ANALYSIS OF PRE-IMPACT AND IMPACT PHASE IN REAL HIGH-SPEED CRASH VIDEO RECORDINGS

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ABSTRACT

The effectiveness of advanced restraint systems is often reduced or compromised by uncorrect or unforeseen body movements before the impact, determining the known "out-of-position" situation; it is however very difficult to simulate these movements with dummies, or even with volunteer drivers.

This paper analyzes a series of crashes happened in a span of over ten years in a famous driving school based at a racing circuit in Italy, with cars equipped with videorecorders and telemetry, allowing to gather both visual and numerical informations not only upon the impact itself, but also upon the preceding seconds, and the driving mistake that caused the crash.

This sample comprises impacts against barrier and rollovers; from videorecording analysis it is possible to draw realistic information upon occupants' movements in the pre-impact and impact phases, both inertial and voluntary, and upon their kinetic parameters.

KEYWORDS

Accident Investigations - Injury Probability - Passive Restraint Systems

ONE OF THE MAIN PROBLEMS IN THE DEVELOPMENT OF ADVANCED RESTRAINT SYSTEMS IS REPRESENTED BY OCCUPANT OUT-OF-POSITION (OOP), that may interfere in the real-world activation, dampen the system effectiveness and produce severe and even fatal lesions.

Therefore, smart restraint systems cannot be effective without a detailed knowledge of the driver and passenger movements in the narrow time that precedes an impact; these movements may regard the whole body, by inertial effects, or body parts, such as upper limbs or the head, by instinctive self-protective actions.

Moreover, forensic experience shows that it is often harsh to correlate the suffered lesions with impact dynamics and vehicle deformation; therefore, a keen knowledge of the pre-crash events may provide relevant information also concerning expertise and crash reconstruction.

Studies with simulations with volunteers have been performed [1,2,3,4,5,6,7]; of course, elementary ethic rules forbid any chance to simulate a crash in realistic driving conditions. Moreover, volunteer drivers would be conscious of the impending impact and of the finality of the study, so depriving the situation of any resembling to reality.

Impact simulation with dummy crash tests or by software, for instance with FEM simulation or Multibody, presents the same problems and may be as far from reality as an "in vitro" pharmacological research.

With this background, we analyzed a series of videorecordings of real road events during driving instruction courses, with sudden and not programmed driving crisis and real impacts in rather common situations. Even if driving on a closed circuit is formally not reality but a kind of artificial situation, it shares most of the reactions and events of open road driving.

MATERIALS AND METHOD

This study is based on the analysis of a series of real car crashes, happened during the Driving School "Guidare Pilotare", based at the circuit of Misano Adriatico (Italy) and directed by former professional driver Siegfried Stohr; all lessons are given on closed road, whose ring is represented in Figure 1, and are recorded for didactic purposes. All driving takes place in one direction, without oncoming traffic and usually without close contact between vehicles.

Fig. 1 - Map of the Misano circuit.

The Driving School archives contained a huge number of mistakes with loss of control and various consequences; we selected all the events comprising at least one impact against external structures, or a partial rollover.

None of the cases had been programmed or allowed, in any way; therefore, we can assume a "genuine" pattern of car driving, even if at high speed or if in difficult conditions.

All drivers were belted; most of the cars were equipped with four-point harness belts, which replaced the original three-point belts.

All cars were stock BMW 3-series, roaming two generations (E 28 ed E36), with only one case involving a BMW Z3; all vehicles were fitted with supplementary rollbar, one main videocamera on the rear seat, one smaller videocamera pointed at the footwell, and a telemetry equipment with real time information upon braking force, gas opening, speed and axial or transversal acceleration (Figure 2). Telemetry data were obtained directly by the main electronic controlling unit of the ignition and accessory services.

These cars are equipped with an inertial switch that after a mild impact activates the internal lights, the external warning lights and unlocks the doors; therefore, observing the activation of internal lights provides a further indication upon the instant of the crash.

This effect can be better seen in the cases LBI 2 and RBI 1, both in dark hours, and in the rollover case RO 1; only the more recent cases implied airbag-equipped cars, or cars with assisted gear, and only one case involves airbag activation (Table I).

