PRE-CRASH PHASE ANALYSIS USING A DRIVING SIMULATOR. INFLUENCE OF ATYPICAL POSITION ON INJURIES AND AIRBAG ADAPTATION.

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ABSTRACT

This paper deals with an approach to analyze driver behavior during critical events using a driving simulator. A scenario of an unavoidable crash is simulated. Eighty subjects have participated to this experiment. Drivers' behavior is video recorded, as well as many mechanical and physiological measurements. Most of drivers are observed to swerve away to avoid the collision. This leads many of them to have one arm in front of the steering wheel at time of crash. The drivers' trunk and arm positions during the collision, observed on the simulator, are analyzed with numerical simulations of a 56 km/h frontal collision. The results of the computational runs put forward injurious situations, especially when the driver's arm is behind the steering wheel and hits the head under airbag deployment. Then, an experimental campaign of airbag deployment with a hybrid III 50th percentile dummy is carried out to correlate numerical simulations. Finally, new airbag generations, allowing slower deployment, are tested. They induce a reduction of injury severity in the case of Out of Position (OOP).

INTRODUCTION

Vehicle safety is the major issue when designing a car. Many studies deal with the communication between drivers and driver support systems, with aim to assist driver from normal driving situation to critical one. Large improvement in active and passive safety technologies in vehicle has helped to reduce the number of accidents significantly. Active security operates before an incident and includes prevention (Anti-lock Brake Systems, Electronic Stability Program, etc) to avoid a crash. Passive safety concerns the period after the crash, it tries to protect occupants and pedestrians to minimize car occupant injuries. Main examples of passive security systems are airbags and seat-belts. These restraint systems are designed to minimize injuries during an impact by smoothly absorbing the kinetic energy of the occupant during a crash event [7].

In order to quantify the efficiency of the passive security systems on injury severity, normalized crash tests are performed with crash test dummies. The injury level is approximated using specific criteria related to critical body segments such as the Head Injury Criteria (HIC) and the Thoracic Trauma Index (TTI). Precise rules are imposed by the norm to position the dummy, whose posture must represent a seated and restrained driver. Particularly, the hands are on the steering wheel and the superior part of the torso leans against the backseat. Thus, passive systems efficiency does not take into account the driver anthropometry, real comfort driving position and reflex reactions facing an incident. The non normalized postures are called 'out-of-position' (OOP) postures. Some OOP postures, defined to be the most prejudicial for car occupants, have been tested by the NHTSA. For example, crash tests are performed with a dummy positioned with the torso as close as possible to the steering wheel, or, with the dummy face (nose) touching the top of the steering wheel [11]. In these tests, the dummies are not restrained by the seat-belt. Nevertheless, the standardized and these OOP crash tests do not take into account real postures that a driver or a passenger adopts at the time of crash.

This study is designed to investigate how a car driver modifies his posture just before a frontal crash and then to quantify the influence of these observed pre-crash postures on injury mechanisms by computer simulation. Experiments are performed by using car driving simulators, in which an unavoidable frontal accident is carefully designed. Risk pre-crash positions are observed and are modeled using a digital human model. Static airbag deployment test are performed to validate simulations with a hybrid III 50th percentile dummy. Finally, new generation of airbags is tested, using bonded bags. This allows a slower deployment, in order to reduce injuries.

METHODS

The LAMIH driving simulator, SHERPA

Two experimental campaigns are carried out with the static and the dynamic LAMIH car driving simulator, SHERPA (French acronym for 'Simulateur Hybride d'Etude et de Recherche de PSA Peugeot Citroen pour l'Automobile'). A description of the static car driving simulator can be found in [8]. The dynamic driving simulator is derived from a Peugeot 206 mounted on a hexapod composed by six electric jacks (Figure 1a). The front and rear scenes are projected by LCD screens. For both campaigns, the same crash scenario is reproduced.

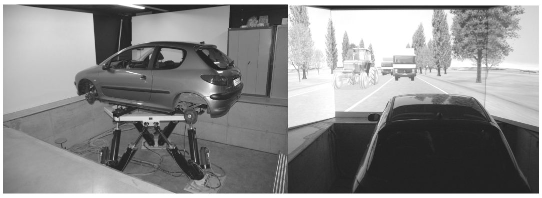


Figure 1. a) Dynamic driving simulator. b) 180° front visual field before a crash.

Experimental design

The experiment is designed to investigate the influence of driving responses on crash occurrence. Each subject encounters an emergency traffic event during the experimental drive. The subjects believed they were participating to an ergonomic study so they could not predict the existence and the location of the collision. The scenario is as follows.

The collision occurs on a main road segment. The driving environment is composed of a road with two lanes, separated by a white line. This road is bordered with trees. A truck suddenly appears into the lane used by the host vehicle (i.e. driving simulator) such that the scenario could not be expected by the subject. This vehicle overtakes a tractor on his way. The presence of trees along the side of the road and the trucks make the crash unavoidable (Figure 1b). To increase the level of reality, a real physical impact is added. At the moment of the virtual crash, a substantial foam rubber block impacts the windscreen of the car, and the sound of a truck horn is emitted.

Eighty randomly-selected subjects have been recruited to participate to this driving experiment. Most of subjects are aged between 22 and 30 years old, with more men than women. The mean weight and height of the subject is 78 kg and 1.77 m respectively. All participants have a valid driving license. Half of them have driving experience of 8-27 years. The other half of the subjects has their driving license for less than 7 years.

Experimental procedure

Subjects first provide their personal information—sex, age, and driving experience. Anthropometric data are measured in a calibrated space to allow a postural reconstruction method [5,6].

Experimental instructions are given for the driving task and subjects are instructed by assistants in how to operate the simulator.

After a short training session designed to familiarize the subjects with the simulator, each subject is asked to drive a 50-kilometer dual carriageway (35 to 40 minutes). The run is mainly composed of main roads, with a small section of motorway. Throughout the trip, regular traffic is reproduced so that subjects respect the Highway Code and adapt their driving to the presence of other cars. Five minutes before the end of the experiment, a stress situation occurs to make the driver attentive: a car, approaching a crossroad from the right, runs the stop sign, which may lead to an accident with the subject vehicle. This situation is designed to remind subjects that unpredictable events may happen at any time. After a few minutes, the unavoidable crash situation is introduced. At the end of the run, drivers are asked to fill out questionnaires evaluating their driving characteristics (behavior patterns), their reactions to each separate situation and the realism of the experiment.

Measurements

For both campaigns, the videos of front and back screen, as well as driver views are recorded during the experiments (Figure 2).

Figure 2. Interiors views of video recording during the crash.

