times for the European vehicles

		Dacia Sandero	Seat Ibiza	VW Up!
Airbag visible	FWRB	22	18	12
Airbag visible	FWDB	25	29	24

The measured IARVs from the driver dummy in the European vehicles are shown in Figure 5. Although no full width test is required in Europe, all vehicles are below the legal limits of the UN-R 94, even with the proposed 42 mm chest deflection. Note that thorax acceleration is not a performance criterion included in the regulation. Comparing the FWRB versus the FWDB, there were slightly higher injury risk values in the FWDB tests in particular for the Seat Ibiza and the VW Up!. The Dacia Sandero seemed to be less sensitive in regard to the two test configurations having the smallest change in both IARV and airbag visible times.

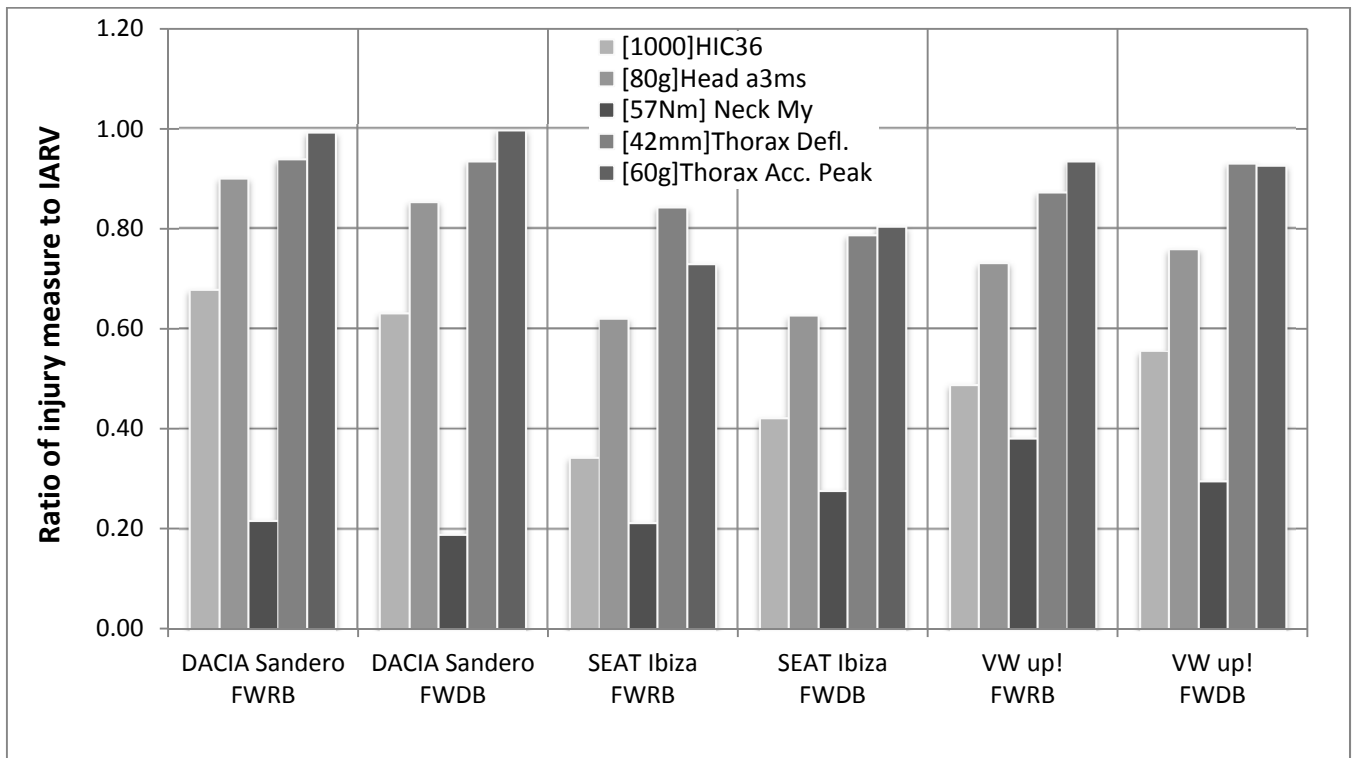


Figure 5 Driver dummy relative IARVs for the European vehicles FWRB and FWDB according to Table 2

The evaluation of belt routing was difficult from high speed videos. However, the inboard camera showed a shoulder belt routing close to the neck for all vehicles. In one vehicle, submarining was observed on the front seat passenger side. Reasons for the submarining are likely due to the 25% position of the front passenger seat in the longitudinal direction and due to the fact that the vehicle was probably not designed for this test and dummy configuration.

Crash tests with Japanese Vehicles (FWDB and FWRB)

The Japanese cars in FWRB and FWDB tests are shown in Figure 6. Japanese domestic minicars do not have crush cans because there are no damage evaluation tests with a low test speed, contrary to the situation in Europe. The three tested cars have a simple structure with front rails and cross beam, although not necessarily connected at the same vertical position. In the FWRB test, the front-end of the front rails were folded in the three cars. The Suzuki Wagon R did not have a bumper cross beam and its tall and narrow front rails penetrated the honeycomb in the FWDB test. The engine and other structures were pushed rearward by the honeycomb leading to larger intrusions into the passenger compartment compared to the FWRB tests.

Honda Life

Suzuki Wagon R

Toyota Yaris



Figure 6 3/4 view of the front of the Japanese vehicles tested in FWRB (top) and FWDB (bottom)

Test data from Honda Life, Wagon R and Toyota Yaris (acceleration shape, velocity and OLC calculated) are presented in Figure 7. Although the vehicles are from a different market (and accompanying legislative requirements) than the vehicles tested in Europe, similar trends could be observed. The similarities are important to note in light of the fact that Japanese regulations include a FWRB test so that the crash pulses in Figure 7 represent vehicles with explicit design requirements to address a FWRB. The pulses in Figure 4 reflect vehicles without an explicit requirement for FWRB testing and represent the designs directed by the company's internal requirements. The European vehicles may be modified for international markets but pulses in Figure 4 can be considered as an indication of general vehicle design, independent of the FWRB. However, it can be assumed that the European vehicles are specifically designed for the Euro NCAP offset test.

