FRONTAL IMPACT PROTECTION: APPLICATION OF AN UPGRADED CHEST INJURY CRITERION - THE EQUIVALENT DEFLECTION (DEQ)

Daniel Cerdan,
Richard Zeitouni,
Céline Adalian
PSA Peugeot Citroën
France
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ABSTRACT

The equivalent deflexion (Deq) is a new criterion foreseen to be used in Euro NCAP to better assess the chest protection in frontal impact. It has the particularity to discriminate the contribution of two parameters on chest deflexion:

- contribution of the seat-belt (with a small surface of load application, which is damageable for the occupant),
- contribution of the airbag (with a larger surface of load application, which is more acceptable for the occupant).

Such a criterion will help car manufacturers to design adequate restraint systems with an appropriate combination of airbag and seat-belt to better protect the vulnerable occupants.
To better understand this new criterion, PSA Peugeot Citroën launched a study to quantify the performances of its current vehicle platforms with respect to the Deq.

Physical tests were analysed on different car platforms with several restraint systems characteristics. Each time, the Hybrid III rodpot and the shoulder belt load were recorded and analysed.
This analysis shows that the sensitivity and reproducibility of the Deq measurements are equivalent than the Rodpot ones.

Because the Deq criterion needs the chest deflexion measured on the Hybrid III rodpot and the shoulder belt load, there are some questions raised by other researchers about sensitivity of Deq and about the pertinence of Deq with respect to Rodpot.

This question is investigated for a nominal restraint system as proposed in Peugeot and Citroën cars. This was done via Design of Experiments made with HIII 50th and HIII 5th models respectively in ODB 64 km/h and Full-width rigid test 50 km/h. The outcome is that for good restraint systems already built to be protective (load limitation less than 5kN), Deq would prevent to use combination of relative high load limitation with very soft airbags, contrary to Rodpot.
But this study is just at its initial phase because of time constraints, because not all the biomechanical criteria were analysed (eg. neck load and moments) and because only one vehicle was investigated. Therefore, we would suggest carrying out the same analysis for restraint solutions widely different than ours.

INTRODUCTION - AIM OF THE STUDY

Self-protection of car occupant is a crucial topic all over the world. Restraint systems have to be designed to protect various sizes of occupants involved in several type of crash and therefore several types of crash pulses.
Frontal impact on a rigid obstacle are the most severe impacts with respect to change of velocity (deceleration) sustained by the occupants.
This test configuration will be used worldwide in the near future (already in China, Japan, Korea, USA [1] + possible new regulation on frontal impact and Euro NCAP 2015[2]). It will also be used with a more demanding level of protection in order better protect vulnerable users.
One of the crucial body segments is chest, with the injury coming from chest compression. But the current dummies in use (Hybrid III 50th and Hybrid HIIII 5th) are criticized because of two main reasons:

- chest compression is measured via the rodpot sensor that is sensitive to seat belt path
- injury thresholds were built on old restraint systems (belt only, no airbag loading) and therefore they do not represent the actual risk sustained in case of a combined loading

Indeed, the seat-belt is a restraint offering a small surface of load application, which is more damageable for the occupant that the airbag and its load application spread on a larger surface. For a same level of force, a localized loading is more damageable that a spread one.

To overcome these critics and because the next generation of frontal impact dummies is not available yet, a new criterion, called equivalent deflection (Deq) was designed [3] and recently upgraded [4].

This criterion, Deq, is foreseen to be used by Euro NCAP for its new full-width rigid frontal test (0°, 50 km/h) that will be applicable from 2015 [2].

The purpose of our research is to better understand how Deq works and what would be the consequence of designing a restraint system with Deq compared to a restraint system designed with Rodpot only.

Before going into the details of this research, it is worth to define the formula that will be used throughout the paper.

PARAMETERS DEFINITIONS AND THRESHOLDS

As presented in [4] Deq formula (Deq linear) is somewhat complex and needs to be computed via a macro to exactly reflect its scientific origin. But as a first order approach Trosseille et al. [4] also proposed a simplified formula where Deq is simply a combination of maximum seat belt force and maximum Rodpot deflection. This is the formula used in this research

Deq definition and formula as used in this research

The simple equation used for Deq, as given in [4], is:

$$Deq = 3.5*USBF + 0.84*Rodpot \quad (1).$$

Where:

- « USBF » is expressed in kN and is the maximum seat belt load measured on the upper part of the diagonal strap.
- « Rodpot » is expressed in mm and is the maximum chest deflexion measured by the rodpot on the Hybrid III dummy.

Thresholds used to compare the performances of Rodpot and Deq

Even if we talk about "deflection" for Rodpot as well as Deq, we cannot say that both are directly comparable. Indeed, the 1 mm of Deq is not equivalent to 1 mm of Rodpot. Therefore, to compare the two criteria, we decided to use the performance thresholds that are currently discussed within the Euro NCAP Frontal Impact Working Group. The following tables (Table 1 and Table 2) present the thresholds used respectively for Rodpot and Deq.

Table 1.
Performance thresholds used to calculate a chest score – Rodpot thresholds for the 2 dummies

Rodpot thresholds	HIII 50th	HIII 5th (Hypothesis)	Score
Lower performance	50	41	0pt
Higher performance	22	18	4pts

Table 2.
Performance thresholds used to calculate a chest score – Deq thresholds for the 2 dummies

Deq thresholds	HIII 50th (Hypothesis)	HIII 5th (Hypothesis)	Score
Lower performance	61	50	0pt
Higher performance	32	26	4pts

Between the lower and higher performance thresholds, the score is calculated via sliding scale. Therefore, if we want to target a 3 points score on chest we should aim at the following values (see Table 3).

Table 3.
Rodpot and Deq target for a 3pts performance for each of the 2 dummies

Criteria value to reach 3pts	HIII 50th	HIII 5th
Rodpot	29	23.75
Deq	39.25	32

Now the main parameters and thresholds have been defined, we will start the analysis with an assessment of the scattering and the reproducibility of the two criteria.