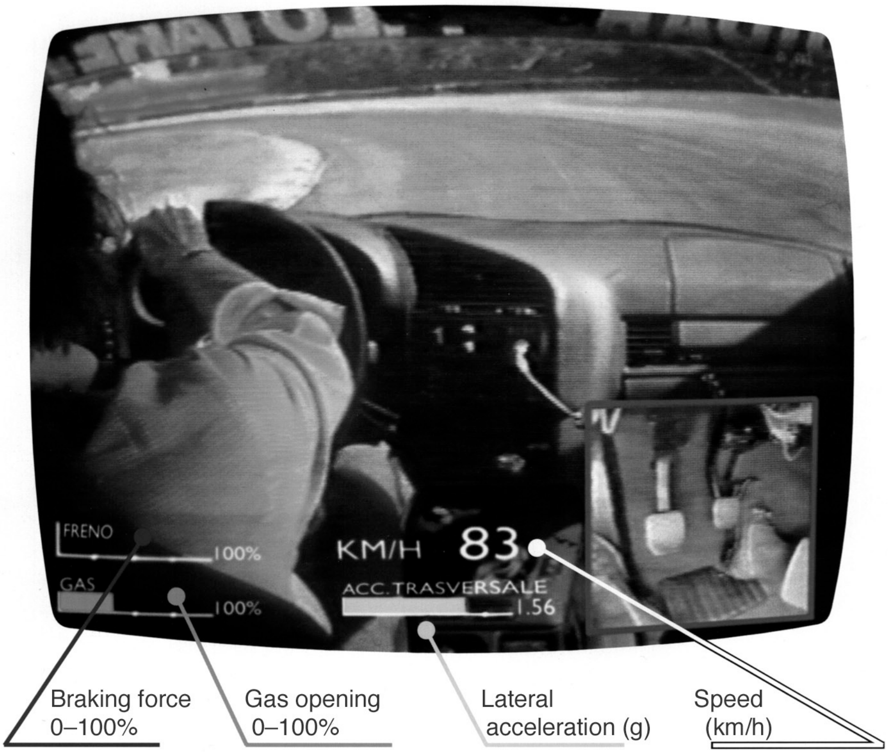

Fig. 2 - Example of data in videotelemetry.

Case	*Concise description of impact pattern*	*Principal direction of impact*
LBI 1	Sideslip after left curve, barrier impact	left side (9 hours)
LBI 2	Sideslip after left curve, rotation, barrier impact	frontal (11 hr)
LBI 3	Too fast, full rotation, barrier impact	left side (9 hr)
LBI 4	Oversteering, sideslip, rotation, barrier impact	frontal (12 hr)
LBI 5	Sideslip after left curve, rotation, barrier impact	posterior (5 hr)
LBI 6	Sideslip after left curve, barrier impact	posterior (5 hr)
LBI 7	Oversteering, barrier impact, feet under pedals	right side (3 hr)
LBI 8	High-speed left oversteering, rotation, barrier	right side (3 hr)
LBI 9	High-speed left sideslip, rotation, barrier	right side (4 hr)
RBI 1	Gear mistake, power oversteering, barrier	frontal (12 hr)
RBI 2	Oversteering on wet surface, barrier (*car model: Z3)*	left side (9 hr)
RBI 3	Power oversteering, barrier, head contact	right side (2 hr)
RBI 4	Oversteering, barrier, airbag activation	frontal (1 hr)
RO 1	Oversteering, rotation, off-road, full rollover	above (180° rotation)
RO 2	Sideslip, off-road, partial rollover and rebound to position	right side (100° rot.)
RO 3	Sideslip, off-road, partial rollover and rebound to position	right side (45° rot.)
RO 4	Sideslip, off-road, partial rollover and rebound to position	right side (60° rot.)

Legend - LBI: Left Barrier Impact; RBI: Right Barrier Impact; RO: Rollover.

Table I - Summary of cases and their principal characteristics.

The original VHS recordings have been digitalized, and divided into each single frame by means of the software Innovision Max-Traq, which allows to mark significant points and trace them sequentially, so providing their timing and movements. All measurements have been performed in software, or directly on screen.

All video recordings had been acquired at 25 frames per second (fps), therefore providing information of events and body position with a temporal scansion at 40 milliseconds; sometimes, shocks to the car and the videocamera impose a blurred resolution to the recording, or darkens the whole scene for some frames.

Therefore, the accuracy of data is sometimes jeopardized by the video quality; to minimize this problem, in the worse sequences we tried to interpolate the values obtained by adjacent frames.