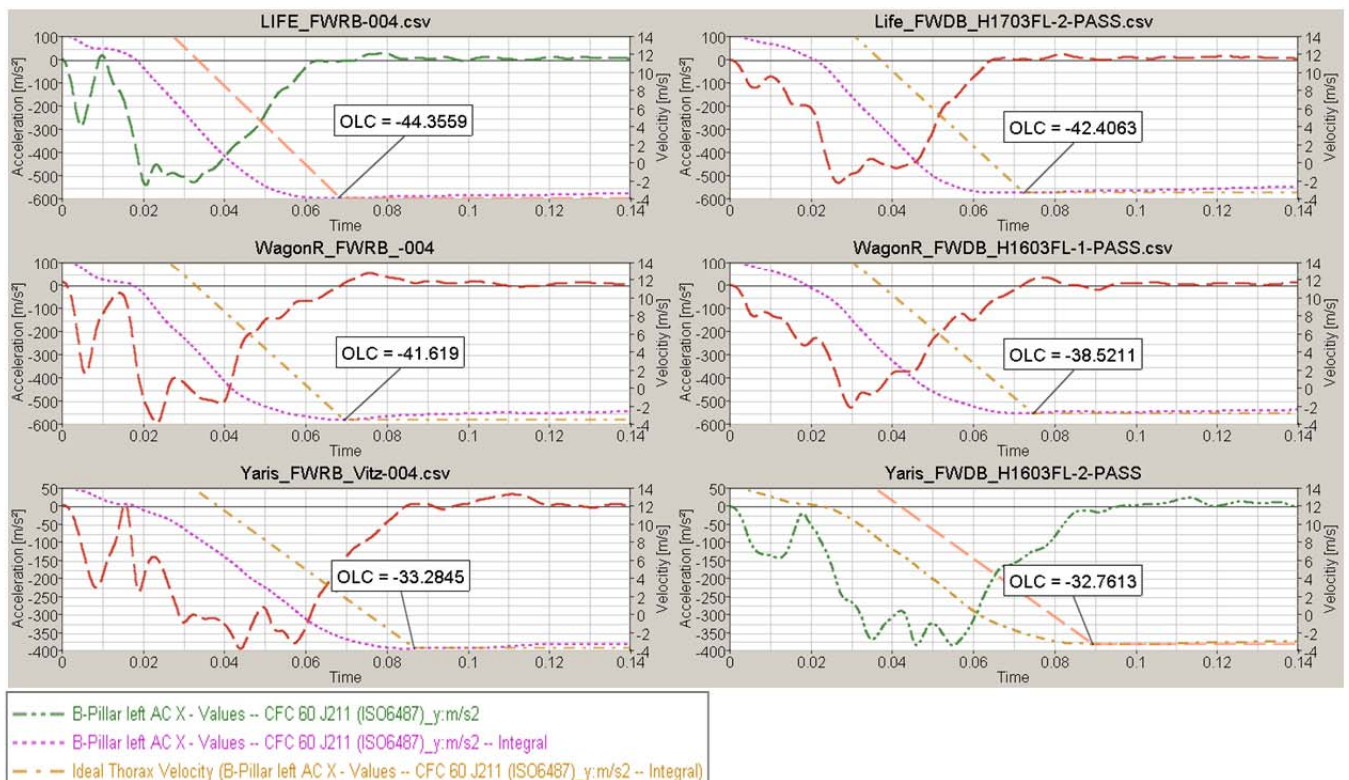


Figure 7 Vehicle acceleration (b-pillar, x-direction, driver side), velocity and OLC for Life, Wagon R and Toyota Yaris; FWRB (left) and FWDB (right)

The pulses in the FWRB case (left side Figure 7) again exhibit the same early peak as the European vehicles. This peak is influential in the triggering of the airbag and it is again evident that the FWDB modifies the pulse from the FWRB case, especially the first 20 ms which are critical for the airbag deployment algorithm. The vehicle with the least difference in the pulse between the tests (Yaris) had the smallest change in deployment times (Table 6). The Suzuki Wagon R was the most affected with the change in barrier face and exhibited the largest change in deployment times. The late seatbelt pretensioner trigger time of the Suzuki Wagon R in FWDB tests caused large dummy loading and high chest acceleration. Due to the airbag deployment delay, the HIII dummy moved forward and the neck shear force in the forward direction was applied on the chest, which resulted in large shoulder belt tensile force and chest deflection. This trend was obvious for the Suzuki Wagon R FWDB test because of high vehicle deceleration and later airbag deployment.

The Toyota Yaris is the most similar to European vehicles of those tested in Japan. The Suzuki Wagon R and Honda Life are classed as minicars, unique to the Japanese market, and have greater OLC numbers than the European vehicles tested. Accordingly, the Japanese minicars had higher loadings on the dummies due to their high deceleration pulse, which likely resulted from their limited front end length.

Table 6 Airbag visible times for the Japanese vehicles

		Honda Life	Wagon R	Toyota Yaris
Airbag visible	FWRB	14ms	16ms	16ms
Airbag visible	FWDB	24ms	28ms	22ms

In Figure 8 the dummy loadings for the Japanese vehicles are shown, expressed as the ratio of injury measure to IARV. Here, the trend of higher numbers within the FWDB test is more obvious than was seen for the European vehicles. In particular the two minicars had much higher IARV numbers and even above the limit for the thorax deflection (note: here the proposed 42 mm is used). The Toyota Yaris seems to be more robust in the two test scenarios.