The driver-vehicle-environment interaction parameters are measured, such as impact velocity, time of crash, steering wheel position, state of the pedals, gear lever position and the arrangement of the vehicles on the road. Furthermore, mechanical and physiological measurements are added for the second campaign with the dynamical driving simulator. Mechanical data include the forces and torques transmitted by the driver to the steering wheel, the seat and the brake pedal. Physiological data include heart rate, respiratory and electrodermal activities, skin temperature and electromyography data of few muscles of the upper and lower limbs (triceps brachii, biceps brachii, trapezius, wrist extensor, quadriceps, soleus muscle, tibialis anterior, ischio). All these signals are triggered with videos and simulators events. These physiological measurements can be used to investigate human incident detection. The mechanical measurements serve to improve computational simulations.

Results

Simulation realism

Subjective and objective data are collected to evaluate the realism of the experiment [8]. Subjective data include both the driver's verbalizations and their answers to questions evaluating their driving behavior and their reactions. Objective data include the time needed to release the accelerator, to brake, to engage the clutch, to change gears, as well as, the amplitude of the braking and swerving maneuverings provoked by the truck passing. It can be concluded that most of the subjects have reacted as they would have done in real situation.

General driving characteristics

All subjects react to the traffic accident by actions on pedals and/or steering wheel. General driving performances are presented in Table 1. The average speed in town is calculated from the host vehicle speed at 50 m after the enter town panel and its speed at 50 m before the exit town panel. The collision occurs on a main road segment. The average driving speed of the host vehicle is 76.3 km/h. This speed is quite steady until the truck appears on the lane (the truck is visible at 150 m). Then, most of subjects brake. The average deceleration rate is 1.6 m/s². The overlap of the vehicles during the impact is 61.8% and the angle between the truck and the host vehicle vary from -18.8° à 5.1°. Most of subjects try to avoid the truck on the left. Six percent of drivers avoid the collision.

Table 1.
General driving performances

	Mean	Min	Max	SD
Motorway speed (km/h)	122.6	97.8	135.7	8.6
Highway speed (km/h)	65.3	59.4	71.0	3.0
City speed (km/h)	48.9	32.9	60.0	5.9
Speed at 150m before crash (km/h)	76.3	50.7	96.1	10.3
Speed when truck passes (km/h)	78.5	58.4	94.5	8.6
Speed at crash time(km/h)	70.6	45.7	90.8	10.1
Collision overlap (%)	62.4	4.4	99.3	27.0
Collision angle (°)	-2.0	-18.8	5.1	5.1
Distance when truck passes (m)	29.6	18.3	39.0	4.7
Deceleration from truck passing to crash (m/s²)	1.6	3.8	-0.4 (Acc.)	1.0

Effort analysis

The Figure 3 indicates the position and the positive direction of force sensors. A pressure map is added to locate efforts on the seat.

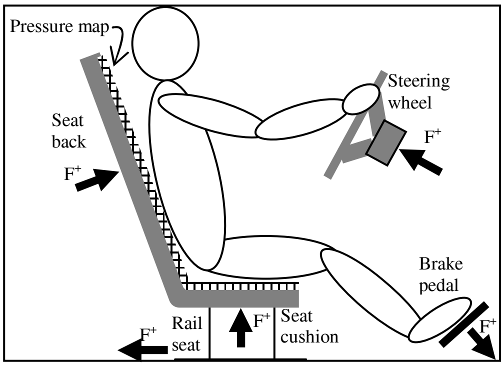


Figure 3. Sensor positions.

At the end of the experiment, subjects are asked to push the steering wheel and the pedals with maximal voluntary efforts, with hands placed in a 10 and 2 o' clock position. The efforts measured in the seat, the steering wheel and the pedals are denoted F_{full}. The same experiment is reproduced but with pulling on the steering wheel. The values of F_{full} are used to normalize efforts measured during experiment. If the driver pushes the steering wheel during impact, the F_{full} efforts measured during pushing out are used to normalize the values. If the driver pulls on the steering wheel during the crash, the F_{full} efforts measured during the pulling on are used to normalize the values. This normalization allows to compare driver efforts independently of their morphological variability.

Four situations are analyzed:

1) Quiet situation: time interval from -50s to -5s before the truck appearance time in the frontal view.

2) 150 m before crash: time interval from -0.5s to 0.5s of the truck appearance time.

3) Truck passing: time interval from -0.5 s to 0.5s of the white line crossing time.
4) Crash: time of the collision (the vehicle hits the truck).
For each driver, the efforts exerted on the seat (cushion and back), the steering wheel, the adjustment rail of the seat and the pedals are computed for each situation. Except for the crash time, these forces correspond to mean values computed on the corresponding time interval.
For each situation, inter-individual statistics are presented (Table 2.):
-Min F: minimum effort among all drivers
-Min F/ F_{full}: minimum ratio among all drivers
-Max F: maximum effort among all drivers
-Max F/ F_{full}: maximum ratio among all drivers
-Mean: mean of all drivers efforts and ratio
-Std dev.: standard deviation

Table 2.
External forces during track

Seat back	Min (F)	Min (F/F_full)	Max (F)	Max (F/F_full)	Mean value	Std dev.
Quiet situation						
F (N)	**-220.7**	-70.9	**-42.9**	-220.7	-131.2	47.1
F/F_full (%)	38.6	**5.8**	6.9	**38.6**	17.1	7
F_full (N)	-571.8	-1231.1	-622.3	-571.8	-811.9	259.1
150 m before crash						
F (N)	**-199.4**	-76.2	**-41.7**	-198.1	-127.7	46.2
F/F_full (%)	24	**6.2**	6.7	**34.6**	16.6	6.5
Fsat(N)	-831.3	-1231.1	-622.3	-571.8	-811.9	259.1
Truck pass						
F (N)	**-233.8**	-32	**-32**	-233.8	-132.3	50.3
F/F_full (%)	40.9	**5.1**	5.1	**40.9**	17.1	7.2
F_full (N)	-571.8	-622.3	-622.3	-571.8	-811.9	259.1
Crash						
F (N)	**-1078.3**	-225.2	**-225.2**	-1078.3	-503.3	194.5
F/F_full (%)	188.6	**19.1**	19.1	**188.6**	66.6	32.9
F_full (N)	-571.8	-1176.8	-1177	-571.8	-811.9	259.1

