CAR TO CAR FRONT CRASH EQUIVALENT PROTOCOL

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ABSTRACT

The target of front crash protocols is to finally represent a « Car to Car » (C2C) impact, which is the most frequent configuration in real life. But C2C is a too complex and costly configuration to be applied on experimental and even numerical point of view.

Particularly, a numerical C2C simulation will require many finite elements (F.E.) and so heavy calculation time (with in addition, more numerical bug risks, because modeling the front interface between the 2 cars is complex) ; and also, the Post calculation analysis is much more heavy (2 different cars to be analyzed + twice as biomecanic criteria if dummies models are implemented).

Furthermore, some specific criteria (specially compatibility criteria) can't be rated during a C2C crash test, because they need a deformable barrier (which represents a medium car of the market) to be measured : as car front face aggressiveness characteristics, and global car's stiffness (dynamometric force measurement on barrier trolley).

The goal of this study is to define the front crash protocol which responds the best at the following problem:

-to represent the physics of C2C front crashes

-to be easier to use in car design process

For that purpose, we will follow the method below :

FIRST, we will carry out a theoretical study of the C2C front crash, in order to understand its physical main phenomenon, under 3 different and complementary aspects:

-Mathematical aspect with simple models,

-Numerical aspect with F.E. calculations,

-Experimental aspect with C2C tests analysis.

SECONDLY, we will exploit the obtained results, in particular:

-Mathematical models to well represent kinematics and global interaction of each car,

-Numerical modelling to be efficient to qualify energy absorption, front face interaction area and Pulse of the tested car,

-Experimental results to be able to give global physical characteristics usable in car design.

THEN, we will discuss and answer to the following questions:

-Limitations and disadvantages of theoretical and numerical approaches,

-What is the best relevant protocol to represent a C2C front crash and if it is reliable (comparison with others protocols and parametric studies),

-How to provide a better compatibility.

Finally, we will conclude and open the field.

The numerical study was conducted with the cooperation of ACTOAT company and the C2C tests at UTAC laboratory.

CONTEXT

The accidentology situation shows that the C2C front collisions are the most serious and frequent cases.
Of course, there are some cases where geometrical compatibility won't be possible to improve (as the example of a low sedan car and a truck collision):

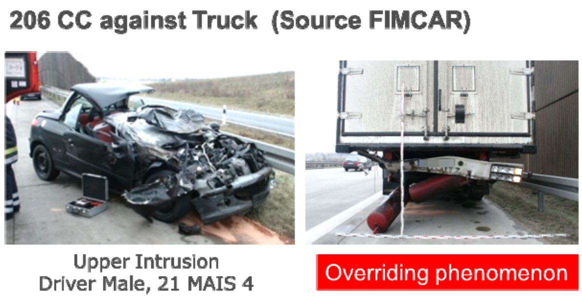

Figure 1 : exemple of Bad compatibility impossible to redduce

But majority of collisions involve current sedan cars themselves, everywhere in the world.
That is the reason why we have first studied the "State of the Art", by making a comparison between the geometrical design of front face of a great number of cars (with mixing their mass, size, height differences) :

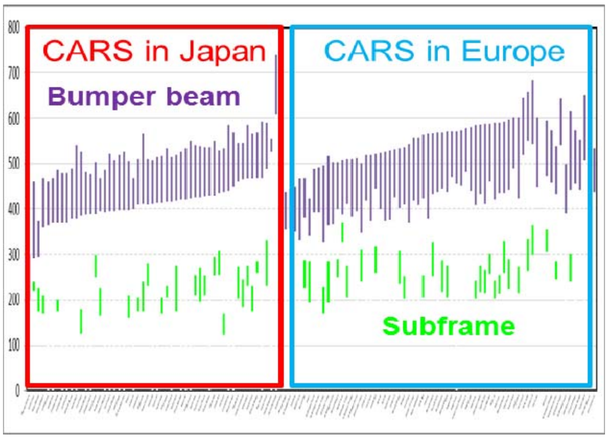

Figure 2 : geometrical comparison oh height of bumper beam & sub-frame

Conclusion : in Japanese and European car markets, majority of cars have a good structural engagement divided into 2 different areas : a lower areas (lower load path or longer sub-frame) and a upper area (bumper structural beam) ; more than one half of the cars haven't still extended their structural engagement in the lower area and still remain aggressive :

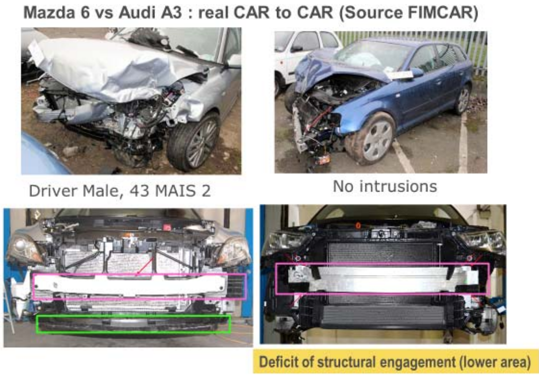

Figure 3 : example of deficit structural engagement in a real C2C front crash

But today, the current crashtest protocols using normalized impactors (rigid wall or offset deformable barrier) aren't able to show correctly this interaction phenomenon between 2 different cars.
So it is a worldwide highest safety priority to define and use a protocol which can correctly represent a C2C front crash : this is the goal of our following study.