SCATTERING AND REPRODUCIBILITY OF DEQ AND RODPOT MEASUREMENTS

Method

Using our database of Euro NCAP type test (frontal ODB test 64 km/h with HIII 50th driver and passenger), we compared tests carried out on the same car model. Some tests were carried out at the same crash test lab, and others were carried out in a different lab. Therefore we can assess the overall reproducibility of the measurements.
Several car models were analysed.
Finally, to compare the Deq results with the Rodpot ones, we used the sliding scales as described in Table 1 and 2.
Again, Deq is computed via Eq 1.

Results

Figure 1 presents the results. Each colour represent a car model coupled to an occupant (driver or passenger) and the rodpot score (in colour) is compared with the associated Deq score.

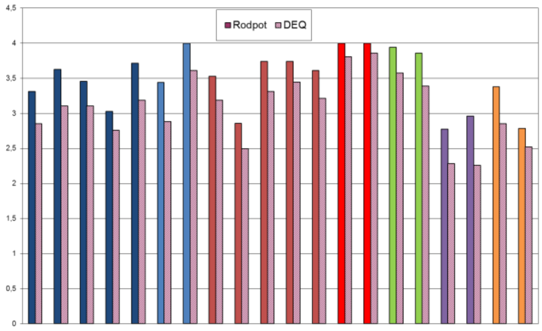

Figure 1. Comparison of Rodpot score and Deq score on several car models and occupant.

Comparing the results of a same colour provides an assessment of reproducibility.

First of all, looking at the average score of each car model/occupant (Figure 2) allow us to show that the assessment was made on cars having a wide variation of performance but always at the level of good cars (we are not looking at poor performers, but at current cars designed to be good (5 stars) in Euro NCAP). The Rodpot score goes from 2.9 pts to 4 pts.

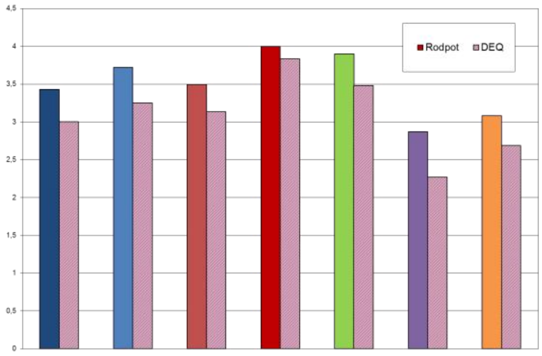

Figure 2. Average score for Rodpot and Deq for each couple car model / occupant

Now, in order to look at the scattering, we can have a look at the delta of measurement for each couple car model / occupant. Figure 3 presents the average scatter for each couple, for Rodpot and for Deq score.

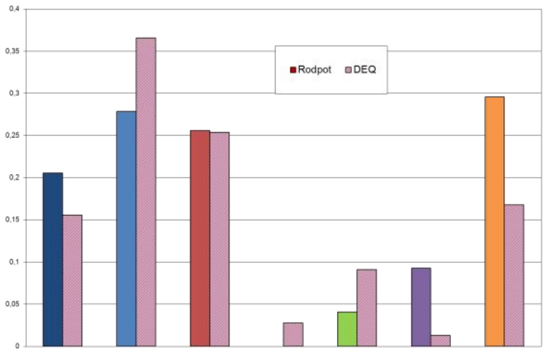

Figure 3. Average scatter in the Rodpot and Deq scores for each couple car model / occupant

It is good to recall our aim: is the Deq more scattered than the rodpot? With this set of data, no clear conclusion can be made. Both seem to be scattered in the same way.

Looking at the absolute scatter (max score - min score) for each couple under study, as shown in Figure 4, there is no additional trend to highlight.

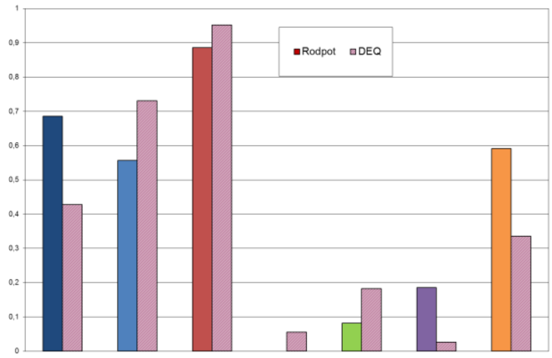

Figure 4. Absolute scatter (max score – min score) for Rodpot and Deq scores for each couple car model / occupant

A final check could be to look at the relative scatter, in order to erase the fact that lower score will give by definition lower scatter. This is presented in Figure 5. The relative scatter is reckoned as the absolute scatter (figure 4) divided by the average scatter (figure 3).

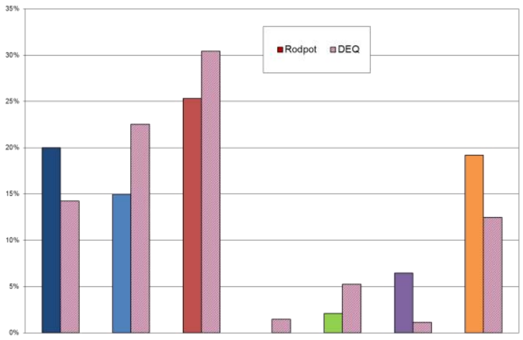

Figure 5. Relative scatter for Rodpot and Deq scores for each couple car model / occupant

With Figure 5 we can say that whatever the performance of the car, both Rodpot and Deq are scattered by about the same amount.

Conclusion on scattering

We analysed a set of results taking current car models tested in the Euro NCAP ODB test, using driver and passenger dummies, and using tests carried out in different labs, or in the same lab but with different dummies. Looking at the scatter of these results, one can conclude that the overall reproducibility of Deq is of the same magnitude than the Rodpot one. Nothing shows than Deq is more sensitive to scatter than Rodpot, even if some people were stressing this problem because of the external measurement needed to reckon Deq (upper diagonal belt load).

Even if it was not the main purpose of the assessment, it is interesting to stress that the score reached by the Rodpot is always better than the one reached with the Deq. This is shown in Figure 1 and Figure 2. But Figure 6 show it even more obviously.