The videorecordings also illustrate the movements of the passenger; however, in this sample he is not a casual guest, but a professional and expert driving teacher, with perfect knowledge of the circuit, of the possible mistakes and their fallout. Therefore, his behaviour is very different from a real world passenger, and shall not be examined into detail in this paper.

Unluckily, images of the exterior of the damaged cars and information upon belt pretensioners activation were not available.

RESULTS

A. General report

We selected and studied 17 cases, comprising impacts against left barriers (9 cases), right barriers (4 cases), and rollovers (4 cases); their main features are described in Table I.

B. Driver movements related to car frame

The movements of head and cervical region of the driver have been calculated by video analysis and then related to their progression in time, so calculating also data upon velocity and acceleration with reference to the car frame, and evaluating as far as possible the maximum lateral displacement at the level of the temporoparietal region and of the C7 vertebra, as reported in Table II. In some cases, the quality of the video recording imposed some approximation, or prevented at all such further evaluations.

The initial loss of control of the vehicle was comprised in a range between 35 and 180 km/h, with a mean value at impact around 80-90 km/h and orthogonal component (against barrier) around 30-35 km/h.

C. Reaction times and intervals

The subdivision of the movies into single frames allowed to evaluate and calculate also the reaction time of the driver, being able to individuate the time of loss of control, the time of the first steering wheel manoeuvre (if any), of the first pedal action (if any), and of the first visible upper arms muscular contraction (arm bracing).

Of course, not all the potential reactions came always into action: some drivers were very active, with combined steering and braking or gas modulation, while other drivers used only the steering wheel or the brake pedal, or waited passively without any attempt to regain control and directionality of the vehicle. These values too have been scheduled in Table II.

D. Lesions following car crashes

All the practical lessons of the Driving School are kept under rigorous safety rules; the Misano circuit is provided with strategic barriers and escape ways, there is always an expert instructor, usually a professional racing driver, and all the vehicles are routinely controlled and equipped with supplementary passive safety devices.

Therefore, even potentially harmful and violent impacts did not inflict any traumatic lesions to car occupants.

Nevertheless, some mild contact against rigid structures inside the passenger compartment has been reported in 4 cases; one case been associated to a mild whiplash injury (AIS 1) and one to a minor facial bruising (case RBI 4); an isolated case (RBI 3) has been associated to a contusive lesion (minor head trauma, AIS 1).

Case	A(m/s)	B (s)	C (s)	D (s)	E (m)	F (mm)	G (m/s)	H (m/s)	I (g)	J (g)
LBI 1	N.R.	N.R.	0.300	None	0.1	0.01	0.83	0.1	1.4	0.2
LBI 2	35.5	0.160	0.200	0.920	0.13	N.R.	0.65	N.R	<3	<3
LBI 3	>25	N.R.	0.680	0.970	0.8	90	5.0	1.12	6.0	2.1
LBI 4	33.4	None	0.200	N.R.	0.1	50	<1	N.R.	<2.5	N.R.
LBI 5	38.9	0.600	0.120	0.520	0.08	N.R.	1.0	N.R.	2.5	N.R.
LBI 6	36.16	None	0.160	0.600	0.2	40	2.0	0.5	4.0	1.4
LBI 7	29.72	1.00	N.R.	0.800	1.0	50	12.5	3.75	20	6.5
LBI 8	44.44	0.440	0.080	0.150	0.7	30	3.5	1.5	3.5	1.5
LBI 9	51.4	0.400	0.480	0.800	0.6	80	N.R.	N.R.	>10	N.R.
RBI 1	>10	N.R.	0.400	0.400	<0.1	<20	N.R.	N.R.	>2.5	N.R.
RBI 2	19.44	0.360	0.400	0.600	0.1	<20	1.25	0.25	3.0	1.5
RBI 3	27.22	1.560	0.840	0.280	0.9	80	7.5	1.0	12.5	3.5
RBI 4	37.5	0.360	0.160	None	0.3	50	N.R.	N.R.	N.R.	N.R.
RO 1	N.R.	0.640	0.320	N.R.	<0.1	50	0.5	N.R.	<3	<3
RO 2	N.R.	0.640	0.720	N.R.	<0.1	N.R.	N.R.	N.R.	<3	N.R.
RO 3	25	N.R.	None	None	0.1	None	0.5	N.R.	<3	N.R.
RO 4	N.R.	N.R.	0.450	N.R.	0.15	N.R.	2.1	N.R.	0.5	N.R.