Cushion seat	Min (F)	Min (F/F_full)	Max (F)	Max (F/F_full)	Mean value	Std dev.
Quiet situation						
F (N)	**-687.9**	-351.9	**-300.0**	-527.3	-401.7	90.8
F/F_full (%)	82.4	**64.1**	89.8	**92.0**	78.9	7.6
F_full (N)	-834.4	-548.9	-334.2	-573.0	-509.9	104.5
150 m before crash						
F (N)	**-687.6**	-348.6	**-300.2**	-530.9	-408.1	88.7
F/F_full (%)	82.4	**63.5**	89.8	**92.6**	80.2	6.9
F_full (N)	-834.4	-548.9	-334.2	-573.0	-509.9	104.5
Truck pass						
F (N)	**-708.5**	-366.7	**-300.8**	-533.5	-408.3	89.7
F/F_full (%)	84.9	**66.8**	90.0	**93.1**	80.3	6.9
F_full (N)	-834.4	-548.9	-334.2	-573.0	-509.9	104.5
Crash						
F (N)	**-522.5**	-114.1	**-114.1**	-516.1	-259.5	102.5
F/F_full (%)	62.6	**24.0**	24.0	**110.2**	51.1	18.0
F_full (N)	-834.4	-475.7	-475.7	-468.2	-509.9	104.5

Seat rail	Min (F)	Min (F/F_full)	Max (F)	Max (F/F_full)	Mean value	Std dev.
Quiet situation						
F (N)	**79.4**	82.5	**199.1**	133.3	125.9	33.2
F/F_full (%)	19.9	**15.3**	32.6	**42.1**	25.2	7.4
F_full (N)	399.8	538.4	611.4	316.5	520.4	122.0
150 m before crash						
F (N)	**79.2**	81.8	**198.9**	134.8	125.5	33.4
F/F_full (%)	19.8	**15.2**	32.5	**42.6**	25.1	7.5
F_full (N)	399.8	538.4	611.4	316.5	520.4	122.0
Truck pass						
F (N)	**80.1**	87.9	**205.5**	137.4	129.0	34.5
F/F_full (%)	20.0	**16.3**	40.8	**43.4**	25.8	7.6
F_full (N)	399.8	538.4	503.9	316.5	520.4	122.0
Crash						
F (N)	**216.5**	216.5	**821.0**	760.1	537.2	151.6
F/F_full (%)	28.8	**28.8**	134.3	**240.2**	111.5	48.1
F_full (N)	752.5	752.5	611.4	316.5	520.4	122.0

Steering wheel	Min (F)	Min (F/F_full)	Max (F)	Max (F/F_full)	Mean value	Std dev.
Quiet situation						
F (N)	**-34.4**	16.4	**16.4**	-34.4	-6.8	13.0
F/F_full (%)	8.3	**-5.8**	-5.8	**8.3**	0.6	3.6
F_full (N)	-414.6	-284.1	-284.1	-414.6	-124.1	461.4
150 m before crash						
F (N)	**-29.8**	20.2	**20.2**	-28.7	-7.1	13.5
F/F_full (%)	-3.9	**-7.1**	-7.1	**7.3**	0.8	3.6
F_full (N)	769.8	-284.1	-284.1	-394.6	-124.1	461.4
Truck pass						
F (N)	**-60.7**	-14.0	**22.8**	22.8	-14.9	20.6
F/F_full (%)	8.4	**-4.5**	14.7	**14.7**	3.8	5.2
F_full (N)	-724.4	313.4	155.1	155.1	-124.1	461.4
Crash						
F (N)	**-561.1**	29.3	**210.2**	210.2	-92.7	167.2
F/F_full (%)	135.3	**4.7**	135.6	**135.6**	38.0	40.6
F_full (N)	-414.6	629.3	155.1	155.1	-124.1	461.4

Brake pedal	Min (F)	Min (F/F_full)	Max (F)	Max (F/F_full)	Mean value	Std dev.
Quiet situation						
F (N)	**-0.1**	-0.1	**1.8**	1.4	0.5	0.5
F/F_full (%)	0.0	**0.0**	0.2	**0.7**	0.1	0.2
F_full (N)	571.0	571.0	817.3	207.5	529.0	241.6
150 m before crash						
F (N)	**-0.4**	-0.4	**2.1**	1.3	0.5	0.6
F/F_full (%)	-0.1	**-0.1**	0.3	**0.6**	0.1	0.2
F_full (N)	416.6	416.6	817.3	207.5	529.0	241.6
Truck pass						
F (N)	**0.4**	0.4	**87.1**	30.0	26.6	21.5
F/F_full (%)	0.1	**0.1**	14.0	**14.5**	5.8	4.2
F_full (N)	722.0	722.0	621.8	207.5	529.0	241.6
Crash						
F (N)	**78.4**	96.1	**502.9**	291.1	245.0	122.7
F/F_full (%)	29.6	**11.8**	80.9	**85.9**	51.1	21.1
F_full (N)	265.4	812.8	621.8	339.0	529.0	241.6

Each table corresponds to a measurement channel (cushion seat, back seat, longitudinal adjustment rail of the seat, steering wheel, brake pedal).

Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 present the evolution of the ratio F/F_{full} for all measurement channels and for all drivers.

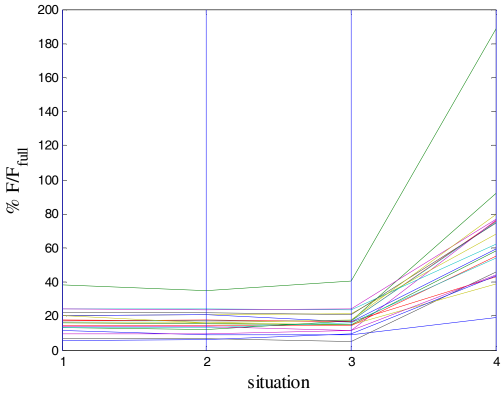


Figure 4. Evolution of seat back ratio for subjects until crash.

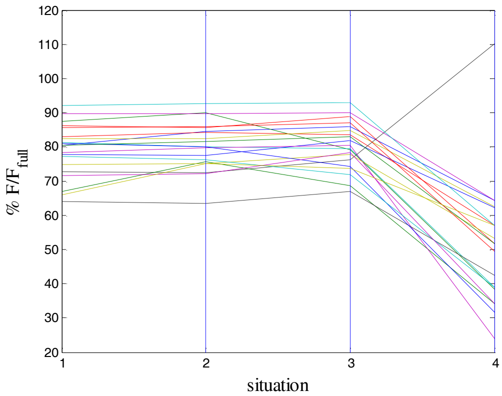


Figure 5. Evolution of cushion seat ratio for subjects until crash.

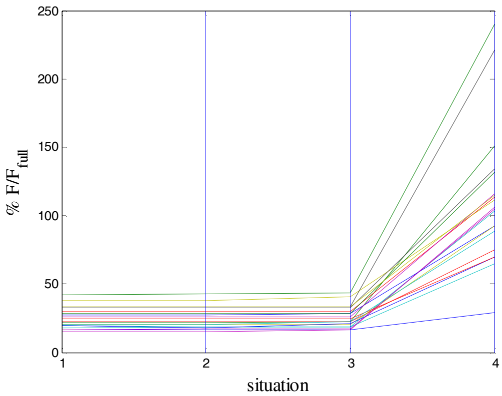


Figure 6. Evolution of seat rail ratio for subjects until crash.