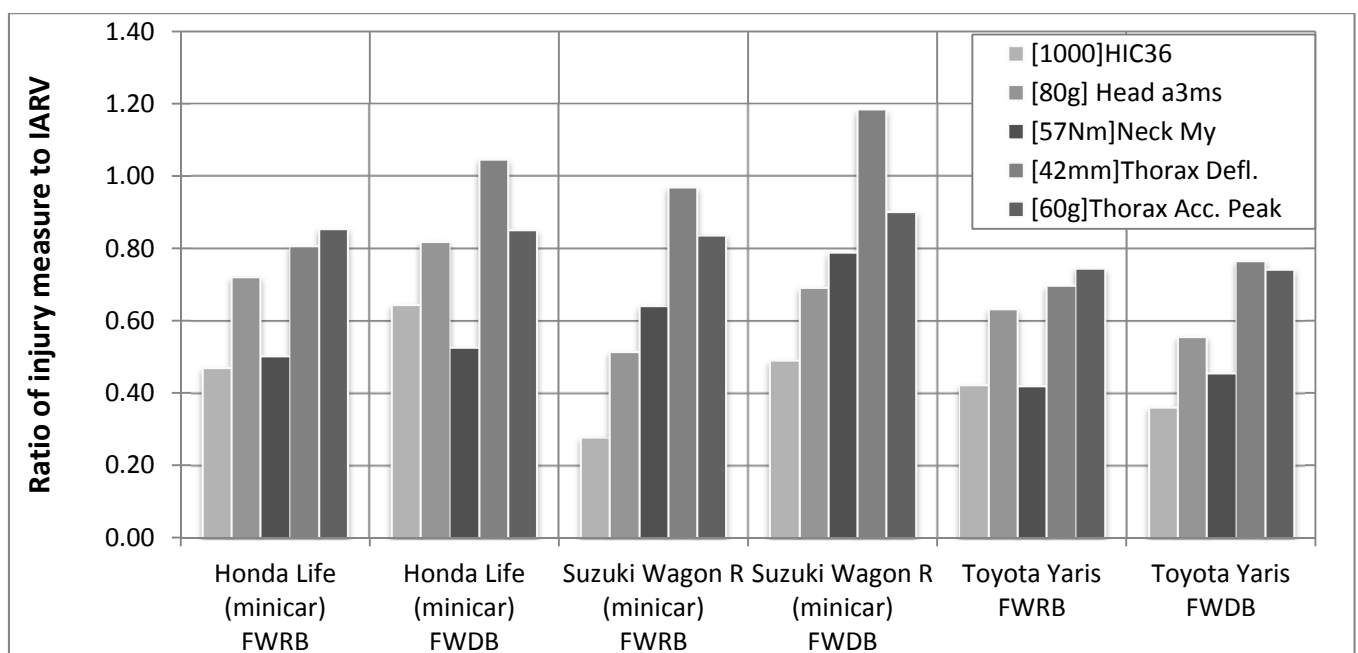


Figure 8 Driver dummy relative IARVs for the Japanese vehicles FWRB and FWDB according to Table 2

In Figure 9, a one-to-one comparison of the crash pulse in the different test configurations (measured close to the B-pillar) is given for each vehicle. Interesting to note is that for some vehicles (VW Up!, Suzuki WagonR, Honda Life) a very strong initial peak up to 40 g was measured in the FWRB configuration which was not the case in the FWDB configuration. The Japanese vehicles had a more noticeable relaxing of the initial peak in the FWRB, returning to 0 g. This unloading behavior was not as prominent in the European vehicles.

The airbag visible (or deployment time) is also presented with the acceleration data in Figure 9. It is clear that the FWRB trigger times (dotted vertical lines) occur during or shortly after the initial peak and always earlier than 25 ms. The FWDB pulse, due to its lower initial accelerations, extends the deployment time of the airbag

compared to the FWRB test condition.

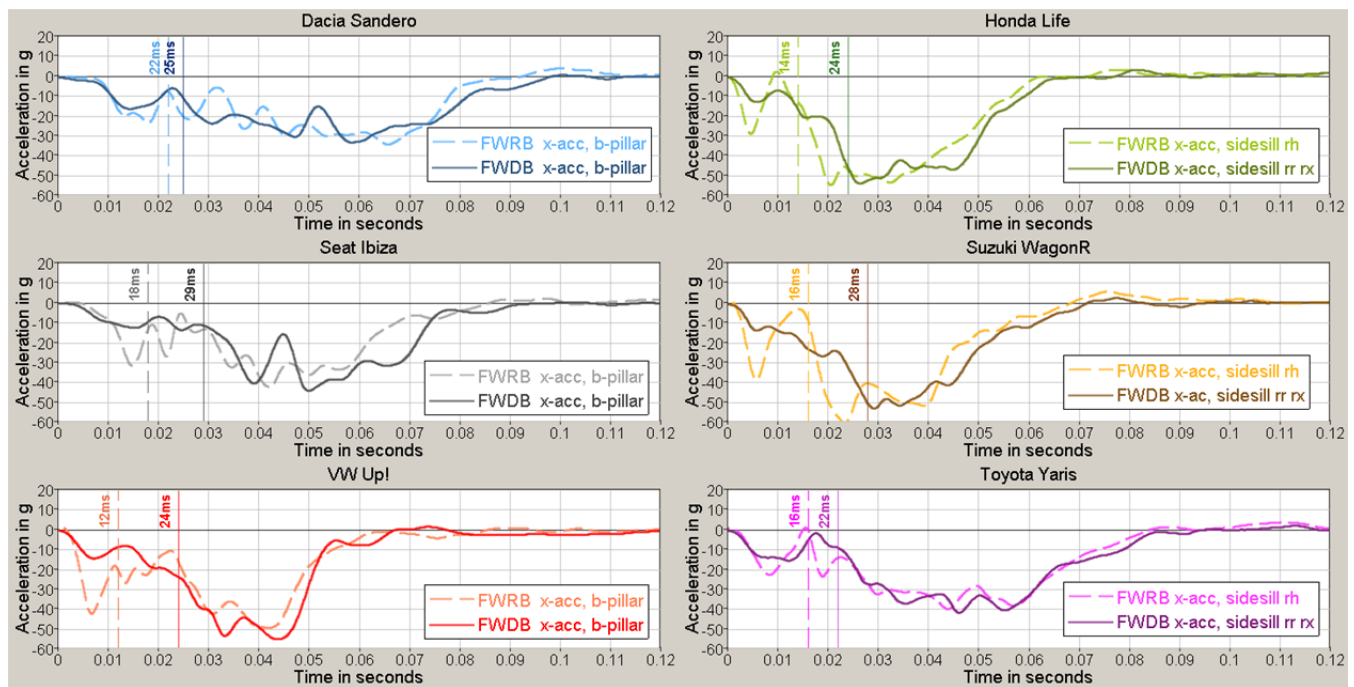


Figure 9 Overlay of crash pulses for one-to-one comparison FWRB and FWDB including the airbag visible times