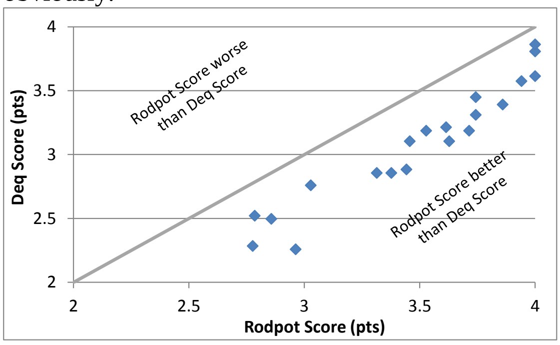

Figure 6. Deq Score as a function Rodpot Score

We already recalled that Deq was made to discriminate seat-belt only loadings from seat-belt + airbag loadings. This should give incentive to lower load limitations that will be beneficial for vulnerable occupants.
In order to highlight this fact, we can analyse our set of results (measured on current cars) with a last point of view: we can look at the seat-belt score with respect to chest score measured with Rodpot or with Deq. This is given in Figure 7.

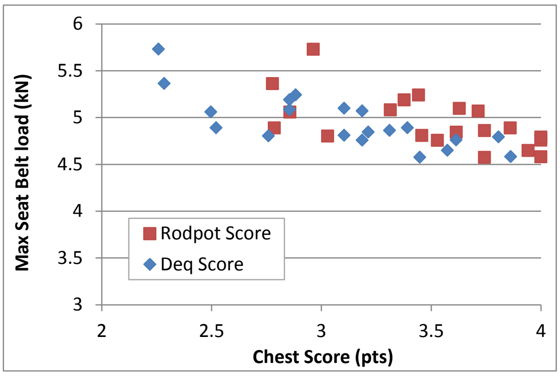

Figure 7. Maximum seat belt load measured in our set of results expressed as a function of chest score reckoned respectively via Rodpot or via Deq

For sure we have cars that reaches good results (chest score >3 pts) but they are assessed only in ODB 64 km/h test and with the HIII 50th dummy. The question is now to know if there would be other restraint systems characteristics that would get the same level of score, but taking into account full-width test and HIII 5th and 50th.

This is what is presented in the next part of our research.

DESIGN OF EXPERIMENTS TO COMPARE DEQ AND RODPOT AND TO STUDY THE PARAMETERS INFLUENCING THESE TWO CRITERIA

Method

The purpose of this chapter is to quantify the restraint system characteristics that could influence Rodpot and Deq.
For this study, we used numerical model (Madymo) widely used to design restraint systems.
The model was correlated on physical tests (full scale and sled tests).
The model of reference is the model with the actual driver restraint system currently fitted on a brand new vehicle.
Then we made a Design of Experiments (DoE) to assess the influence of several restraint characteristics on Deq and Rodpot.
This DoE is made with 2 dummies, 2 values of column collapse, 4 values of seat belt load limitation and 4 values of airbag vent diameter (in fact 3 for each dummy, 2 being common to both dummies).

The dummy positioning fulfils the current Euro NCAP ODB protocol for HIII 50th and the foreseen Euro NCAP Full-width rigid test:

- HIII 50th is set-up in mid rails, fully down position
- HIII 5th is set-up in fully forward, mid height position

HIII 50th is tested with an ODB 64 km/h pulse. Its kinematics and the restraint system are shown in Figure 8.

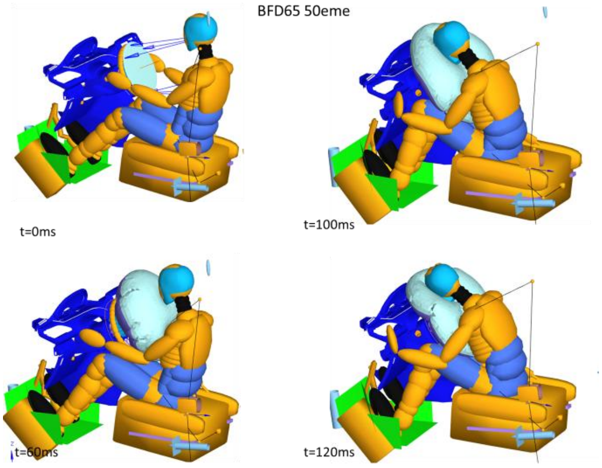

Figure 8. HIII 50th kinematics and restraint system behaviour in an ODB 64 km/h

With the same restraint system as for HIII 50th, the HIII 5th model sustained a Full-width 0° 50 km/h test, as shown in Figure 9.

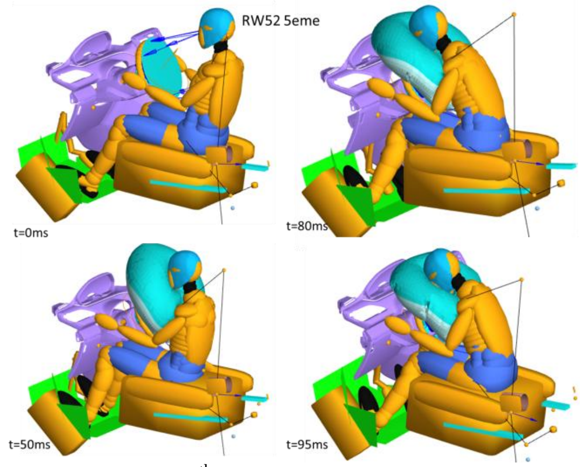

Figure 9. HIII 5th kinematics and restraint system behaviour in a Full-width 0° 50 km/h

As already stated, 3 main parameters of the restraint will be varied, to assess their influence of Rodpot and Deq:

- seat belt load limitation
- airbag vent diameter
- length of column collapse

The DoE for HIII 50th is made with the variations presented in Table 4.

Table 4.
Parameter variations for HIII 50th DoE

Parameter	Value
Load limitation (N)	2640 / 3300 / 3960 / 4620
Vent diameter (m)	0.040 / 0.0475 / 0.055
Length of column collapse (mm)	0 / 100

This gave a 24-cases DoE.

The DoE for HIII 50th is made with the variations presented in Table 5.