METHODOLOGY

First, we carry out a theoretical study of the C2C front crash, in order to understand its physical main phenomenon, under 3 complementary aspects :

Mathematical Approach

A Simple One-Dimensional Model By applying the momentum conservation and the « soft impacts » hypotheses, we can calculate the change of Delta velocity of each car :

$$\Delta v_1 = \frac{m_2}{(m_1 + m_2)}(v_1 + v_2)$$

$$\Delta v_2 = \frac{m_1}{(m_1 + m_2)}(v_1 + v_2)$$

This simple formula only gives us some orders of scale ; for example : in a CAR vs TRUCK crash, the mass ratio is high (e.g. a collision involving a truck of 40000kg mass and a heavy car of 2000kg mass, yields a mass ratio of 20:1) : the change of velocity of the car will be multiplied by 20 compared to the truck.

A Mathematical Improved Model In real accidentology, the most current case is a CAR to CAR crash with a partial overlap (50% of the width); so to be more precise, we need to take in consideration the rotation phenomenon of each car.

In addition, the « soft impacts » is a too restrictive hypothesis; more realistic is to introduce a part of « elastic impacts » with the introduction of restitution coefficients (normal and tangent coefficients: e_n et e_t) :

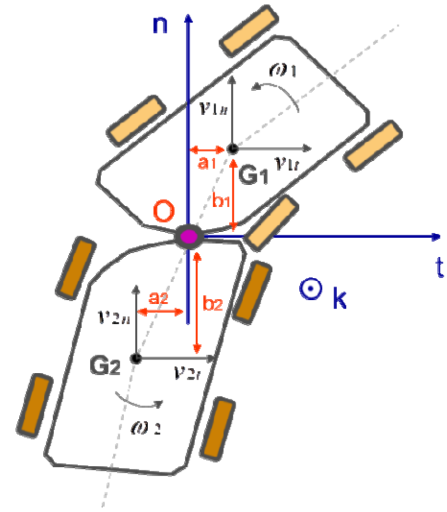

Figure 4 : mathematical modeling of a C2C with 6 degrees of freedom

We apply the impulsions theory at each car :

CAR 1 :

$$\begin{cases} m_1.(v_1{'}_t - v_{1t}) = \int_{t_1}^{t_2} F_t.dt = P_t \\ m_1.(v_1{'}_n - v_{1n}) = \int_{t_1}^{t_2} F_n.dt = P_n \end{cases}$$

CAR 2 :

$$\begin{cases} m_2.(v_2{'}_t - v_{2t}) = -P_t \\ m_2.(v_2{'}_n - v_{2n}) = -P_n \end{cases}$$

And also the kinetic momentum theory :

CAR 1 :

$$m_1.l_1^2.(\omega_1{'} - \omega_1) = \int_{t_1}^{t_2} M_z.dt$$
$$= \int_{t_1}^{t_2} (-a_1.F_n + b_1.F_t).dt$$
$$= -a_1.P_n + b_1.P_t$$

CAR 2 :

$$m_2.l_2^2.(\omega_2{'} - \omega_2) = -(-a_2.P_n + b_2.P_t)$$
$$l_1^2 = a_1^2 + b_1^2$$

Then, we write the kinematics conditions with restitution coefficients which gives us 2 another equations :

CAR 1 : $(v_{1t} + b_1.\omega_1 \,;\, v_{1n} - a_1.\omega_1)$

CAR 2 : $(v_{2t} + b_2.\omega_2 \,;\, v_{2n} - a_2.\omega_2)$

$$\begin{cases} (v_2{'}_t + b_2.\omega_2) - (v_1{'}_t + b_1.\omega_1) = \\ -e_t.\{(v_{2t} + b_2.\omega_2) - (v_{1t} + b_1.\omega_1)\} \\ (v_2{'}_n - a_2.\omega_2) - (v_1{'}_n - a_1.\omega_1) = \\ -e_n.\{(v_{2n} - a_2.\omega_2) - (v_{1n} - a_1.\omega_1)\} \end{cases}$$