Simulation study with human body models

A simulation study was conducted with the Toyota Yaris to compare the kinematic differences and the chest loading in the FWRB and FWDB test configurations. Figure 10 shows the side view during the different simulations. Note that the simulations used the same interior and restraint system design but were not exact replicas of the tested vehicles. The pulse and airbag trigger information from the tests were used as inputs but the model is only for research purposes and cannot be considered accurate enough for commercial design. However, the use of identical models allows for comparison between the test cases.

The simulations were used to identify if different crash loadings, introduced by the different barriers, can be detected with the mechanical crash test dummy. There are differences noted in the pulse (as described earlier) but are they significant enough to actually produce different biomechanical responses in a human?

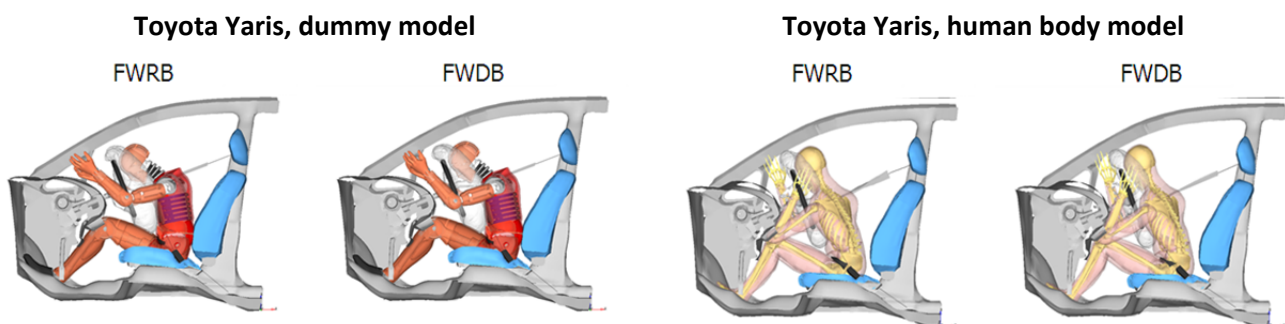


Figure 10 Kinematic analyses of the dummy HIII 50th model and the THUMS model to compare the Yaris in FWRB and FWDB

The simulation results in Figure 10 show the HIII response and THUMS human body simulation. In general there are few differences observable among the dummy or THUMS simulations when they are reviewed as two separate groups. However, it should be noted that there are noticeable differences between the mechanical and human based simulations. The THUMS model exhibits longer forward travel and a different spine response. The HIII has a more rigid thoracic spine and chest. The THUMS spine is more flexible and displays more rotation about the vertical axis which is nonexistent in case of the HIII. Thus, it could be that the dummy is not appropriate to evaluate the injury risk in both tests.

In the simulations, the compartment was intact and intrusion was not considered. Only the acceleration for

the compartment was provided. The airbag visible time was determined from the video of the crash tests, and reflected in the FE model as airbag visible time and seatbelt pretensioner activation time. With the intrusion of the compartment, the kinematics of the lower extremities and the pelvis could change.

Although the human and mechanical dummy models behaved differently, they both exhibited one similar trait – there was little difference in the thoracic response for the different (rigid/deformable) barrier types. The THUMS model does not have a deflection sensor analogous to that in the HIII and different parameters must be used to compare chest deflections. Biomechanical chest criteria are still under development for human body models but comparison of rib strain (note similar strain levels in Figure 11) or general chest deformations in the THUMS model did not identify any significant differences in the occupant response for the different barrier types.

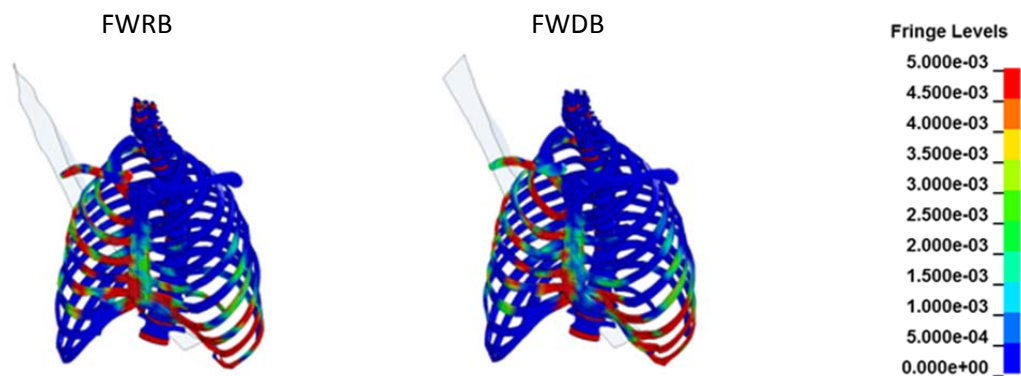


Figure 11 Rib cage strain for the THUMS in the Toyota Yaris model comparing FWRB and FWDB

Analyses of airbag fire times from real world crash data

The results presented previously show that there are small differences in the occupant response for different barrier types. The main difference noted was that the airbag deployment time was always later for the FWDB. To understand the significance of the airbag deployment time, a review of the available real world crash data with the EDR data from NHTSA was undertaken. These data are unique in that both crash pulse and airbag firing times are recorded.