Table 5.
Parameter variations for HIII 5th DoE

Parameter	Value
Load limitation (N)	2640 / 3300 / 3960 / 4620
Vent diameter (m)	0.0475 / 0.055 / 0.0625
Length of column collapse (mm)	0 / 100

This gave a 24-cases DoE.

Direct output criteria were:

- HIC36
- Head resultant acceleration 3ms
- Chest deflection (Rodpot)
- Head clearance
- Chest clearance
- Pelvis displacement
- Upper seat belt load

Head and chest clearance are the remaining distance between head (respectively chest) and steering wheel when the dummy is at its maximum excursion. To avoid any bottoming-out of the airbag, a minimum value of clearance should be kept.

Deq is then reckoned via Eq 1. The purpose of this study is to try to define a relationship between chest deflection and the restraint parameters.

HIII 50th results

<u>Restraint systems parameters influencing Deq</u>

The variation of pelvis displacement is very low, whatever the DoE case (3 mm only). Therefore, we did not take it into account in the remaining part of the study.

This statistical study of the DoE highlighted a strong relationship between Deq and the 3 varying parameters. Table 6 presents the full set of results. It can be noticed that R^2 is close to 0.99 !

Table 6.
Weighting factors and correlation level for Deq expressed in terms of the 3 restraint systems parameters

Deq (mmDeq)	Estimation	Std. Error	t-value	Pr(>|t|)	Quality
Constant	26.435123	0.4558055	57.996494	0	***
Column collapse (mm)	19.047882	1.0018858	19.01203	7.971D-14	***
Load limitation (N)	0.0046527	0.0000667	69.77047	0	***
Vent size (m)	-111.69385	7.9989577	-13.963551	1.926D-11	***
Incertitude	0.2399687				
R	0.9965445				
R² ajust	0.9959989				
F-stat	1826.4793				
p-value	0				

After rounding the weighting factors, we can write the following equation that allows us to approximate the Deq value.

Aprx_Deq=26.4 +19*CC+4.65*LL-0.11*VD (2).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 10 presents the comparison between the Deq as measured in equation 1 (Deq is a function of USBF and Rodpot) and the approximated Deq (Aprx_Deq) as defined thanks to the DoE and equation (2).

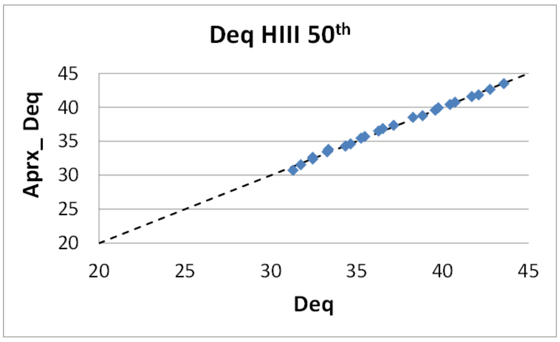

Figure 10. Comparison between actual Deq calculation and approximation made thanks to DoE

It could be interesting to apply the same analysis to the Rodpot to check if the same restraint systems parameters contribute to the rodpot measure and to which extent.

Restraint systems parameters influencing Rodpot

Via the statistical study of the DoE, we highlighted a second strong relationship; this time between Rodpot and the 3 varying parameters. Table 7 presents the full set of results. Here again, R^2 is close to 0.99 !

Table 7.
Weighting factors and correlation level for Rodpot expressed in terms of the 3 restraint systems parameters

Rodpot (m)	Estimation	Std. Error	t-value	Pr(>|t|)	Quality
Constant	0.0289546	0.0005346	54.164454	0	***
Column collapse (m)	0.0256216	0.0011750	21.805474	6.439D-15	***
Load limitation (N)	0.0000022	7.821D-08	27.530502	2.220D-16	***
Vent size (m)	-0.1450788	0.0093812	-15.464911	3.214D-12	***
Incertitude	0.0002814				
R	0.9874674				
R² ajust	0.9854886				
F-stat	499.01552				
p-value	0				

Here again, after simplifying the weighting factors, we can write the following equation that allows us to approximate the Rodpot value.

Aprx_Rodpot=29 +25.6*CC+2.2*LL-0.14*VD (3).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 11 presents the comparison between the Rodpot as directly measured in the test and the approximated Rodpot (Aprx_Rodpot) as defined thanks to the DoE and equation (3).

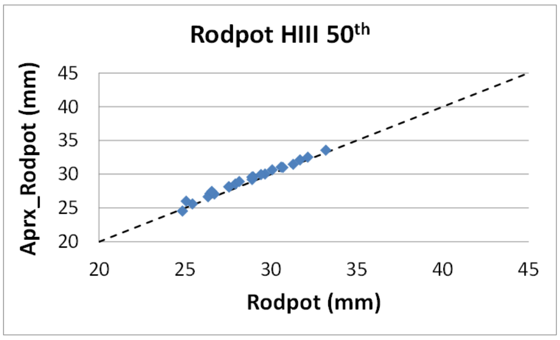

Figure 11. Comparison between actual Rodpot calculation and approximation made thanks to DoE

Comparison between Rodpot and Deq: relative contribution of the restraint systems parameters

Now that we have the two relationships between the chest deflection and the 3 restraint systems parameters, we can compare the weighting factors. This will allow us to highlight the sensitivity of Rodpot and Deq to the restraint system characteristics.

Indeed, if we use the generic formula

$$\begin{aligned}\text{Aprx\_deflection} = \lambda_i &\\ + \alpha_i *CC &\\ + \beta_i *LL &\\ + \gamma_i *VD & \qquad (4).\end{aligned}$$

where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

we can express (λ_D, α_D, β_D, γ_D), the weighting factors of approximated Deq in terms of (λ_R, α_R, β_R, γ_R) the weighting factors of approximated Rodpot.
Then, we are able to say that when the Rodpot sustains 1 unit of variation from CC, LL or DD, the Deq sustains x% of the Rodpot unit of variation. This is an assessment of the relative weight of influence of the restraint systems characteristics on the Deq value, with respect to the Rodpot one. This will be illustrated in Table 8 and Figure 12.