We have now 6 independent equations with 6 degrees of freedom : it is therefore mathematically possible to solve the problem. We write this equation's system on matrix formulation :

$$\overline{\overline{M}} \otimes (\overline{X}_{choc}^{après}) = \overline{B}_{choc}^{avant}$$

Where :

$$\begin{pmatrix} m_1 & 0 & 0 & m_2 & 0 & 0 \\ 0 & m_1 & 0 & 0 & m_2 & 0 \\ a_1.m_1 & -b_1.m_1 & m_1.l_1^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_2.m_2 & -b_2.m_2 & m_2.l_2^2 \\ -1 & 0 & a_1 & 1 & 0 & -a_2 \\ 0 & -1 & -b_1 & 0 & 1 & b_2 \end{pmatrix} \cdot \begin{pmatrix} v_1{'}_n \\ v_1{'}_t \\ \omega_1{'} \\ v_2{'}_n \\ v_2{'}_t \\ \omega_2{'} \end{pmatrix} = \begin{pmatrix} m_1.v_{1n} + m_2.v_{2n} \\ m_1.v_{1t} + m_2.v_{2t} \\ a_1.m_1.v_{1n} - b_1.m_1.v_{1t} + m_1.l_1^2.\omega_1 \\ a_2.m_2.v_{2n} - b_2.m_2.v_{2t} + m_2.l_2^2.\omega_2 \\ e_n.v_{1n} - e_n.a_1.\omega_1 - e_n.v_{2n} + e_n.a_2.\omega_2 \\ e_t.v_{1t} + e_t.b_1.\omega_1 - e_t.v_{2t} - e_t.b_2.\omega_2 \end{pmatrix}$$

We can also solve this equation's system and therefore obtain all the velocities components of each car.

Numerical Simulations

We have realized in 2016 a FINITE-ELEMENTS (F.E.) modelling of a midsize sedan car. Indeed, this kind of car represents an average car among the whole motor vehicle fleet and also the most widespread car.
The first simulation consists in 2 identical cars, with 50% overlap, car against car at opposite 50km/H velocity.

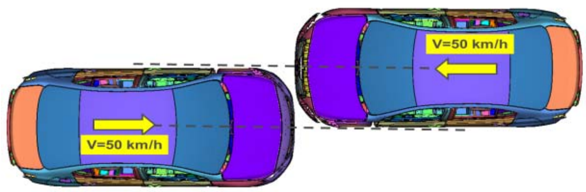

Figure 5 : C2C front crash with F.E. method

Debugging the CAR to CAR model has been difficult and had taken a lot of time; but the final results are relevant: physical behaviour of cars and their deformation modes are symmetric :

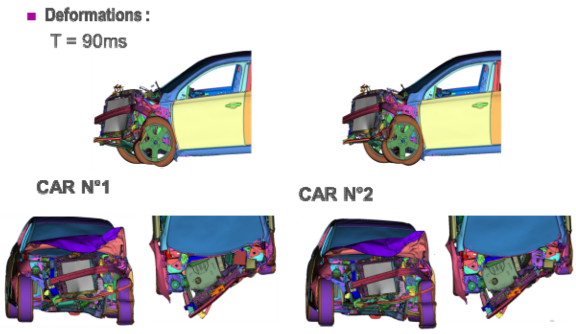

Figure 6 : Compared analysis of each car results

Intrusion and pulse levels are comparable between the 2 cars : this is physically relevant and so a check for our calculation :

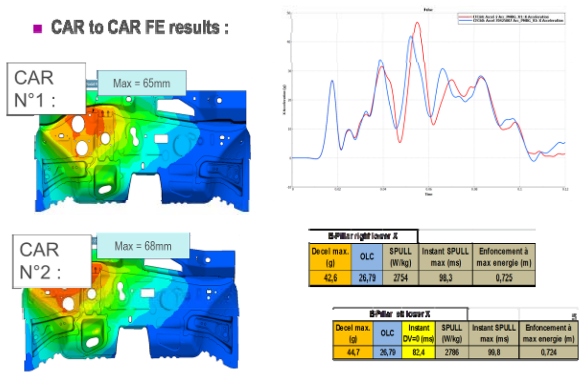

Figure 7 : Compared detailed results of each car

Experimental Method

In context of FIMCAR (Frontal Impact and Compatibility) Group [1], a study about comparison of different crash protocols was conducted (ODB 40% CEVE front crash, 0° RW front crash, PDB barrier different versions & speed) and led up to the new M-PDB (Mobile Progressive Deformable Barrier) protocol :