Previous research [3] presented the results of real world crashes and the discrepancies between deployment times in crashes or tests. This approach was used to further investigate test data reported above. Niehoff et al [15] demonstrated that EDRs were quite accurate, using crash test instrumentation as a reference, when reporting delta V in laboratory crash tests (generally less than 10%). They reported some small time shifts between the signals but the EDRs were able to capture the essential crash information in their limited recording systems.

It is important to understand the times reported for airbag deployment in EDR data in order to properly compare the data to crash test results. Figure 12 shows the key steps in crash detection and airbag deployment. The airbag algorithm first informs the EDR when a signal reaches a “wake up” threshold to initiate a deployment decision. The EDR records and reports the time from actual “wake-up” to deployment, not from the first contact when initial accelerations may be experienced by the vehicle but not enough to “wake up” the EDR recording. Thus, the EDR can only record data after initial contact has been made and results in non-zero values at t=0 for the EDR signal. It is difficult to estimate the time related to crash detection since it is so dependent on the contact characteristics of the structures. The time shift required to align EDR and test instrumentation [15] ranged from -47 to +10 ms for FWRB tests but most EDRs seem to be 2 to 3 ms slower than the reference signal. The deployment times (activation to time visible) of airbags also vary with the model and probably range from 3-5ms. It would not be unreasonable to assume that EDR underestimates airbag deployment times by at least 5 ms and this error could be much higher when car-to-car impacts are concerned.

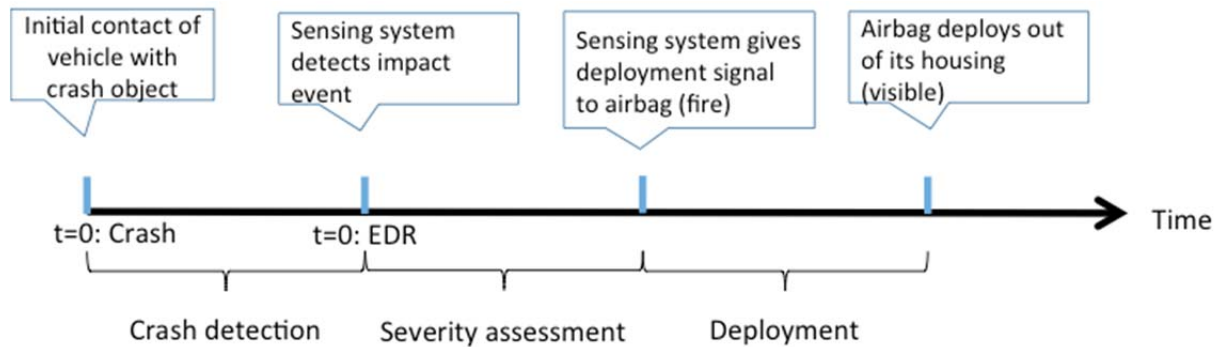


Figure 12 Key time references in airbag sensing and EDR recording

Figure 13 shows the velocity-time curves for full width frontal crashes available from NASS compared to those from FWDB (solid line) and FWRB (dotted line) tests and simulation results for two different vehicle models. There were no available pulses from NASS that were the same ΔV and comparable damage as a full width test. While [15] reported no significant phase shifts in EDR data, Figure 8 contains several EDR pulses that have significant deceleration at $t=0$. This can be attributed to the way the EDRs are triggered and synchronize their time bases (Figure 12).

It is important to note the low initial slope of the real world (EDR) crashes. It was shown earlier that the FWRB pulse has a first peak before 20 ms. This peak is not typical in the FWDB and is totally absent (no sudden changes in gradient) in the EDR pulses collected. The early part of the pulse has a strong influence on the airbag deployment times as seen in the German and Japanese test data. The FWDB in Figure 4 and Figure 7 tend to be closer to the EDR pulses than FWRB pulses in that they do not have high initial slopes or peaks. However, all the test data have steeper slopes than the real world pulses in the first 40 to 50 ms.