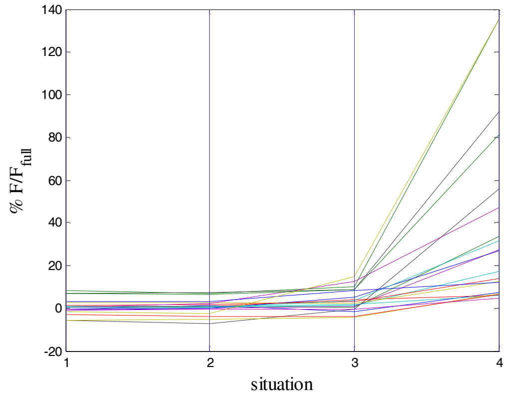


Figure 7. Evolution of steering wheel ratio (compression) for subjects until crash.

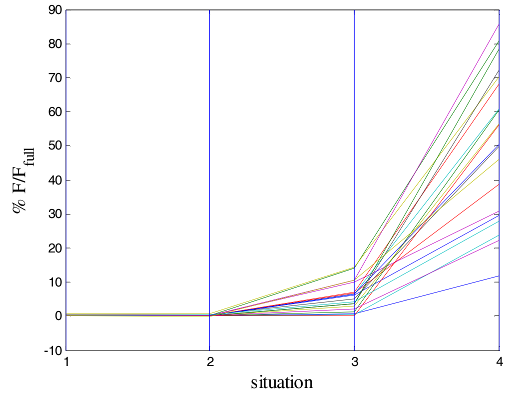


Figure 8. Evolution of brake pedal ratio for subjects until crash.

Global positions of the drivers remain unchanged until the truck crosses the white line. During the quiet situation, no force is exerted on the braking pedal. Then, drivers brake suddenly. The mean effort exerted on the pedal when the truck passes the tractor is 27N. It increases to 245N at the moment of the collision. The maximal effort value recorded at this moment is 503N (81% of F_{full} pedal). This induces an increase of seat back and rail efforts and a decrease of seat cushion efforts. The mean value of seat back and rail efforts are steady until the time of crash (130N) then grow to around 500N. The seat cushion effort reduces from 400N to 260N. Only one person embeds in the seat cushion (increase of cushion seat force). The mean efforts exerted on the steering wheel passes from -10N to -93N (pushing out) at the moment of the impact. At this time, the maximum value is 561N and corresponds to 135% of F_{full} steering wheel. This can be explained by the fact that F_{full} efforts are sustained efforts while driving efforts are instantaneous efforts.

Hands and Chest positions

Injury to the upper body is the main risk in a frontal crash. The positions of chest and hands are analyzed from the recorded videos at the moment of impact.

Hand positions

At the beginning of the experiment, subjects adopt a 10 and 2 o'clock position or 9 and 3 o'clock position. Comfort position is observed only after twenty minutes. For the left arm, subjects often rest their arm by putting their elbow on the window sill or the forearm on their thigh. For the right arm, drivers often rest their arm by laying their right hand on the gear lever or the forearm on their thigh. Subjects regularly come through one comfort position to another one.
Then, during the crash event, most of drivers try to control the situation by swerving, to avoid the truck in front of them. Table 2 and Table 3 describe upper limb positions when the truck overtakes the tractor and at the moment of impact, respectively.

Table 2.
Hand positions at truck pulling out time

Positions	*Left hand*	*Right hand*	*%*
1	On the steering wheel	On the steering wheel*	65.74
2	On the steering wheel	On the gear lever	18.57
3	On the steering wheel	On the right thigh	7.14
4	On the left thigh	On the steering wheel	2.86
5	On the air	On the steering wheel	2.86
6	On the hub	On the steering wheel	1.43
7	On the steering wheel	On the handbrake	1.43

* whose 2,86 % have their left elbow on the window sill
* whose 5,72% have their right forearm laid on their right thigh

Hand position analyses, at the moment of truck pulling out (Table 2.), show that more than 90% of the subjects have their left hand on the steering wheel and their right hand either on the steering wheel (66%), the gear lever (19%) or the right thigh (7%). These positions correspond to an evolution position instead of a comfort position, since these positions are observed when subjects see the truck at the horizon. Indeed, subjects generally replace their hands on the steering wheel when a disturbing event appears in their vision field (for example, when the subject is overtaken, when a truck is approaching or when a vehicle is braking).
At the moment of impact, more than 90% of the subjects have their left hand on the steering wheel and their right hand on the steering wheel (54 %) or on the gear lever (37 %) (Table 3). The remaining 9% of the subjects have their left hand on the steering wheel and their right hand on the handbrake, their thigh or intermediate position (for example between the steering wheel and the gearshift).

Table 3.
Hand positions at the time of impact

Positions	*Left hand*	*Right hand*	*%*
1	On the steering wheel	On the steering wheel	52,86
2	On the steering wheel	On the gear lever	35,71
3	On the steering wheel	On the air*	7,14
4	On the steering wheel	On the handbrake	1,43
5	On the steering wheel	On the thigh	1,43
6	On the air	On the steering wheel	1,43

* for example when the subject tries to take the gearshift.

The distribution of the hand positions in the environment is presented in Figure 9.

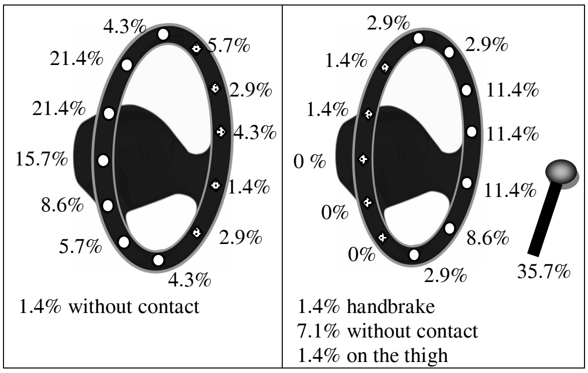


Figure 9. Percentage of subjects' left and right hand positions on steering wheel.

In 17% of cases, the left hand is in a 1 to 5 o'clock position. For 2.8% of cases, the right hand is in a 10 or 11 o'clock position. All these positions, which represent a total of 19.8 % of cases, are potential risk positions. Indeed, in these cases, the forearm is placed in front of the hub and is likely to be projected against driver face under airbag deployment. Prior to impact, 100% of the subjects have braked and 54.26% have declutched. This can explain that 35.7% of the subjects have their right hand on the gear lever. Indeed, a strong braking is often associated with declutching. Concerning the normative position in a frontal impact, 21.4% of subjects have their left hand in a 10 o'clock position, 11.4% have their right hand at 2 o'clock, but only 7.14% of subjects are in a 10 and 2 o'clock position.