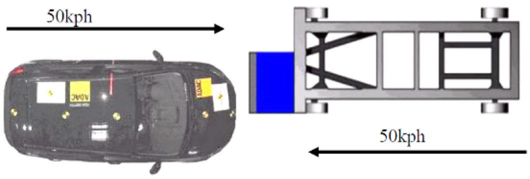

Figure 8 : M-PDB Front Crash protocol

An in-depth analysis were also conducted on a « Supermini » car population in order to rate the relevance of M-PDB protocol about partner-protection. In order to evaluate the test severity, different test pulses for Supermini cars were compared (all tests coming from FIMCAR database):

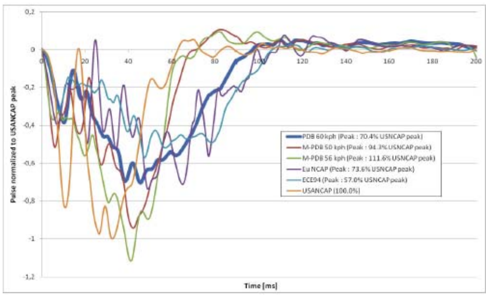

Figure 9 : Extract from FIMCAR Data Base

One first observation was that M-PDB pulses were intermediate between RW Pulse (NHTSA) and ODB CEVE Pulse (CEE) : on one side, the crash duration of a RW front test is very short because it show a immediate stop of the engine against the rigid wall ; on the other side, the crash duration of a ODB CEVE front test is longer because the CEVE barrier stiffness is now too soft compared to new cars generations.

As a conclusion, FIMCAR chose the M-PDB protocol [2] to be more representative of a CAR to CAR crash test because the PDB Barrier (ADAC version), with its progressive stiffness, allows to represent the engine impact on the other car and the increase of car body stiffness at the end of crash (cockpit resistance); moreover, it can qualify and measure the « car compatibility » with the footprint of the tested car inside the barrier.

RESULTS

Mathematical Study

We programed and solved this matrix system: we obtain the final velocities of the 2 cars and therefore the delta velocity of each car. In order to exploit this mathematical model, we fix the car 1 mass (1577 kg as such an average car), and then, we make variation on the car 2 mass : between 850 kg (supermini car) and 2500 kg (heavy car).

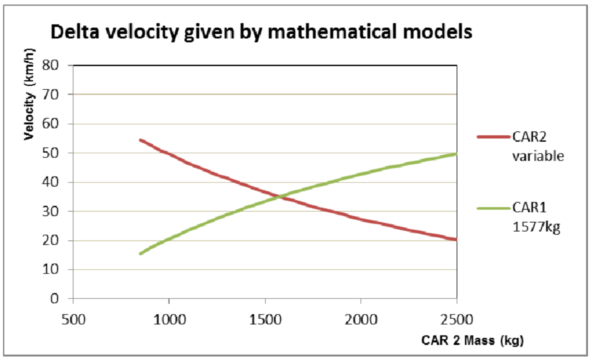

Figure 10 : Results velocity curves of model

Remark: when the masses are the same, the delta velocity of the 2 cars is of course the same (crossing point of the 2 curves) : this is a check of the validity of our mathematical model.

Using the velocities found by our model, we can now calculate the residual kinematic energy of cars at the end of crash. If we suppose that stiffness of cars is identical (case of crash between the same cars), we can also calculate the delta of kinematic energy of each car. Then, making the hypothesis that crushing distance is equally divided between the two cars, we can assume that delta of kinematic energy is equal to absorbed energy for each car.

We applied the same mass variation for the car 2, car 1 mass is fixed:

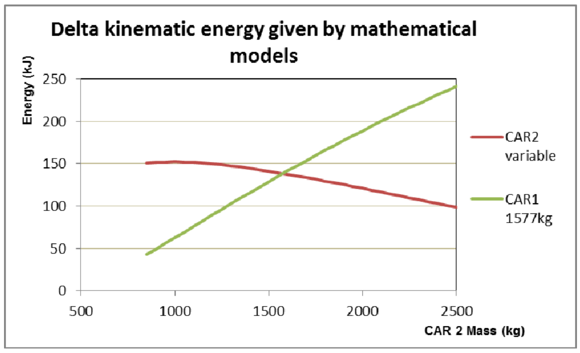

Figure 11 : Results energy curves of model

Thus, we show the « mass aggressiveness » phenomenon: absorbed energy is directly influenced by the difference of cars mass.

Then, we introduce the Ratio of absorbed energy between CAR 2 and CAR 1, and we take the mass of car 1 as a parameter.