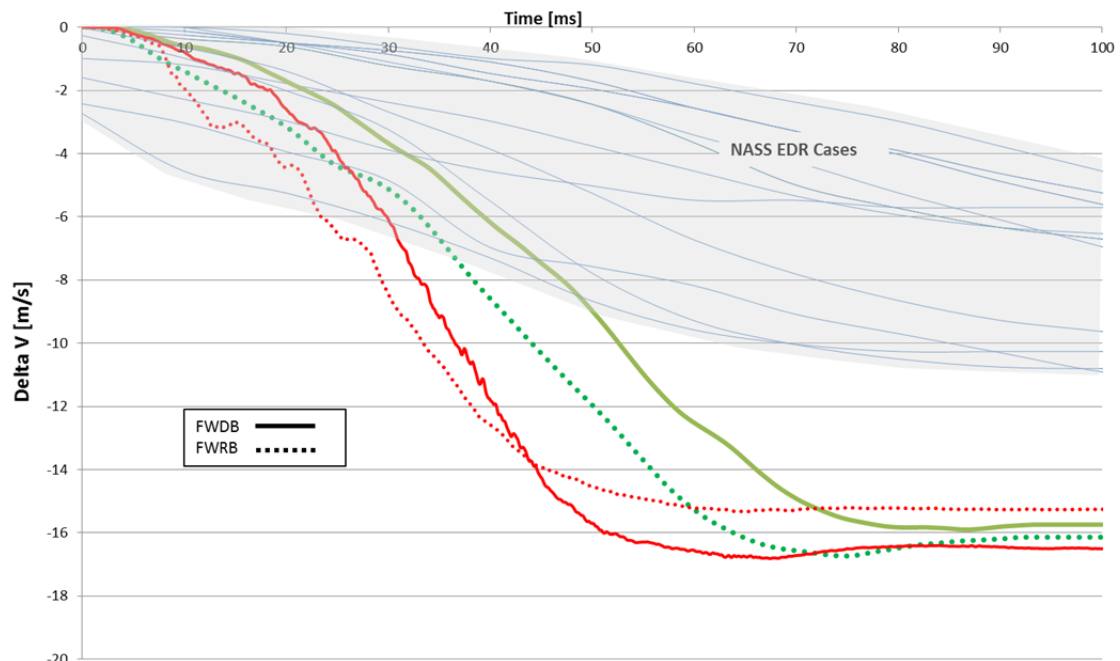


Figure 13: Delta V profiles for typical FWDB, FWRB and EDR Information from NASS

To further investigate the relationship between pulse and airbag deployment, Figure 14 shows the airbag deployment times for both test and real world crashes. The values are plotted with OLC to provide a connection to the results presented in Figures 4 and 7. The use of OLC allows the severity of the pulse to be connected to the deployment times. It is important to remember the time estimation error discussed with Figure 12. As a result, all the EDR cases can be considered “conservative” in that the actual deployment times must be longer due to both initial detection delays and subsequent deployment times for the restraint system. Figure 14 shows clearly that the FWRB cases, as a whole, have the earliest deployment times compared with the FWDB for a given OLC. There is quite a spread (10 to 40 ms) in the EDR deployment times but they tend to be later than

both FWDB and FWRB times, especially if the phase lag is included by increasing the EDR times by at least 5 ms. The cause for this difference in deployment times has to do with the initial interaction of the vehicles with the collision object. The FWRB causes the crash loads to build up directly while the FWDB requires the vehicle to deform enough of the first, softer, layer before crash loads will rise to levels detectable by the sensing system. In the real world, vehicles are generally not interacting with homogeneous barriers but usually with non-homogeneous collision objects. This produces the wide variance in the deployment times as the structural interaction of the colliding objects will determine how quickly the sensing system can detect the crash and decide when to deploy the airbags. Note that none of the vehicles were designed for the FWDB and that the firing times may be different if the FWDB would have been a regulation.

The airbag deployment or firing times can be seen to vary most in real world crashes; there is less variance in the FWDB, and even less variance is noted for the FWRB.

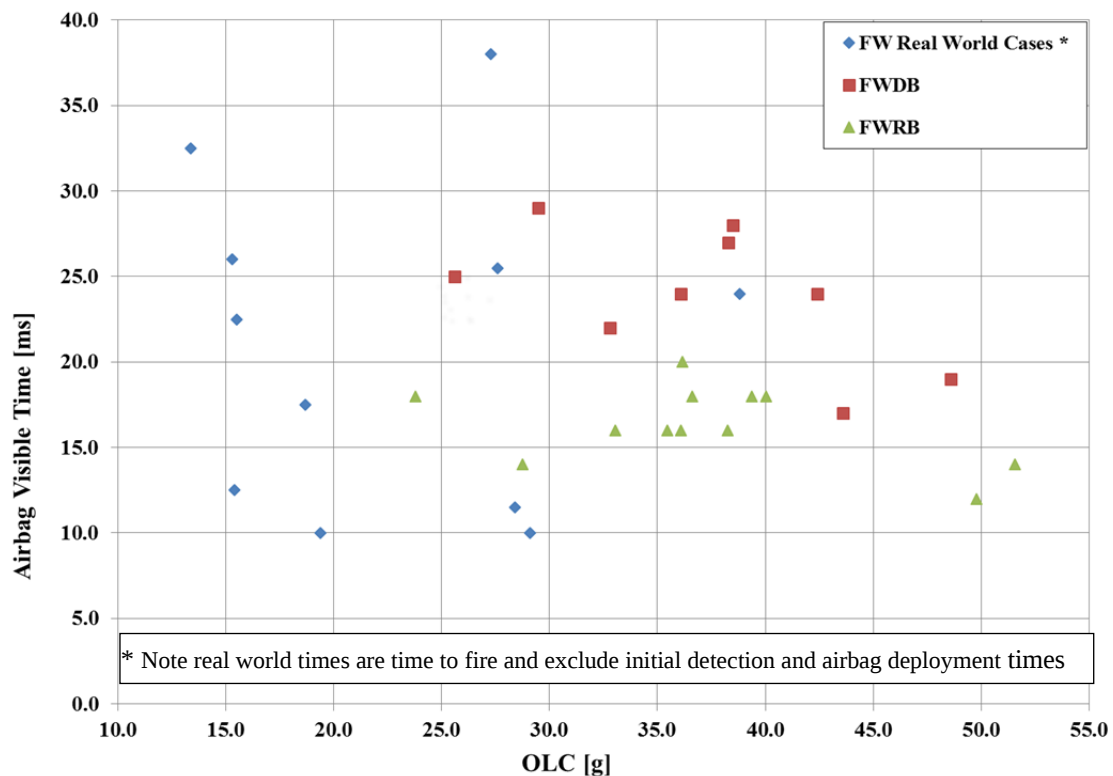


Figure 14 Dependence of Airbag Deployment Time on OLC

Analyses of tibia index

The tibia index is a criterion to evaluate the fracture risk due to bending and axial loading of the tibia. It has been shown that the tibia index depends on the intrusion into the passenger compartment. However, there is little research of the suitability of the tibia index in full width tests. Figure 15 shows the tibia index in FWRB, FWDB and ODB tests. Basically, the tibia index has a linear relation between the FWRB and FWDB tests though the tibia index in FWRB was extremely high in one car (Figure 15 (a)). The tibia indices in FWRB and ODB tests are compared in Figure 15(b). In many cars, the tibia index was higher in FWRB than in ODB tests, especially for minicars which are more likely to have high vehicle accelerations. The tibia indices in FWRB tests are shown to be dependent on the vehicle acceleration (measured in OLC) and the firewall intrusion measured after tests, Figure 15 (c) and (d). The tibia index tends to be higher with increasing OLC whereas there is a little trend between the tibia index and the intrusion. On the other hand, in the ODB tests (Figure 15 (e) and (f)), the tibia index is more related to the intrusion than the vehicle acceleration.