Legend - N.R.: not relevant or measurable; A: Speed at loss of control;
B: Time from loss of control to pedal reaction; C: Time from loss of control to steer reaction;
D: Time from loss of control to arm bracing reaction;
E: max. head movement inside vehicle, measured at temporoparietal level;
F: max. movement at C7, measured at biacromial level;
G: max. velocity head/vehicle; H: max. velocity at C7 level;
I: max. acceleration head/vehicle; J: max. acceleration at C7 level.

Table II - Summary of results from video analysis.

DISCUSSION

A. Considerations by each impact category

1. Left barrier impacts (LBI)

In the case LBI 1, the loss of control is due to a partial off-road on grass, with very scarce ground adherence and immediate sideslip; the crash is relatively slight, with minor body movements, thanks to the dissipation of energy during the vehicle rotation.

In the case LBI 2, a sideslip on wet road surface causes a frontal impact against the opposite barrier; the vehicle does not completely stop against the barrier, and deceleration and movements are relatively reduced. During the sideslip, the driver performs a clear self-saving manoeuvre.

In the case LBI 3 (Figure 3) the reaction times of the female driver are rather prolonged (600-800 ms); the crash happens on the left side after a long off-road sideslip during around 4 seconds, with a complete turnaround (360°) and a significant reduction in speed before the impact. In this case the self-saving manoeuvres are particularly well defined and visible, with more than one attempt to get as far as possible from the menaced side of the car, and with a huge rebound after the impact itself. It is also clear how the driver's head is positioned outside the shape of the headrest; in case of collision with another vehicle, severe whiplash injuries could have been produced.

Case LBI 4 is a power oversteering due to excessive gas opening, with a rather fast reaction time at loss of control. Although the driver remains in a correct position and the barrier is made by deformable components (piled tyres), at the time of impact the internal movements are sharp and significant, with evident bracing, but associated to low deceleration values.

Fig. 3 - Frames from the case LBI 3; see description in text.

Fig. 4 - Frames from the case LBI 5; see description in text.

Both cases LBI 5 (Figure 4) and LBI 6 present rotation of the car and therefore a posterior and oblique impact direction; both the drivers maintain posture and self-control, but they rotate the head to the their right side, to look towards the impending impact. This pattern could have severely influenced the consequences of a harder impact in real conditions on open road, for instance in case of collision with an oncoming vehicle.

In case LBI 5, the max. relative acceleration is around 2.5 g, while vibrations in video recording at impact time do not allow more precise evaluations for head and torso.

Fig. 5 - Frames from the case LBI 7; see description in text.

The barrier impact in case LBI 6 is almost tangential, with relative acceleration around 4 g and very low (160 ms) steering wheel reaction times; loss of control was due to a gear mistake (from 5th to 2nd gear) after a large curve, on wet road surface.

Case LBI 7 (Figure 5) is a barrier impact after full vehicle rotation; because the vehicle loses only a few of its speed and stops against the barrier, this case presents the most severe deceleration in the whole specimen.

Head lateral excursion reaches 1000 mm, and the relative acceleration reaches 20 g; both reaction times (1000 ms) and self-protection times (800 ms) are high, with clear bracing posture; moreover, the left foot is badly positioned and framed within the pedals.

Case LBI 8 is associated to relatively mild decelerations despite the high speed at loss of control (around 160 km/h); the driver did not try self-saving manoeuvres but activated an effective bracing, so maintaining a correct position and reduced head and torso movements.

Also case LBI 9 is associated to high speed at loss of control (over 180 km/h), with significant values of velocities and accelerations; unluckily, the videocamera suffered vibrations and reduced video quality at the impact, so making very difficult their numerical evaluation.

2. Right barrier impacts (RBI)

In these four cases, the driving mistake is generally based on an excess in gas opening while concluding a curve, with oversteering and loss of control.

Because the right barrier is close to the lane, there is very little time between the driving crisis and the following impact, which is more frequently frontal, with no space available to allow prolonged car sideslip and rotation.

In case RBI 1, loss of control is triggered by a gear mistake (from 5th to 1st), with immediate power oversteering and change in direction; it is interesting to note that this driving mistake is not rare in the Driving school.

The impact against the barrier is associated to relatively low speed; the lacking time for self-saving manoeuvres allows driver a good position during the crash, whose timing may be observed also by the activation of the internal lights by means of the automatic inertial switch.

Fig. 6 - Frames from the case RBI 3; see description in text.