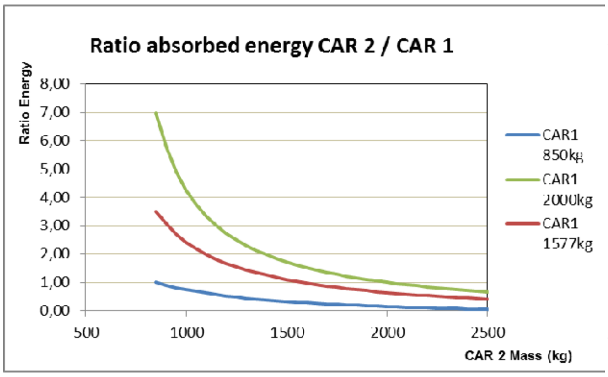

Figure 12 : Ratio absorbed energy with mass parameter

Of course, a difference of stiffness of the car can also still makes even worst the mass aggressiveness, because, generally heavy cars have also higher stiffness.

Conclusion: We can see that small cars are always put at a disadvantage compared to the bigger ones. As it is well known that there is a strong relationship between delta velocity and occupant injury risks, small and light cars which have higher injury risk, due to this mass aggressiveness.

Numerical Study

We search now the most representative protocol in term of absorbed energy, using the followed method:

First, we have calculated the EES with the following formula:

$$EES[m/s] = \sqrt{v[m/s]^2 - \frac{2 \times E_{ODB}[J]}{m[kg]}}$$

We find 48km/h (a few less than the M-PDB protocol); this is a confirmation of the FIMCAR conclusions : 50km/h speed of the M-PDB protocol is lightly more severe than the current others protocols and a speed of 56km/h would be too high to represent a CAR to CAR real crash.

Then, we have compared the energy absorption curves, functions of time, between the different front crash protocols, on our medium size sedan car (1577 kg with two THOR dummies inside):

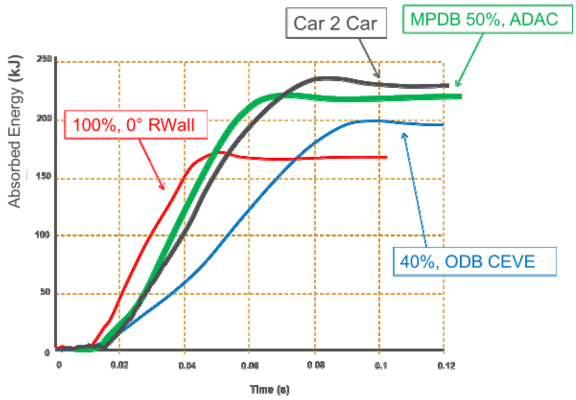

Figure 13 : Car absorbed energy comparison of different F.E. calculations results

Secondly, we chose the most representative protocol in term of car pulse: we consider the pulse of our CAR to CAR font crash and we successively compare it to the Pulse of the other main protocols:

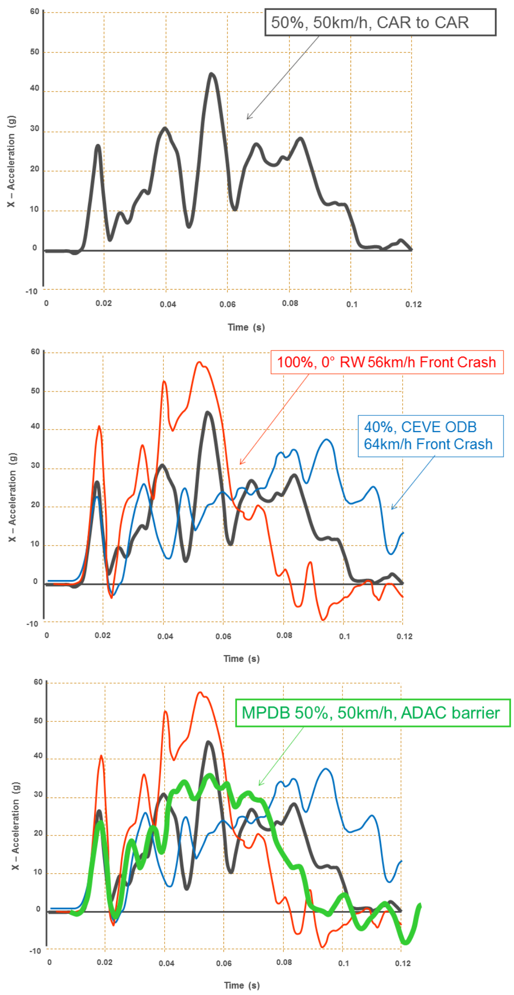

Figure 14 : Successively comparison of different F.E. calculations results on Pulse criteria

Conclusion: We can see that CAR to CAR is different from:

-0°, RW Front Crash : crash duration too short and medium value of pulse too stiff

-40%, CEVE ODB Front Crash: crash duration too long and medium value of pulse too smooth

The conclusion is clear: M-PDB Protocol with a speed of 50km/h is the most representative protocol of our CAR to CAR result (in term of absorbed energy, car pulse and intrusions).