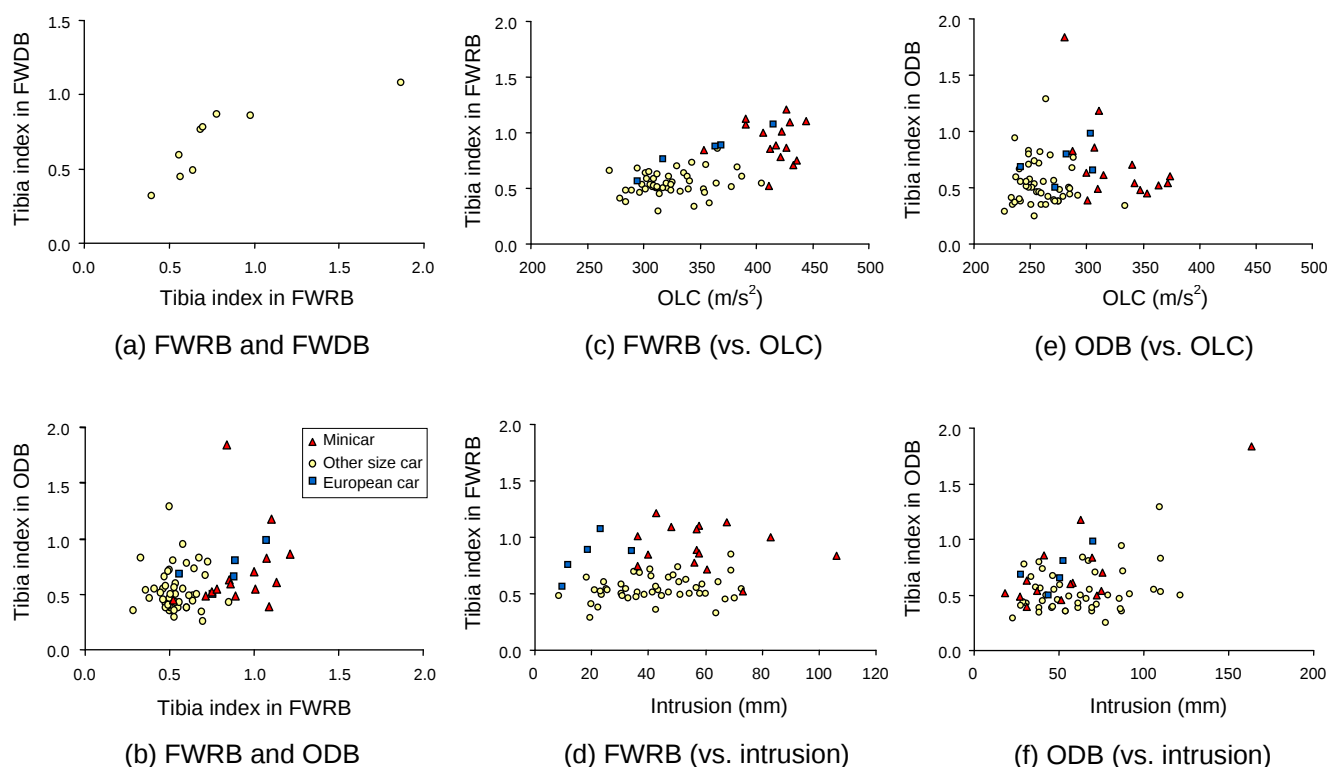


Figure 15 Tibia index, OLC and intrusion measurements in FWDB, FWRB and ODB tests (FWRB and ODB test data were from JNCAP 2008-2012)

IV. DISCUSSION

There have been several recent activities reviewing the requirements for frontal impact protection, particularly in Europe, where there is no requirement for a full width crash test if the vehicle can meet all the requirements specified in the UN R-94 ODB test. The FIMCAR project and UNECE Informal Working Group on Frontal Impact have been reviewing the full width test with and without a deformable barrier face. The study herein provides a comprehensive review of the performance of both barriers and suitability for assessing occupant protection.

A total of six vehicles have been reviewed in matched tests between the FWRB and FWDB. The most interesting result is the lack of significant differences in occupant response. Although there is a tendency for the occupant to have higher injury risks in a FWDB test, the differences are for some vehicles quite small and not of a magnitude that would clearly identify one procedure over the other.

The pulse severity, indicated by OLC, was slightly higher in the European FWDB tests than in FWRB tests while the opposite seemed to hold for the Japanese minicars. The Japanese minicars are a special design and it is not clear from this sample if the results of the minicars can be used to predict the performance of all the Japanese fleet. Interestingly, both European and Japanese vehicles had, in general, higher dummy measurements in the FWDB. There does not seem to be a monotonic relationship between OLC and injury severity, at least not for the sample of vehicles studied, as the Japanese minicars had higher OLC in the FWRB. Interesting to note is that analyses of the OLC with crash tests from a USNCAP test in Eickhoff [16] have shown that most OLC values were between 30 g and 40 g, while minicars tested in JNCAP had frequently an OLC above 40 g.

Although the HIII dummies used in crash tests showed only small differences between the barrier types, the HIII is not a human and may not be able to fully detect changes between test conditions that may be relevant for a human. THUMS modeling was used to conduct a paired analysis of the dummy and human response in these two crash test types. Even with a presumably more sensitive human model, there was no clear result that could identify the FWRB as being better or worse than the FWDB for future crash regulations in terms of injury criteria. The main injuries of interest are those to the thorax and all the tests and modeling work indicate that there is little difference between the two tests. However, the IARV used here indicate that in all tests the thorax

loading was more severe and closer to the limits than the other body regions. This is consistent with the accident studies reporting a higher frequency of chest injuries than other body regions and suggests that chest injury criteria in legislation should be reviewed to be more in line with real world conditions.