The following table recalls the weighting factors presented in Eq (2) and Eq (3) (so the (λ_i, α_i, β_i, γ_i)) as well as the relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R).

Table 8.
Simplified weighting factor used to approximate Rodpot and Deq as a function of restraint systems parameters and relative weight

	Aprx_ RodPot	Aprx_ Deq	Deq factor as a percentage of Rodpot factor*
Constant (mm)	29	26.4	91%
Factor for Column Collapse when expressed in mm	25.6	19	74%
Factor for Load Limitation when expressed in kN	2.2	4.65	211%
Factor for Vent Diameter when expressed in mm	-0.14	-0.11	79%

* Deq / Rodpot, that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R and γ_D/γ_R)

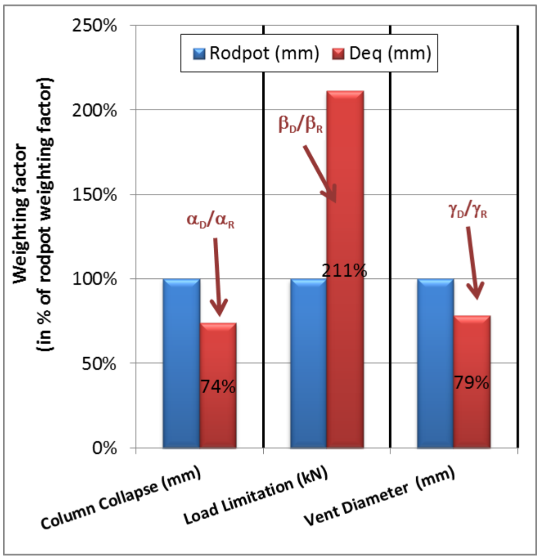

Figure 12. Relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R).

Thanks to this analysis, we can state that Deq is more sensitive than Rodpot to Load Limitation and less sensitive to Column Collapse and the airbag Vent Diameter. This will definitely give incentive to design restraint systems that have a lower load limitation. This is good for elderly occupants that are more fragile on chest and shoulder. It will also do not prevent the design of stiffer airbag. That was the case with the rodpot and that was not good for real occupant protection. Indeed, accident analysis and biomechanical studies already stressed that restraining the occupant by an airbag and its widely spread load is better than using only a seat belt load.

Design of restraint system: what are the new possibilities? What are the forbidden ones if Deq is chosen?

Another way to analyse the data is to draw the graph shown in Figure 13. It is derived from the DoE results and shows the Deq values in function of their Rodpot ones.

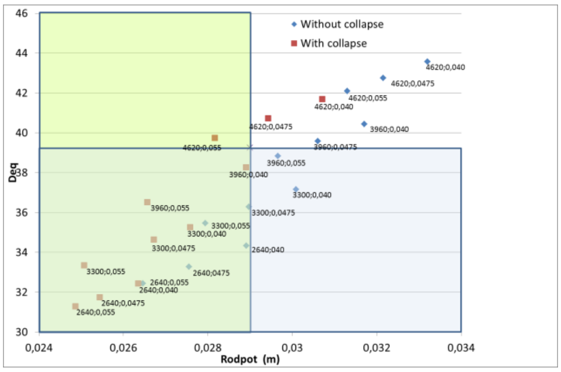

Figure 13. Deq measure in function of Rodpot – from HIII 50th DoE

The green rectangle (a vertical rectangle) represents the loading cases for which the Euro NCAP score of the Rodpot is 3 points or above.
In the same philosophy, the blue rectangle (an horizontal rectangle) represents the loading cases for which the Deq score is 3 points or above.
The red dots represent the DoE cases with 100 mm of maximum column collapse allowed. The blue dots represent the cases with no column collapse. For each dot, the other DoE parameters values are recalled (seat belt load limitation and airbag vent diameter).
The dots that are in the common zone (green+blue) are the load cases where whatever the chest deflection criterion, the score will be above 3 points. The pure green zone concerns load cases where Rodpot score is above 3 points but Deq score would be lower than 3 points. The pure blue zone concerns load cases where Deq score is above 3 points but Rodpot score would be lower than 3 points. Finally, the white zone concerns cases where nor Rodpot, neither Deq would score 3 points.

But we also need to look at the other injury criteria to filter the results. This is made by several steps.

Figure 14 presents Deq in function of head clearance for all the DoE points collected. In addition, the lower performance foreseen for Deq is shown in red (max Deq) and the upper performance foreseen for Deq is shown in green (min Deq).

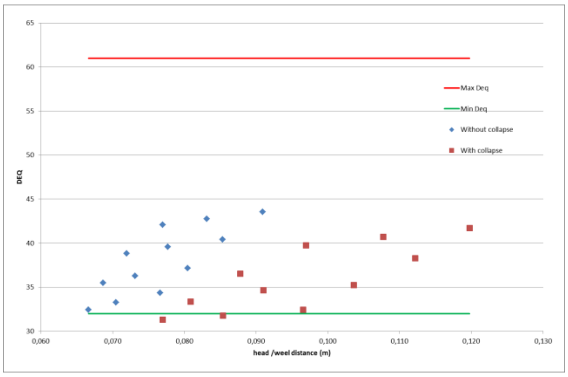

Figure 14. Deq in function of head clearance for DoE – from HIII 50th DoE

No case would be removed from HIII 50th DoE when looking at head clearance. This means that head clearance is not a limiting factor for a good Deq score.

The second step is to look at chest clearance. Figure 15 presents Deq in function of chest clearance for all the DoE points collected. Here again, the lower performance foreseen for Deq is shown in red (max Deq) and the upper performance foreseen for Deq is shown in green (min Deq).