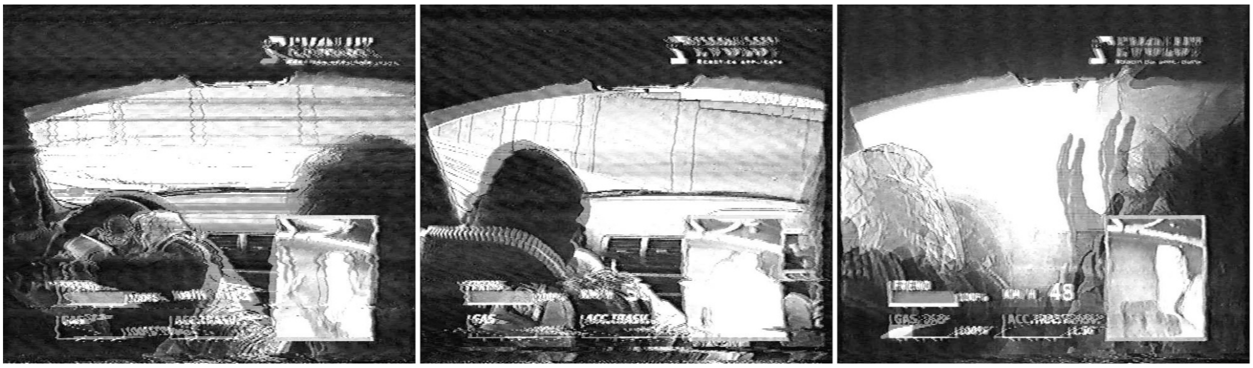

Fig. 7 - Frames from the case RBI 4; see description in text.

Case RBI 2 is the only one with a different car model (Bmw Z3); it shows an oversteering at night and on wet road surface, with relatively slight impact, moderate head and torso movements and max. acceleration valuable around 3 g.

In case RBI 3 (Figure 6), after an oversteering and a complete rotation the barrier impact is associated to a max. head acceleration around 12.5 g, with slow reaction times (840 ms for steering wheel reaction, 1560 ms for pedal reaction) and clear self-defensive position. This case, associated with seat belt slack, regards the only contusive lesion (minor head trauma, AIS 1) in our sample, by violent contact between driver and passenger.

Case RBI 4 (Figure 7) is one of the more recent and by now the only one with airbag activation; the opening of the dashboard cover is visible in the second frame of Figure 7.

Telemetry controls have surely a certain lag, but show an approach speed at the point of impact at around 50 km/h.

The driver’s head moves forward significantly before the airbag deployment and there is a slight contact between head and airbag, without apparent out-of-position; after the bag deflation, both driver and passenger seem uncomfortable for the powder diffusion inside the car.

It must be remarked that the proximity between the road and the right guardrail strictly resembles the configuration on open roads, and therefore these four cases resemble more strictly than others what really happens in the real world.

3. Vehicle rollover (RO)

Our sample comprises a complete rollover, and three partial rollover on the right side with rebound on the four wheels at the end of the evolution.

The first case (RO 1, Figure 8) is a complete rollover (180°), with clockwise rotation, preceded by a sharp and fast sideslip; unluckily, telemetry was not activated, but only the footwell camera. The sideslip and the rollover of this car have been also accidentally recorded by the camera fitted inside a following vehicle.

The movie shows that during the rotation phase head and shoulders of the occupant remain rather stable, even if the forward movement of the knees implies a significant hip displacement; during the rollover phase, both occupants perform a self-saving manoeuvre raising (or better lowering, given the real upside-down position) their arms to the roof.

Of course, the supplementary rollbar prevented any significant roof intrusion and therefore preserved the passenger compartment frame during the rollover.

In the case RO 2 (Figure 9), the female driver reacts badly to the loss of control, squirming and waving hands on the steering wheel, with nervous self-saving manoeuvres; the sharp lateral stop causes an inclination slightly over 90° on the right side, with following rebound to the ground on the four wheels.

In the cases RO 3 and RO 4, the rough off-road phase provides significant accelerations to the occupants; the vehicle stops suddenly, with an inclination around 45° on the right side; both drivers maintain a correct position thanks to arm bracing and to the absence of panic manoeuvres. The case RO 4 suggests clearly the time of max. head deceleration, even without telemetry, observing the trajectory of the driver's sunglasses, which maintain their velocity and inertially fly within the car.