Testing Study and Tests

As the M-PDB test let us measure dynamometric Force, It is possible to predict global FORCE / Displacement at the exchange area of the two cars in combining together the two characteristic of cars with a simple mechanical principle : the car which deformed is the one which have the lower stiffness.

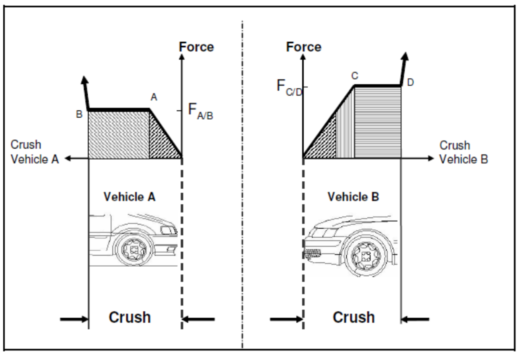

Figure 15 : case of a C2C frontal impact against cars with different stiffness

We apply this method to a real CAR to CAR front crash Peugeot 3008 vs Renault CLIO (test conducted by UTAC):

Figure 16 : C2C Peugeot 3008 vs Renault CLIO (performed by UTAC)

We first calculate the global displacement of the 2 cars together (solid movement) and after, we deduct it from global displacement and finally separate each car displacement:

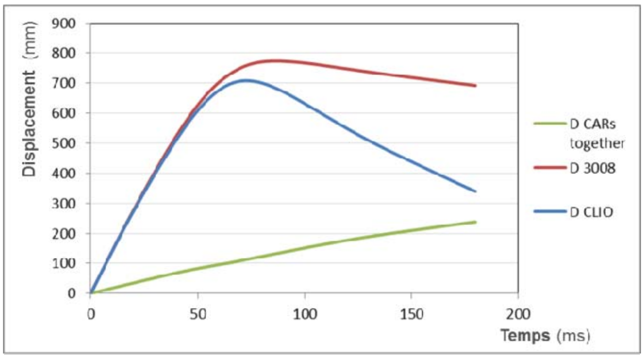

Figure 17 : Displacement separation method applied on test results

Below, we can see the comparison of crushing characteristics (Force / crushing distance) of each car :

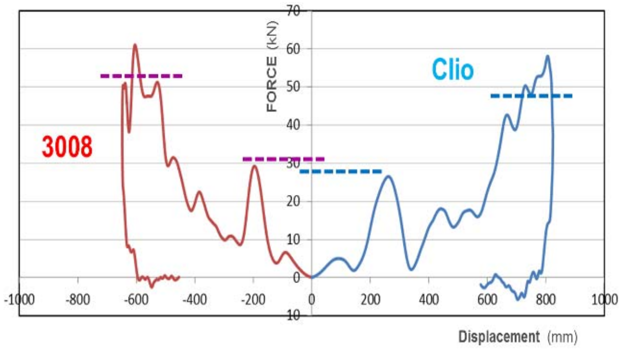

Figure 18 : Crushing characteristic of each car

We see that stiffness of those 2 cars are near : force level of front unit at the beginning and also, force level of cockpit at the end of crash.

Nevertheless, Peugeot 3008 and Renault CLIO have different silhouettes (medium SUV for 3008, small Sedan car for CLIO), this CAR to CAR test shows that those cars are quite « compatible » due to the combination of 2 principles: a good structural engagement and a near stiffness. Only mass aggressiveness stills remain because it can't be reduced.

LIMITATIONS AND DISCUSSION

Limitation of theoretical and F-E Calculations

We have seen that results of mathematical models are only useful to understand phenomenon and give us order of scales.

Concerning F.E. calculations, some difficulties comes from this kind of modeling:
-<u>First problem</u>: calculations time but also time to prepare/debug models are too extensive: no compatible to use it, every day, in iterative design process.

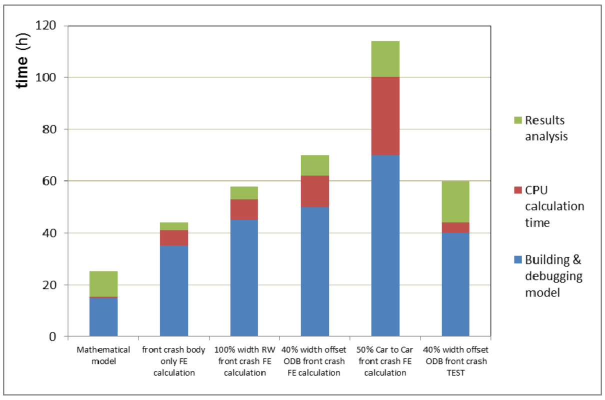

Figure 19 : Time comparison between different kind of F.E. calculations

-<u>Second problem</u> : there is a paradox between the complexity of the C2C model itself and the limited results than it can provide for the car design ; indeed, with this kind of FE-model, it is difficult to separate the absorbed energy between each car, and quite impossible to sum the global Force that one car applies to the other one.