Upper body positions

The positions of the upper body are observed when the truck is approaching the driver's car. Five classes of behaviours are defined (Figure 10):
(i) Posture 1 - 22 % have no postural change,
(ii) Posture 2 - more than 67 % move backward to anticipate the crash,
(iii)Posture 3 - at the same time, 57 % of those who move back make a rotation of their chest,

(iv)Posture 4 - less than 3 % make a trunk rotation without moving backward,
(v) Posture 5 - 8 % move head towards the steering wheel.

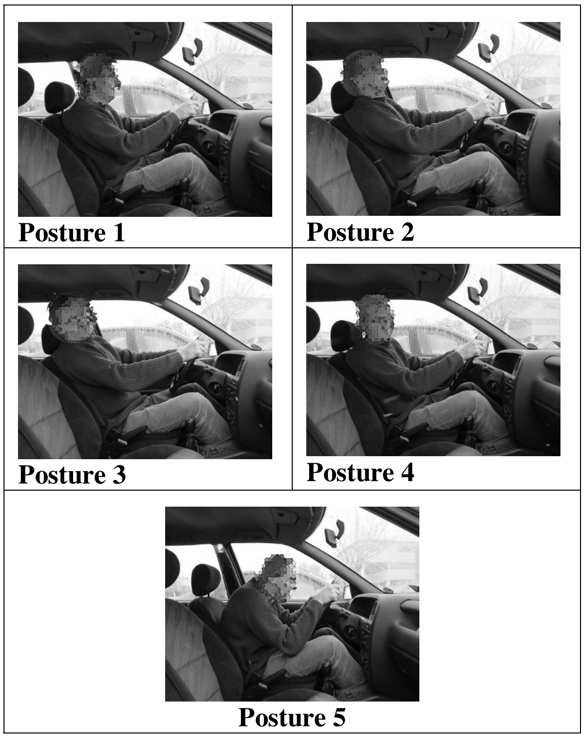


Figure 10. Upper body positions.

These results clearly show that very few subjects adopt a standardized chest driving position during the collision. The influence of these driver positions (hand positions and upper limb movements) on injuries are investigated numerically with the software Madymo®. Upper limb injury criteria are compared between a standard 10 and 2 o'clock position and OOP observed on the driving simulator.

BIOMECHANICAL ANALYSIS

The biomechanical analysis is made with a numerical model of the crash dummy Hybrid III 50th percentile male available in Madymo® database. The position of the dummy is determined from real driver pre crash posture by a postural reconstruction method.

Pre-crash posture measuring

A postural reconstruction method like in [5,6] can be used to approximate joint angles of driver upper limbs at time of crash. From at least two photos of different views taken in a calibrated space, the software MAN3D developed by the INRETS [12] allows to adjust the anthropometric dimensions and joint angles of a virtual dummy on an experimental subject. These data can be transferred to Madymo to position the numerical dummy model as in real conditions.

Madymo® simulation

For this study, the existing model for frontal crash available from Madymo® is used. Load applied to the virtual dummy (Hybrid III 50th percentile male dummy) corresponds to the deceleration undergone by a car during a head-on collision at 56 km/h. Non finite element seat-belt is used to secure the dummy. Simulations are performed for five different chest postures and two various hand positions (Figure 11 and Figure 12). Contacts between arm and head, and, between arm and airbag, are added. Their definitions are based on existing contacts between other limbs and airbag (thorax/airbag).
The peak linear acceleration, the HIC15 and the 3-MS injury criteria are calculated for the head. Injuries to the neck are predicted by the neck injury predictor Nij. The Nij is the collective name of four injury predictors corresponding to different combinations of axial force and bending moments: NTE tension-extension, NTF tension-flexion, NCE compression-extension, NCF compression-flexion. For frontal collision, the neck injury predictor of NTF (tension and flexion moment) is usually higher than the other neck injury predictor. The neck injury predictor can be evaluated in two different manners. According to the Madymo, none of predictor may exceed a value of one. Nevertheless, the FMVSS No.208 specification [3,10] requires that none of the four Nij values exceed 1.4 at any time during the event. In this study, the Nij is evaluated according to Madymo assessment. All these values are reported in Figure 11 and Figure 12.
Posture 1-1 represents the normalised driving posture. The peak linear head acceleration reaches 62.7 g. The head injury criteria values, HIC15 are estimated at 342.
All head injury criteria values, for the other four chest postures with hands at 10 and 2 o'clock, increase as compared to the model at normalised posture (Figure 11). Nevertheless, lower head injury criteria values are recorded for the posture 4-1 according to posture 2-1 and posture 3-1. This can be explained by the distance between the torso and the steering wheel. Indeed, for these latter postures, the dummy has the upper body leaned against the seatback. So, a greater distance exists between the dummy torso and the steering wheel than for posture 4-1. This allows the dummy to take speed during impact. Thus, the dummy hits the airbag with a higher speed and a greater impact force. The slight head rotation in posture 3-1 increases the maximum head acceleration and injury criteria compared to posture 2-1 without head rotation.

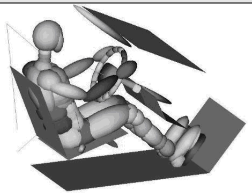
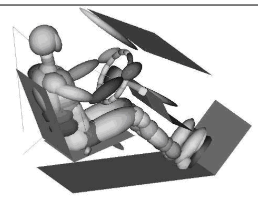
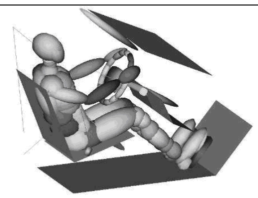
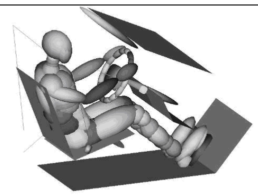
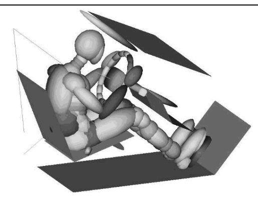
Chest \ Hands	Standard position
Standard position posture 1-1 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 62.7 $342.0_{15.0ms}$ 56.4 0.4
Backward movement No chest rotation posture 2-1 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 78.2 579.415.0ms 71.6 0.46
Backward movement Chest rotation posture 3-1 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 78.4 $610.0_{15.0ms}$ 72.8 0.46
No backward movement Chest rotation posture 4-1 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 66.9 $412.3_{15.0ms}$ 61.5 0.38
Forward movement No chest rotation posture 5-1 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 91.3 809.415.0ms 84.2 0.74

Figure 11 - Postures and injury criteria for a standard hand position.