These rollover cases are generally related to minor decelerations than the cases associated to barrier impact, showing a deceleration peak only when two wheels stop in some small ditch outside the lane and give to the car the fulcrum that ignites the rollover phase, at the end of the car evolution.

Unluckily, the hard vibrations impressed to the car at the beginning of the rollover caused the deterioration of video quality, with loss of interesting data.

Compared with dummy simulations, these cases differ radically in the dynamics of the occupants; particularly, they maintain their physiological seating position far longer that dummies do in simulated crashes; that could be due to the different centre of gravity of the human body, and to the effectiveness of arm and leg bracing.

Figure 8 - Frames from the case RO 1; see description in text.

B. Dynamic movements during the pre-impact phase

1. Emergency control and panic manoeuvres

From the instant of loss of vehicle control to the instant of impact, drivers have time to activate corrective and/or self-defensive manoeuvres, according to situations and to their driving skills; of course, also psychological elements affects this behaviour.

From a biomechanical point of view, these movements are interesting as long as they may influence the position of the body at the final impact, and hence its relations with restraint systems, particularly if active and inflatable.

In the majority of the cases, with different patterns, drivers were more or less out-of-position while their car was travelling on the opposite lane, that could have been the most dangerous time in an open road evolution.

Almost all of the cases demonstrate crossing of forearms at the centre of the steering wheel, interfering with the space that will be filled by an opening airbag cover, with high risk of severe lesions. One case was associated to accidental activation of horn, to remark how close was the driver's arm to the cover; this effect had already been observed during pre-impact simulations with volunteers [6,7].

The position of the videocamera allowed good appreciation of lateral dislocations, but only indirect appreciation of longitudinal ones; the entity of visible movements was however greater than supposed, with not satisfying containment by the seat, even if anatomically conformed in these cars.

2. Arm and leg bracing and self-defensive postures

In these cases there is no broad evidence of strong active muscular contraction, at least for what concerns upper limbs.

The footwell camera allows evaluation of leg bracing, which appears to be effective predominantly at the left side; the right leg appears to be more depending upon the braking action. Some bracing appears in the rollover cases, maybe because rollovers allow some more reaction time to the driver, and is surely effective in minimizing body displacement.

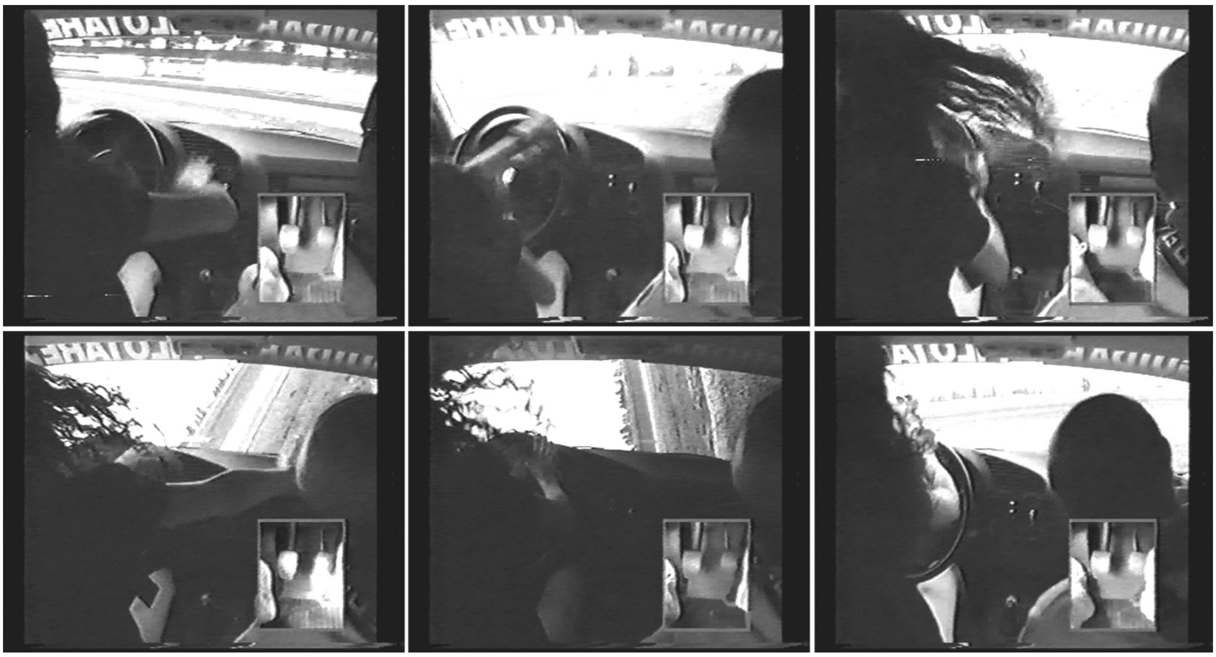

Figure 9 - Frames from the case RO 2; see description in text.