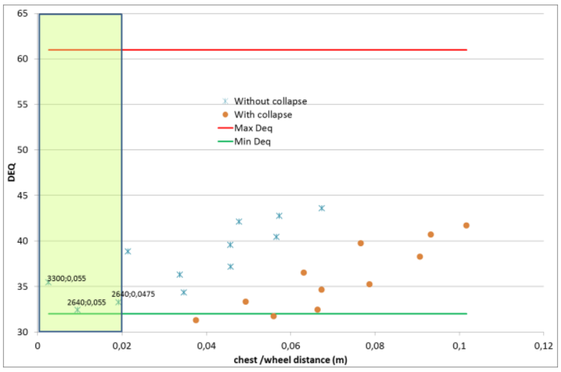

Figure 15. Deq in function of chest clearance for DoE – from HIII 50th DoE

In the case of chest clearance, some load cases have to be excluded because the value was too low (below 20 mm). These excluded cases are the ones located in the green zone of Figure 13. And they all belong to the “no collapse” cases. Their Load Limitation (LL) and Vent Diameter (VD) characteristics are:

- (LL 3300 ; VD 0,055)
- (LL 2640 ; VD 0,055)
- (LL 2640 ; VD 0,0475)

Removing these 3 cases from Figure 13 will give the following results, as shown in Figure 16.

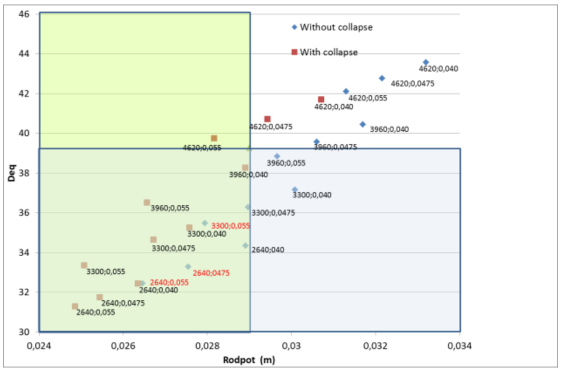

Figure 16. Deq measure in function of Rodpot with the three load cases to be removed because fo chest clearance – from HIII 50th DoE

When designing a restraint system targeted to reach 3 points with the Rodpot, all the loaded cases included in the green rectangle would be possible. This means that load cases with 4600 N load limitation or less would have been possible. But on the other hand, almost no case without collapse would have been allowed.
Indeed only two blue dots are close to 29 mm (the 3 points limit for Rodpot for HIII 50th).

On the other hand if we have to design a restraint system targeted to reach 3 points with the Deq, all the loaded cases included in the blue rectangle would be possible. This means that load cases

above 3960 N load limitation would have been forbidden. But on the other hand, some cases without collapse would have been allowed. Indeed some blue dots are in the blue zone, the ones with stiffer airbags.
There is a common zone where load cases answer to both Rodpot and Deq 3 points target.
Because of Deq, seat belt with too high load limitation would be excluded, but additional points with stiffer airbag become possible.
The danger would be to stiffen to much the airbag and therefore increase too much the head acceleration and HIC. But looking at HIC and head acceleration collected in the DoE, there is no point exceeding 80g.

Using only Rodpot would allow us to design a restraint system with a column collapse + 4620 LL and 0.055 VD - that is to say a case with a high load limitation compensated by a soft airbag (high vent diameter). This case would not be allowed with Deq, which is good for occupant protection. On the contrary, using Deq would allow us to design restraint system without a column collapse + 3960 LL and 0.055 VD or without a column collapse + 3300 LL and 0.0475 VD.

HIII 5th results

<u>Restraint systems parameters influencing Deq</u>

The same philosophy is applied to HIII 5th.

Here again, the statistical study of the DoE highlighted a strong relationship between Deq and the 3 varying parameters. Table 9 presents the full set of results. It can be noticed that R^2 is close to 0.99 !

Table 9.
Weighting factors and correlation level for Deq expressed in terms of the 3 restraint systems parameters

Deq (mmDeq)	Estimation	Std. Error	t-value	Pr(>|t|)	Qualité
Constant	22.948772	0.5176913	44.329064	0	***
Column collapse (mm)	18.404334	1.0015762	18.37537	5.396D-14	***
Load limitation (N)	0.0039661	0.0000679	58.440457	0	***
Vent size (m)	-89.477628	8.1777539	-10.94159	6.824D-10	***
Incertitude	0.2453326				
R	0.9948621				
R² ajust	0.9940914				
F-stat	1290.8865				
p-value	0				

Rounding the weighting factors leads to equation (5).
Aprx_Deq=22.9 +18.4*CC+3.97*LL-0.09*VD (5).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 17 presents the comparison between the Deq as measured in equation 1 (Deq is a function of USBF and Rodpot) and the approximated Deq (Aprx_Deq) as defined thanks to the DoE and equation (5).

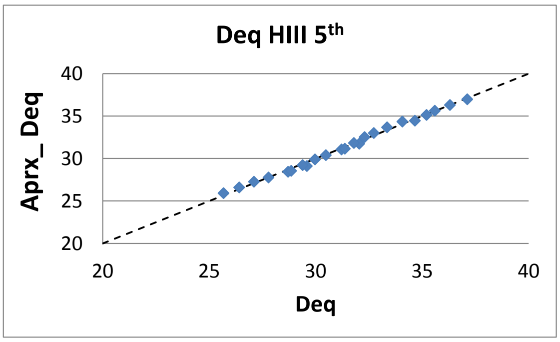

Figure 17. Comparison between actual Deq calculation and approximation made thanks to DoE

Applying the same analysis to the Rodpot is given below.

<u>Restraint systems parameters influencing Rodpot</u>

Table 10 presents the full set of results for Rodpot and HIII 5th. R^2 is close to 0.98 !

Table 10.
Weighting factors and correlation level for Rodpot expressed in terms of the 3 restraint systems parameters

Rodpot (m)	Estimation	Std. Error	t-value	Pr(>|t|)	Qualité
Constant	0.0241555	0.0005723	42.204518	0	***
Column collapse (m)	0.0231688	0.0011073	20.923386	4.441D-15	***
Load limitation (N)	0.0000015	7.503D-08	20.315348	7.994D-15	***
Vent size (m)	-0.110853	0.0090411	-12.261022	9.286D-11	***
Incertitude	0.0002712				
R	0.9804082				
R² ajust	0.9774694				
F-stat	333.61136				
p-value	0				

Rounding the weighting factors leads to equation (6).
Aprx_Rodpot=24.2 +23.2*CC+1.5*LL-0.11*VD(6).
where :

- CC is the Column Collapse, in mm
- LL is the Load limitation, in kN
- VD is the airbag Vent Diameter, in mm

Figure 18 presents the comparison between the Rodpot as directly measured in the test and the approximated Rodpot (Aprx_Rodpot) as defined thanks to the DoE and equation (6).