The most significant finding in the study was the relationship between airbag deployment timing and crash configuration. The results in Figure 13 show that the latest times for airbag deployment are those in the real world, followed by the FWDB and then the FWRB. In all cases a FWDB had a later deployment time than the FWRB and may be an issue for further investigation. A review of real world crashes shows that the initial crash phase is not characterized with high acceleration peaks as seen in a laboratory test. The reasons for this are almost totally explained by compatibility. The FWRB is the extreme case where one can consider that all vehicle structures will be able to contact and react with a matching component in the homogeneous hard face. The FWDB is also homogeneous but the deformable face delays the build-up of a crash pulse, thereby delaying the restraint system deployment. The worst cases are found in real traffic where it cannot be guaranteed that a collision partner will always provide a matching, stable reaction surface. Without the establishment of structural interaction, airbag sensing systems must wait until sufficient forces can develop to the point they can be detected, leading to the later deployment times observed in NASS data. The FWDB is more attractive as a full width test candidate if it can be used for compatibility assessment of a vehicle. FIMCAR promoted the FWDB as the best test to improve structural engagement of the structures. Unfortunately there is no compatibility metric that is being reviewed for rulemaking and the FWDB has no obvious advantages in terms of injury assessment. Therefore, it is difficult to promote the FWDB over the FWRB for frontal impact protection.

The performance of vehicle restraint systems relative to airbag visible times needs to be more thoroughly reviewed in the future. There was a clear trend in the Japanese tests that delaying the deployment time increased the injury risk. Mizuno et al. [17] reported that later airbag visible times have been observed in particular for minicars. The European tests had little or no change when the OLC and deployment times increased when changing test conditions from rigid to deformable barriers. The European vehicle with the largest change in OLC and deployment times also exhibited submarining and the chest loading was less severe due to the suboptimal belt routing. The data suggest that airbag deployment times are a critical factor that may explain some of the reasons that real world injury distributions are more severe than laboratory test results would indicate. Follow up on the airbag timing-occupant injury risk is also needed to determine why chest injuries are still common despite the longstanding passive safety requirements in all countries.

The feet and the knee can be caught by the dashboard and footwell due to the initial high deceleration in full width tests. After the introduction of the ODB tests in ECE R94 and NCAP tests, the passenger compartment has become stiff and there are only a few cases where the passenger compartment collapsed and a high tibia index and high femur force occurred. It is likely that in the current cars with high passenger compartment strengths, the tibia index may be more affected by the vehicle deceleration and not by the passenger compartment intrusion. It is necessary to investigate the tibia injuries in real world accidents as well as the mechanism of the tibia injury caused by the vehicle deceleration pulse and ensure that this is not an artifact of the dummy's inertial properties.

The data suggest that pulse shape and restraint deployment strategy are important components for occupant protection in frontal impacts. The real world data demonstrate a large variation in pulses and deployment times. These variations are essentially impossible to address without some type of restraint adaptability. One countermeasure is to provide more predictable pulses in the real world which is a goal for compatibility researchers. More predictable pulses reduce the range of conditions a restraint system must address. This was observed in the tests because vehicles with similar pulse shapes for the two barriers had similar OLCs, deployment times and IARVs. Achieving robust performance in different crash configurations requires more design requirements than occupant response data, such as structural performance evaluations, which are not addressed in any regulation or consumer test today. This can only be achieved if the compatibility test procedures are linked more closely to real world conditions. This suggests that the FWDB is a better tool for assessing and promoting compatibility, and thereby frontal impact protection, than the FWRB.

V. CONCLUSIONS

The aim of this study was to analyse the safety performance of European and Japanese vehicles in the standard full width rigid barrier test (FWRB) and the full width deformable barrier test (FWDB). Real world

accident data were used to identify the crash barrier and restraint system evaluation most representative of real world crashes.

The FWDB is more realistic with regard to airbag visible times and structural loading of the vehicle's front, as seen in car-to-car crashes. IARVs of the dummies were in general higher in the FWDB test configuration. This was most likely due to the later airbag visible times and the different pulse shape. However, no huge differences with regard to the dummy loadings were seen between FWRB and FWDB. The change of IARVs seen with the FWDB, compared to the FWRB, was greatest for Japanese Mini Cars which also had the largest change in OLC and airbag deployment times.

The IARVs used here indicate that in all tests the thorax loading was closer to the limits than the other body regions. This is consistent with the accident studies reporting a higher frequency of chest injuries than other body regions and suggests that chest injury criteria in legislation should be reviewed to be more in line with real world conditions.

The firing times in real world cases had a much higher variance than either of the test configurations (range), and occur later compared to FWRB and FWDB. Pulses in real world crashes are in general lower in terms of severity (Δv). Additionally, the peak in the beginning of the crash event as seen in the FWRB test was nonexistent in the real world crash data. Crash tests have showed that the dummy loadings were in general worse in FWDB compared to FWRB, which is possibly linked to the airbag firing. It is still unknown if it is due to pulse shape or due to the visible times but likely a combination of both parameters.

The analyses of the JNCAP test data regarding the loading of the legs has shown that the tibia index was proportional in the FWRB and FWDB test configurations. It was further demonstrated that the tibia index was often higher in the FWRB test compared to the ODB test. However, the tibia index increases in the ODB test with the passenger compartment intrusions whereas the tibia index increases within the full width test with the crash pulse severity.

Simulations have shown that the HBM has a more complex interaction with the interior than the HIII. Due to the more flexible behaviour, occupant kinematics for all body regions are different. It is important to consider how chest injuries can be addressed with HBMs or new mechanical ATDs like the THOR, but keep in mind the influence on other body regions. There is a need to further correlate specific injury criteria from the dummies to real world data and re-evaluate the threshold values used in legislated crash tests. There is a discrepancy between laboratory results and accident statistics, particularly for chest injuries, that needs to be corrected. The simulations have shown no major differences in occupant chest loading when FWRB and FWDB simulations are compared.

The variance in real world loading conditions requires robust safety systems. This can be achieved both by more advanced restraint system design, but even by developing more compatible crash structures that reduce pulse variability. The different barriers explored suggest that the FWDB is better at reproducing real world deformation and airbag firing times than the FWRB. One step toward this is the FWDB's possibility to further develop the potential to measure forces with a load cell wall in order to establish a requirement for a common interaction zone and improved compatibility.

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