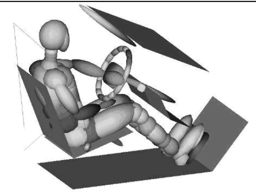
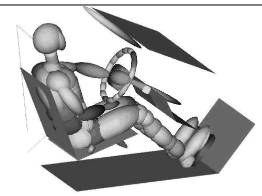
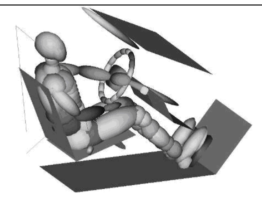
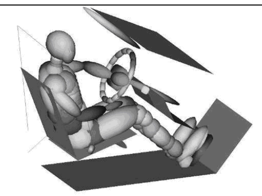
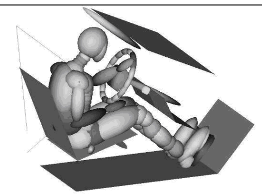
Chest \ Hands	Atypical position
Standard position posture 1-2 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 730.0 $14761_{2.2ms}$ 80.3 4.15
Backward movement No chest rotation posture 2-2 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 761.4 $19814_{2.2ms}$ 96.9 4.27
Backward movement Chest rotation posture 3-2 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 615.5 $12160_{2.3ms}$ 172.7 4.19
No backward movement Chest rotation posture 4-2 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 980.6 $26977_{2.0ms}$ 83.1 2.97
Forward movement No chest rotation posture 5-2 Max.lin.acc (g) HIC15 (<700) 3MS (g) (<80) Max Nij (<1)	 463.1 $5237.2_{1.9ms}$ 46.7 2.97

Figure 12 - Postures and injury criteria for a non standard hand position.

However, posture 5-1 is the most injurious position (the HIC15 is over the Injury Assessment Reference Values (IARV) (<700)). In this case, the dummy head is very close to the steering wheel. During impact, the airbag deploys at very high speed and directly pushes the face of the dummy. As a consequence, the neck bends rearward and the head is launched backward.
A significant increase in the maximum linear head acceleration is observed for the five chest postures with the left hand at the right side of the steering wheel (posture 1-2 to posture 5-2) (Figure 12). The HIC15 for all these models are well over the existing tolerance limit for the frontal impacts. For the five chest postures, the airbag projects the arm against the head. This phenomenon corresponds to a critical situation which can lead to a mortal traumatism. The 3-MS injury criterion, calculated for the head, depends on how the arm hits the dummy head. For the posture 3-2, the left arm hits the right lower chin. As a consequence, the head is turned violently to the left. For posture 2-2 and posture 4-2, the arm hits the dummy at the lower chin. So, the neck is tilt backward. As neck model stiffness is larger in forward/rearward bending than in lateral bending, the 3MS-injury criterion is higher for posture 3-2 with a value of 172.7 g.
The maximum linear head acceleration and the 3MS injury criterion calculated for posture 5-2 have slightly lower values compared to the four other postures. In this case, the arm is very close to the head. So, the coupling between the arm and the head occurs earlier. Hence, the relative velocity is lower. The IARV for the head 3MS-injury criterion is 80 g. Except for posture 5-2, values obtained exceeds this limit.
The Nij values, for posture 5-1 and postures with the left hand on the right side of the steering wheel, exceed the acceptable limits. This indicates that the impact causes lasting neck impairment. Moreover, neck injuries are more likely to occur in the driving posture with one hand placed just in front of the airbag than in other postures.

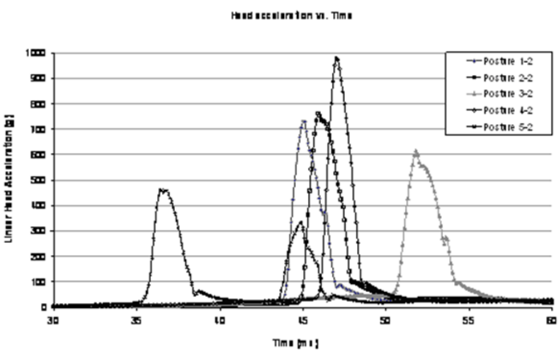


Figure 13. Linear head acceleration versus time plot for models with the left hand at the right side of the steering wheel.

For the atypical postures, extremely high values of linear head acceleration are observed (Figure 13). Using HIC values as injury criteria estimation would not be realistic in this case. Indeed, HIC is a function of the area under graph linear head acceleration over the time interval when a peak is observed. The phenomenon of extremely high HIC scores results from the sharper acceleration spike and substantially shorter HIC time interval (indexed values in Figure 11 and Figure 12) for the models with the left hand positioned on the right side of the steering wheel. The 3MS injury criterion is preferred, here, for the head since the value of maximum linear head acceleration is always being estimated for a time window with a width of 3 ms.

Numerical simulations, realized with Madymo®, show the importance of driver positions at the moment of impact in the assessment of neck and head injuries. However, this first approach shows some limitations. Contact definitions and arm kinematics have to be validated. So, airbag deployment tests are performed with a hybrid III 50th percentile dummy.

AIRBAG TESTS AND NUMERICAL VALIDATION

Tests are performed in collaboration with Zodiac Automotive.
The vehicle environment is reconstructed. The dummy Hybrid III 50th percentile Male is positioned according to car driving simulator experiment observations with its left arm behind the steering wheel (Figure 14). Tests are performed with a conventional airbag (sewn cushion, open event, pyrotechnical technology). Tests are performed in static.

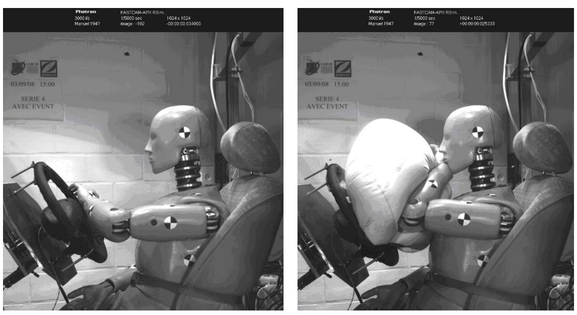


Figure 14. Crash test dummy.

Then, the static test with the conventional airbag cushion is reproduced on Madymo® (Figure 15). The inflator mass flow rate and blowhole characteristics of the numerical airbag model are adapted to reproduce the deployment of the real airbag cushion. The characteristics of the contacts head/arm and arm/airbag are tuned in order to reproduce the experimental linear head acceleration (Figure 15).

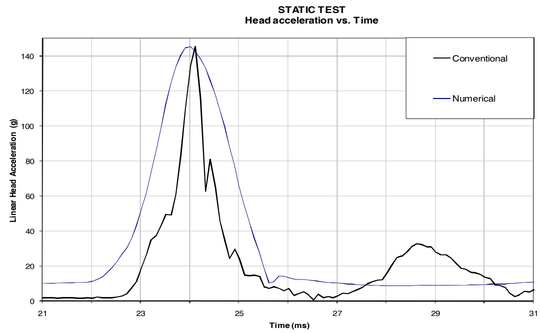


Figure 15. Linear head acceleration for the experimental and the numerical models.