Selection Of The Protocol Efficient For Car Design

We have identified the M-PDB protocol as the most relevant in terms of global kinematics, absorbed energy, Pulse variations & intrusions values
In addition, this protocol can give to us the 2 main physical characteristics required by an automotive car maker, at the beginning of a new project:
- target of energy to be absorbed (to reserve crushing area dimensions),
- Force/displacement target law (to design members of front unit of the car)

But now, we have to make sure of its repeatability and physic stability.
So we ran a complete parametric study on crash conditions & trolley parameters, barrier characteristics and car physical behaviour.

TROLLEY and CRASH conditions : Trolley loading a PDB type barrier (ADAC version) was modelized as following :

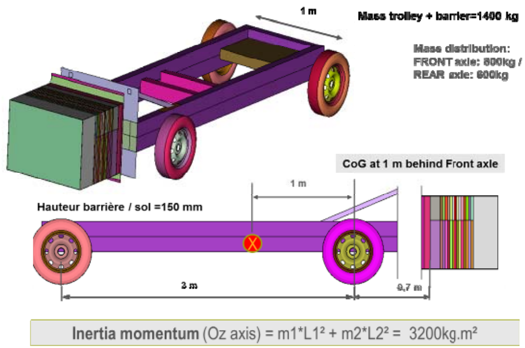

Figure 20 : Trolley & barrier modelling

Trolley PARAMETERS influence : Iterations are conducted, modifying trolley's parameters to study their dispersion on the kinematics of trolley & car:

-<u>Trolley parameters influence</u>: the most influent parameter is the Y- position between barrier and trolley: indeed, on the side of the impact, barrier must cover the wheel of the trolley in order to well represent the interaction between barrier & car and so their kinematics (rotation in the real direction of rotation) :

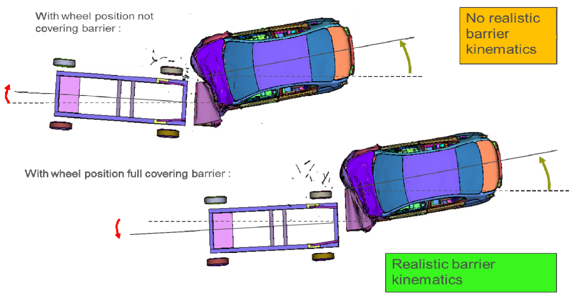

Figure 21 : trolley & car kinematics comparison

The other trolley's parameters (mass distribution, center of gravity location, tire stiffness…) are less influent.

Barrier PARAMETERS influence :

-<u>Height of barrier influence</u> : for sedan cars, we found that the value of the top of the barrier has only a small influence on the car deformations and we have found a better stability with the PDB "ADAC Barrier version"

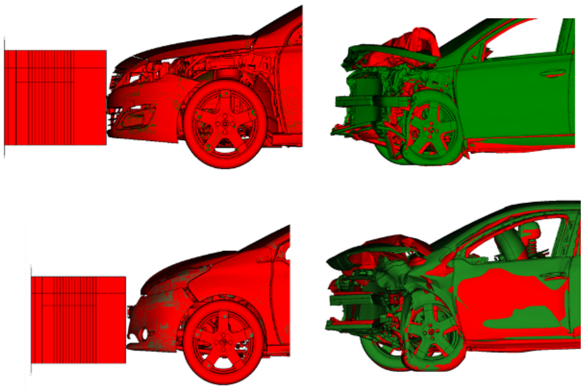

Figure 22 : Barrier & car interaction comparison

Car dispersion influence : <u>Car behavior influence</u>: results on car behavior are only small dispersed (but we have used a car model which has a stable behavior) :