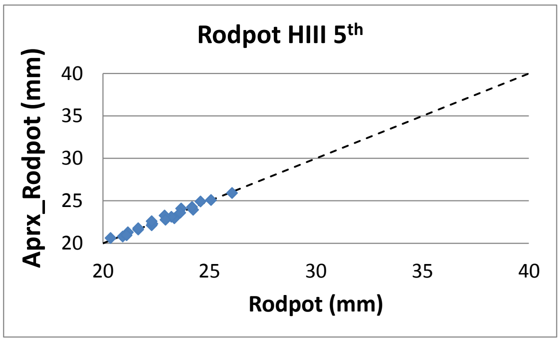

Figure 18. Comparison between actual Rodpot calculation and approximation made thanks to DoE

Comparison between Rodpot and Deq: relative contribution of the restraint systems parameters

For HIII 5th, Table 11 recalls the weighting factors presented in Eq (5) and Eq 63) (so the (λ_i, α_i, β_i, γ_i)) as well as the relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R).

Table 11.
Simplified weighting factor used to approximate Rodpot and Deq as a function of restraint systems parameters and relative weight

simplified weighting factor	RodPot	Deq	weighting factor (Deq / Rodpot)
Constant (mm)	24.2	22.9	95%
Column Collapse (mm)	23.2	18.4	79%
Load Limitation (kN)	1.5	3.97	265%
Vent Diameter (mm)	-0.11	-0.09	82%

* Deq / Rodpot, that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R and γ_D/γ_R)

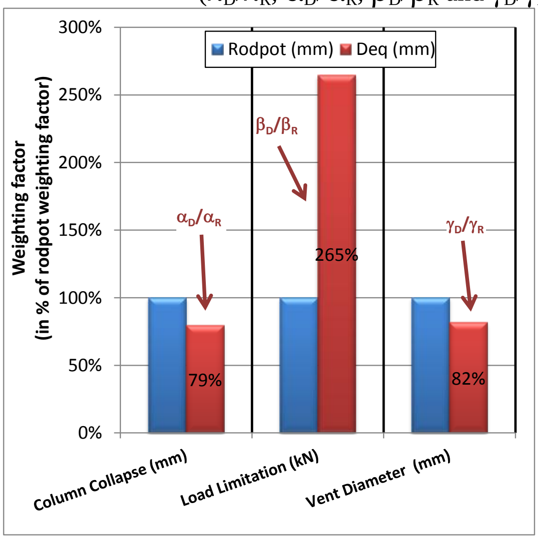

Figure 19. Relative factors of Deq expressed in percentage of Rodpot – that is to say the (λ_D/λ_R, α_D/α_R, β_D/β_R, γ_D/γ_R) for HIII 5th.

Again, for HIII 5th as well, Deq is more sensitive than Rodpot to Load Limitation and less sensitive to Column Collapse and the airbag Vent Diameter.

Design of restraint system: what are the new possibilities? What are the forbidden ones if Deq is chosen?

Figure 20 presents Deq in function of head clearance for all the DoE points collected for HIII 5th. The lower performance foreseen for Deq is shown in red (max Deq) and the upper performance foreseen for Deq is shown in green (min Deq).

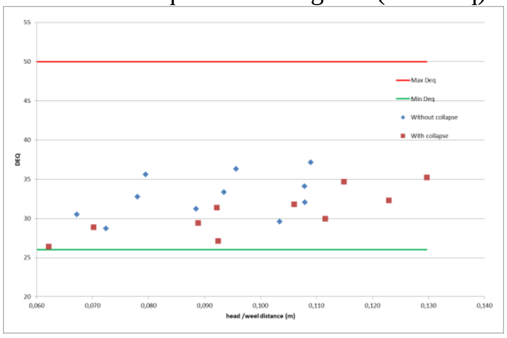

Figure 20. Deq in function of head clearance for DoE – from HIII 5th DoE

Again, no case would be removed from HIII 5th DoE when looking at head clearance. This means that head clearance is not a limiting factor for a good Deq score.

Figure 21 presents Deq in function of chest clearance for all the DoE points collected.

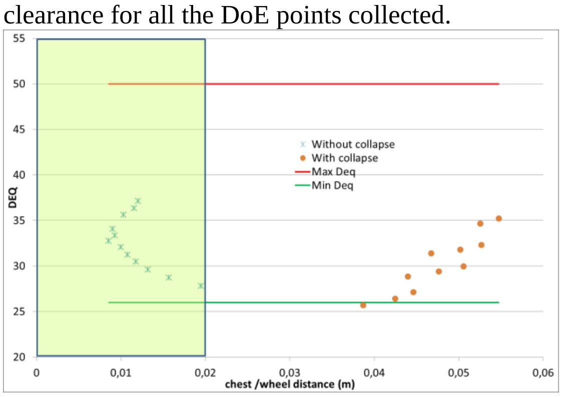

Figure 21. Deq in function of chest clearance for DoE – from HIII 5th DoE

The chest clearance will therefore force us to remove all the load cases without collapse.

Applying this analysis to the DoE results for HIII 5th would give the following results, as shown in Figure 22.

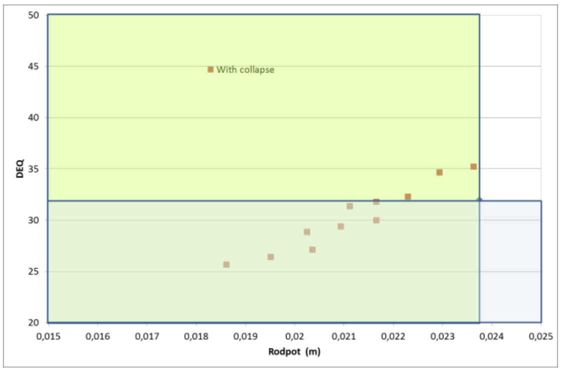

Figure 22. Deq measure in function of Rodpot with the load cases removed because fo chest clearance – from HIII 5th DoE

When designing a restraint system targeted to reach 3 points with the Rodpot, all the loaded cases included in the green rectangle would be possible. This includes all the remaining cases (all the ones with column collapse.
On the other hand, if we have to design a restraint system targeted to reach 3 points with the Deq, all the loaded cases included in the blue rectangle would be possible. This means that 3 load cases would have been forbidden.