Predicted head linear acceleration is correlated reasonably well with test data as shown by the experimental and numerical curves. The timing and value of the peak acceleration is well estimated. The width of the peak is larger for numerical head acceleration. This may be due to damping coefficients for contacts head/arm and arm/airbag.

This validated model is used to reproduce dynamical tests (a 56 km/h frontal collision) (Figure 16). Simulations are performed for the two various hand positions (standard posture with hands at 10 and 2 o'clock and atypical posture with left hand on the right side of the steering wheel) and the dummy back leaned against the seatback (posture 1-1 and posture 1-2). The injury criteria values are presented in Figure 16.

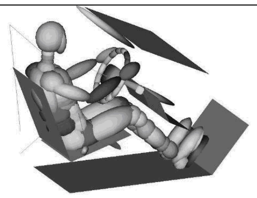
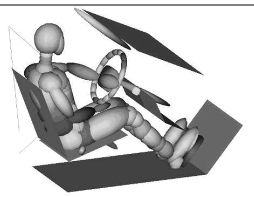
posture 1-1	
Max.lin.acc (g) **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	**50** **$200.0_{15.0ms}$** **44** **0.3**
posture 1-2	
Max.lin.acc (g) **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	**145.0** **$2730_{1.2ms}$** **36** **1.1**

Figure 16. Injury Criteria obtained for the validated model (conventional airbag).

The linear head acceleration obtained with the validated model for standard and atypical postures are illustrated in Figure 17.

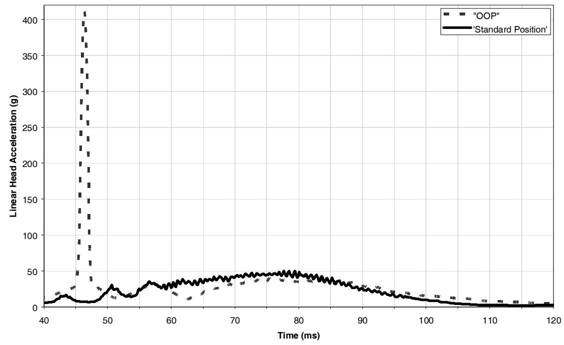


Figure 17. Linear head acceleration obtained with the numerical validated model for a standard and atypical position (conventional airbag).

It can be concluded that contact characteristics strongly influence the results. Values obtained for the normalized position (posture 1-1) are quite similar for the two models. Values obtained with the validated model for the atypical position (posture 1-2) are lower than those obtained with the standard Madymo model. Nevertheless, the atypical position, with the arm behind the airbag, is still injurious for the head and the neck.
The other chest postures need to be modeled with the validated model.

NEW AIRBAGS GENERATION

Nowadays, airbag cushion benefits are clearly demonstrated by statistic when the number of crash is not decreasing. All major OEM are now working on the crash avoidance refer to the last FISITA 2008 conference about car safety. Airbag cushion can use the latest technology to avoid occupant injuries and improve protection of occupants in case of crash.The latest developments in automotive safety technology will permit an early detection of potential crash situations. Recent publications [2] mentioned the possibility to trigger Airbag units about 100 ms before the crash really occurs. Pre-crash detection will permit a slower inflation of the cushion thus preventing the risk of severe damage in case of OOP situation. But it will be impossible to synchronize the triggering of the Airbag unit with the impact of the occupant in the cushion, that the reason why we would need a tight bonded airbag, able to sustain the pressure for a longer time than traditional sewn bag.
The delay between pre-crash triggering and occupant impact will depend on the intelligence of the system. But we can imagine that to be functional under most crash cases, the cushion will have to be available during at least 500 ms.
Some requirements for the Airbag unit can be drawn from this short description: the cushion has to be tight to maintain the pressure during the

requested time; The inflator must be from cold gas technology to prevent the pressure drop due to a quick gas temperature decrease; The cushion has to be fitted with a device that detects occupant impact: the cushion remains tight before impact and has a controlled restraint after impact thanks to the opening of a vent hole.
Following is the description of 2 tests that demonstrates that Airbag units suitable for pre-crash systems are possible using technologies already available on the market:
• airtight bonded cushion using Peribond technology from Zodiac Automotive,
• pure helium cold gas generators form ISI-Automotive,
• patented silicone membrane from Zodiac Automotive.
The first test is to show the difficulty to ensure the specific requirements of a pre-crash Airbag unit with a sewn cushion. A comparison of the pressure drop for a sewn and a bonded cushion is presented on Figure 18. Both cushions are built to have the best performance in terms of leakage:
• low permeability of the coated fabric,
• high construction to have low combing,
• no vents to simulate a system having an intelligent opening at occupant impact,
• pure helium cold gas inflators from ISI Automotive.Prototype

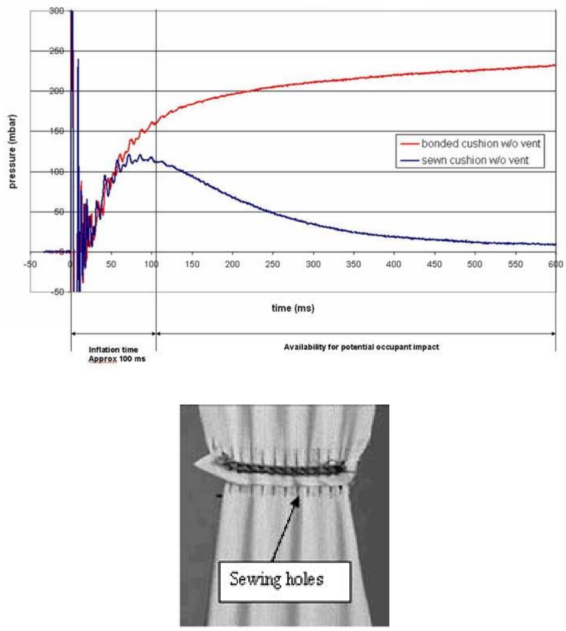


Figure 18. Pressure drop comparison between a sewn and a bonded cushion (left). Sewn cushion (right)

It can be concluded that the bonded cushion is available for occupant impact during more than 500 ms and the pressure level is maintained within 75 mbar, whereas the level of pressure of the sewn cushion is uncertain and is too low at the time of occupant impact. Pressure drop on sewn cushion is due to stitch holes on the fabric and gaps between the 2 fabric panels (Figure 18).
In the second test, a tight peribond bag is impacted after 150 ms. Figure 19 is showing the performance results of both tight peribond assembly and silicone membrane. Airbag pressure is ready for occupant protection during more than 200 ms. The silicone membrane remains closed until the impact, then open to ensure the restrain performance of the impactor.