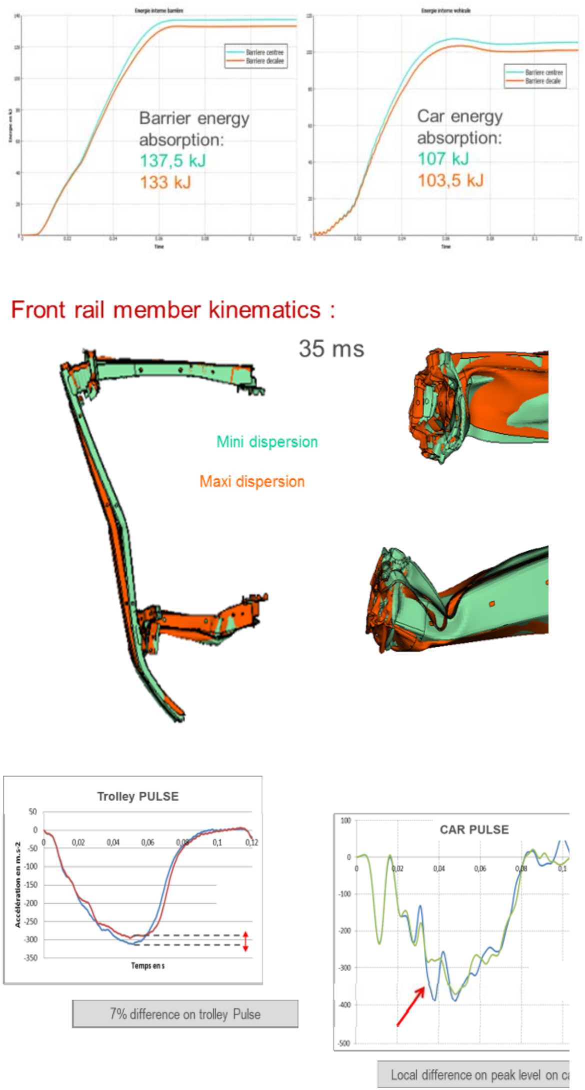

Figure 23 : Dispersion analysis on car behavior

How To Provide A Better Compatibility

As a car maker, we can use these previous results to lead the design of one future car: energy absorption target, force / displacement characteristic, structural engagement area and stiffness of front unit and cockpit are the input data to guide a preliminary draft.

In particular, a lower load path is a good way to make sure a good structural engagement (the first condition to a good compatibility) as we can see with the C2C Peugeot 3008 / Renault CLIO :

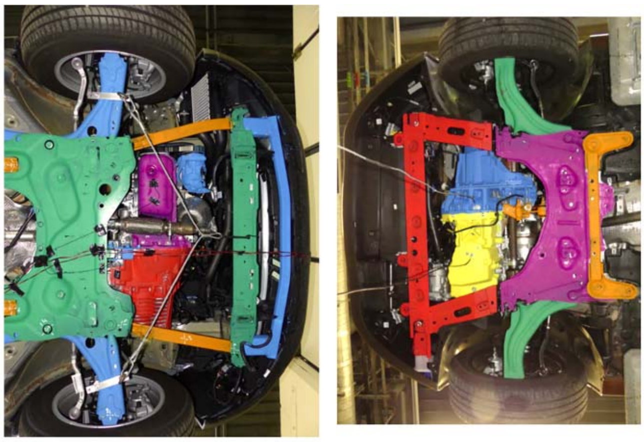

Figure 24 : Lower load paths efficient for a good structural engagement

In a first sight, between those 2 cars, compatibility seems to be quite GOOD.

Figure 25 : Peugeot 3008 & Renault CLIO after C2C test (UTAC)

CONCLUSIONS

The purpose of Compatibility in front crash is to represent a C2C front crash which is the most frequent configuration in real accidentology. But C2C is a too complex and costly configuration to be applied on experimental and even numerical point of view.

Furthermore, some specific criteria can't be directly measured during a C2C test or FE-calculation, as global force entrance between Cars and Barrier, distribution of forces and absorbed energy at the interface between cars. Yet, an automotive car maker needs to use simplified, relevant and quick tools to be efficient in preliminary drafts design of future cars.

That is the reason why we have first developed simplified mathematical models which allow us to forecast and quantify the kinematic parameters of the 2 cars (delta velocity and energy variation): we used them to study the « mass aggressiveness » phenomenon, showing the disadvantage for small cars.

Then, we have determined that the M-PDB 50km/h 50% is the most representative of the C2C configuration (regarding the pulse point of view); we have studied also the repetitiveness/ dispersion of this protocol.

Finally, we have analyzed the phenomenon of structural interaction between front faces of cars; we have used a method to extract « Force / crushing distance » and other physical characteristics which can explain the « geometrical and stiffness aggressiveness » phenomenon.

Of course, the field of compatibility still remains large and open, but this study gives us the efficient physical parameters as input data to specify and design the future cars at PSA Groupe.

TECHNICAL REFERENCES :

[1] -FIMCAR : FINAL REPORT = Review and Metric Development (2013 : Ignacio Lazaro, Nicolas Vié, Robert Thomson, Holger Schwedheim)

[2] -The Development of a Mobile Deformable Barrier Test Procedure (2012 : Richard Schram : TNO)

[3] -EU-Project FIMCAR : Synthesis of test procedure (2011 : Thorsten Adolph, Marcus Wisch)