Using Deq would prevent us to design restraint system with a column collapse and with the following characteristics:

- 3960 LL and 0.0475 VD
- 4620 LL and 0.055 VD
- 4620 LL and 0.0475 VD.

DISCUSSION AND LIMITATIONS OF THE STUDY

To summarize our findings before starting the discussion we can say that the first part of the research was the assessment of scattering in actual measurements of chest deflexion (Rodpot and Deq). This has already been discussed in the partial conclusion on the scattering and reproducibility.

Then we decided to study numerically restraint systems that should give better results when combining 50th and 5th percentile protection i.e. with load limitation lower than the one tested in the reproducibility analysis. For this purpose, we carried out numerical Design of Experiments changing the restraint systems parameters from an actual car to see the consequences on biomechanical results.

This first output of this numerical study was to define the Deq and Rodpot maximum values as a function of restraint systems characteristics (column collapse, airbag stiffness and seat belt load limitation). This way, we saw that Deq is more dependent to load limitation than Rodpot. And on the other hand, Rodpot is more dependent to column collapse and airbag stiffness than Deq.

But this analysis is made by varying the restraint systems characteristics for one unique vehicle model. Our research is not finished and we have planned to study other vehicles to see if the equations would be similar.

Concerning the main outcome of the study, we found that varying the restraint system characteristics allows us to find satisfying cases where some occupant protection principles are fulfilled. But looking at chest deflection via Rodpot or Deq would not give the same selection of cases. At this stage, we should also warn that the analysis did not look at other biomechanical parameters such as neck forces and moment.

In order to decide if one chest deflection criterion is more appropriate than the other, the last thing to do is to combine the results got for the HIII 50th to the ones obtained with the HIII 5th. This is presented in Figure 23 where we kept all the cases selected for Rodpot scores > 3points or for the Deq Scores > 3 points.

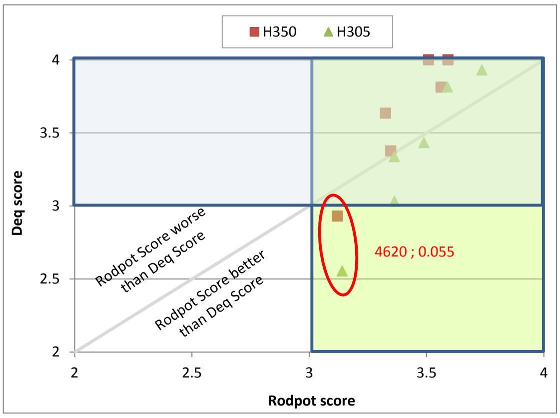

Figure 23. Deq score in function of Rodpot with for HIII 50th HIII and 5th Design of Experiments – Cases selected for Rodpot scores > 3points or Deq scores > 3points

From these figures, we can conclude that 5 restraint cases would be allowed by Deq for HIII 50th and HIII 5th dummies. They are all with column collapse and with:

- 2640 LL ; 0.0475 VD
- 3300 LL ; 0.0475 VD
- 2640 LL ; 0.055 VD
- 3300 LL ; 0.055 VD
- 3960 LL ; 0.055 VD

where LL = seat belt Load Limitation and VD = airbag Vent Diameter.

A 6th one (circled in red in Figure 23) would be allowed by Rodpot and not by Deq. This is the 4620 LL ; 0.0055 VD with column collapse. This means a restraint with a load limitation not very low combined with a soft airbag. In terms of occupant protection, this combination is not desired if we want to protect the elderly.

These five sets of parameters allowed by Deq for the car restraint system should be cross-checked with the other biomechanical criteria not studied here (such as neck criteria) to be sure they are all compatible with a good level of occupant protection on all body segments.

CONCLUSION

One part of our study was to analyse the overall reproducibility of Rodpot and Deq measurement based on current cars tested in the Euro NCAP ODB 64km/h test with HIII 50th. No significant difference or trend was found between the scatterings of the two ways of measuring chest deflection. But we saw that for the restraint systems tested in this analysis, Deq score was always lower than Rodpot score. The score was calculated according to one of the hypotheses of chest deflection thresholds currently manipulated by Euro NCAP.
In order to see how we can get better results, we carried out a numerical programs based on ODB 64 km/h test with HIII 50th and Full-width 50 km/h test with HIII 5th where we varied the restraint systems characteristics (column collapse, airbag stiffness and seat belt load limitation). We looked at the results in terms of biomechanical criteria as well as restraint criteria, such as head and chest clearance. The purpose was to see whether or not Rodpot would allow different restraint systems solutions than Deq. With the set of parameters investigated, we saw that Rodpot would allow one case in addition to the one allowed by Deq, but it is the one with the highest load limitation investigated and the softest airbag investigated. Using a chest criterion preventing from choosing this solution would be good. The limits of the study are that some other biomechanical criteria were not studied in details, such as neck load and moments because their lower quality in numerical correlation. It may limit the number of solution retained in the final selection of restraint parameters.

We also investigate the sensitivity of the two criteria with respect to the restraint systems characteristics.
For HIII 50th as well as for HIII 5th, we found that Deq is more sensitive than Rodpot to Load Limitation and less sensitive to Column Collapse and the airbag Vent Diameter.

As a summary, we can say that Rodpot and Deq are equivalent in terms of scatterings. But using Deq will definitely give incentive to design restraint systems that have a lower load limitation. It will also prevent the design of restraint systems made of higher load limitation combined with soft airbag. This is good for elderly occupants that are known to be more fragile on chest and shoulder.

ACKNOWLEDGMENTS

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