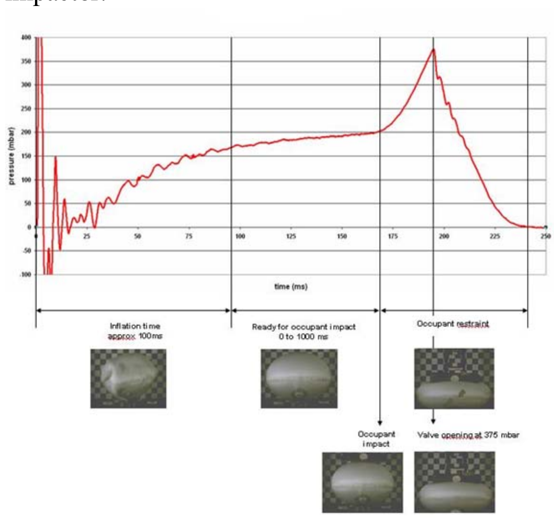


Figure 19. Dynamic test – pre crash simulation.

Then, tests are carried out with the crash dummy positioned with its left arm behind the steering wheel (Figure 14). Tests are performed with a conventional airbag (sewn cushion, open event, pyrotechnical technology) and with two airbag prototypes (bonded cushion, two pure helium cold gas generators (0.095 L – 620 bars) (0.047L – 620 bars), patented silicone membrane). In one case, the two helium generators are released at the same time. In the other case, the small generator is activated first, then the second is released after 10 ms. These cases will be referred afterwards as ‘proto_0 ms’ and ‘proto_10 ms’ airbag respectively. Figure 20 presents the linear head acceleration of the dummy versus time for the three airbag tested.

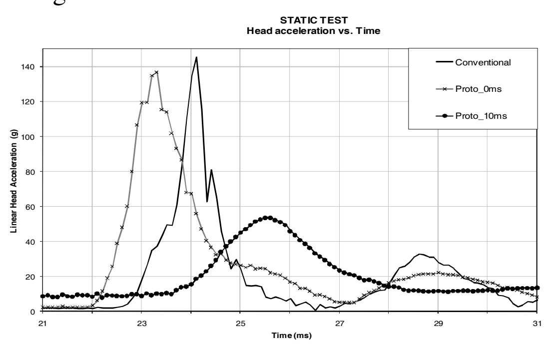


Figure 20. Linear head acceleration obtained for static tests with a sewn cushion (conventional) and bonded cushions (proto_0ms and proto_10ms).

From experimental tests, it can be concluded that the peak linear head acceleration is significantly reduced for the 'proto_10ms' airbag compared to the conventional and the 'proto_0ms' airbags. Indeed, with the 'proto_10ms', the airbag is multi stage inflated. So, the arm is projected less rapidly against the head. This explains the head acceleration decrease.

Prototype Airbags still have to be simulated, that requires characterization of the mass flow of helium generators.

CONCLUSION AND PERSPECTIVES

This paper focuses on frontal pre-crash driving postures. An unavoidable crash is reproduced on a car driving simulator and driver reactions are investigated. The main result is that none of the subjects adopts the standard driving position used in crash experimentations. Indeed, most of subjects swerve away to avoid the collision. This induces forward or backward movements and/or rotation of the chest. Only few person stays in a 10 and 2 o'clock position. Furthermore, a third of the subjects have their left hand placed in front of the steering wheel. Since airbags are usually mounted in the hub, this may represent a rather risky position.

These 'OOP' postures are reproduced with Madymo®. The driver is simulated with the Hybrid III 50th percentile dummy model. Postures observed on the car driving simulator, at the moment of impact, are estimated. A 56 km/h frontal collision is imposed. Head and neck injuries sustained by the driver are assessed. By comparing the numerical response for the models in an 'OOP' posture and in a normalized posture, it is found that head (3-MS and HIC) and neck (Nij) injury criteria are severely increased when the arm is placed in front of the steering wheel. Indeed, in this case, the arm is projected against the head under airbag deployment. Furthermore, the non-normalized chest posture influence too injury criteria. Having the chest and the head too close to the steering wheel induces serious neck and head injuries. In this case, the airbag, deploying at a very high speed, directly pull the dummy face inducing serious neck bending and violent head launching. This is also the case for small size people who usually sit near the steering wheel.

The very high value of HIC and 3MS head injury criteria and the high linear head acceleration peak can be due to the definition of the contact between the arm and the head. So, these numerical results have to be validated. An experimental campaign of static airbag deployment has been done with a hybrid III 50th percentile dummy. Tests are performed with a conventional airbag (sewn cushion, open event, pyrotechnical technology) and with two airbag prototypes (bonded cushion, two pure helium cold gas generators allowing mono or multi stage inflating, patented silicone membrane). The dummy is seated with the left arm in front of the hub. From these experiments, it is observed that bonded cushion is better suitable to maintain pressure until occupant impact and that linear head acceleration of the dummy is significantly reduced with multi stage inflated bonded cushion. Thus, slower airbag deployment could reduce airbag violence.

Currently, the configuration of passive restraint systems is almost universal (driver cushion inside the steering wheel, passenger airbag in the dashboard, side airbags in the seats, curtains in the roof). This configuration is driven by the architecture of the cars but also from specific requirements in terms of time to position (TTP); very quick time for position side airbags due to late detection of side impact and proximity of the door; higher time for frontal airbags due to earlier detection of frontal impact, higher volume to inflate and risks of OOP. Having detected the crash and triggered the Airbags earlier, TTP is no longer a determinant requirement for the conception of protection systems. The way to protect the occupants could be imagined completely differently. For instance, mixing the protection of a curtain and front and rear side airbags in a single airbag unit could lead to great savings in terms of number of generators, wiring, electronic equipments and consequently savings in price and weight. New protective features could also be added to current cushions. For instance, an extension of a driver airbag to protect from the A-pillar on partial side crashes.

It is believed that physiological data obtained from the experimental study on the dynamic simulator can help to find 'human sensor' to detect dangerous situations, as potential collisions between the host vehicle and other road users or obstacles, before the impact occurs (acceleration of heart rate, sudden braking …).

Furthermore, the numerical simulation, realized with Madymo®, shows the importance of driver positioning at the moment of impact in the assessment of neck and head injuries, and the influence of contact definitions on dummy responses. However, this first approach shows some limitations. First, it only represents the global behavior of the subject. Indeed, as the dummy head and arm are rigid, all the kinematical energy of the arm is transmitted to the head. This induces unrealistic high head acceleration and very high HIC value. So, a human model, with a deformable arm, should be used for a better prediction of head and arm injuries. Second, this approach doesn't take into account the driver muscular clenching during crash event. So, active muscles should be included in the model to take into account reflex reactions facing an incident.

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