In lateral impact, not only leg bracing is scarcely effective, but various degrees of feet malpositioning are visible, up to complete jailing beyond the pedals; in case LBI 7, for instance, the footwell-aimed camera shows in detail (Figure 5, frames V-VI) how feet are pushed within the pedal frames well before the main deceleration peak.

This allows some reflections upon passive safety and prevention of ankle and foot lesions, that usually are presumed to be due to incarceration of the extremity by effect of the main deceleration force. A pre-impact derangement of foot position, on the contrary, could dampen the effectiveness of an active device, such as a pedal retractor or a footwell inflatable device, producing a classical out-of-position situation very similar to OOP that lead to airbag injuries.

With this configuration, for instance, the pressure of a deploying inflatable device would have surely forced the trapped left foot back and laterally against the metal structure of pedals, with deep tissue laceration at tibiotarsal or metatarsal level, and potentially with transection of osteoarticular and nervous-vascular structures (from exposed fracture-luxation to sub-amputation), not life-threatening but severely disabling.

3. Relations between head and headrest

Some cases show clear head malpositioning, by effect of the described voluntary or instinctive manoeuvres; particularly, the head may be positioned outside the shape of the headrest itself (for instance, in LBI 3 or RO 2), and therefore be exposed to severe whiplash injuries or even direct trauma. This pattern describes a concrete out-of-position situation, and may affect the performance of headrest systems, especially if inflatable.

In some cases a horizontal rotation of the head is visible, for instance in LBI 9 during car rotation to achieve full vision of what is happening, and of the position of barriers.

Another possible cause of defective interaction between head and headrest is given by strong arm bracing; in this case, the contraction of cervical muscles tends to lower the head towards a “fighter” posture, therefore allowing more distance between the headrest and the occipital region of the driver.

CONCLUSIONS

Our data confirm that the pre-impact phase is highly significant in determining the consequences of a crash, and allow some further considerations.

These findings regard mainly malpositions due to instinctive self-defensive attempts, and relations between upper arms and the steering wheel, between head and cervical region and the headrest, and between feet and pedals.

In the first place, it is difficult to compare some situations with the findings of formal crash tests with dummies, performed at constant speed and without any braking effect or car rotation before the frontal impact.

The movements observed in flesh-and-bones, unalerted drivers are extremely rich if compared with the dummy movements in crash tests, but also if compared with the movements of volunteers during low-speed emergency manoeuvres in programmed simulations [6,7].

Some pre-impact movements are objectively wider than one could expect, determining clear out-of-position situations and therefore dangerous situations in the case of a violent impact against an oncoming vehicle.

In our sample, instinctive self-defensive manoeuvres are more frequently visible than effective arm bracing and/or leg bracing.

In our rollover cases, without barrier impact, both vehicle and occupant decelerations are less severe, with a peak due to the sudden stop of the wheels at the beginning of the off-road rolling phase.

Almost all cases are associated with various degrees of interference between driver’s hands and forearms and the steering wheel airbag cover, just in danger of a possible activation, and therefore at risk for severe and disabling injuries. This seems to represent a challenge even for smart airbag sensors that have been tailored to detect if a large mass as the chest is close or approaching the steering wheel, but could be deceived by a rather thin body segment such as a forearm.

It appears that feet move before the impact, both for leg bracing and/or for braking action, and that they may assume dangerous proximity with the pedals, of even be jailed within them.

The footwell design could be improved to prevent jailing among the pedals, while on the other side the adoption of inflatable devices should be careful tailored in order to prevent dangerous and severely disabling foot and ankle lesions.

Some perplexities arise also about knee airbags; they may perfectly fit a dummy in a crash test, but they had easily interfered with the driver's knee preimpact movements in some of the displayed real cases.

The absolute frequency of rotated steering wheels at impact arises concern also about the adoption of asymmetrical airbags, whose deployment will generate different geometrical forms depending upon the cover opening angle, and possible dangerous body contacts.

The results of this analysis interest also forensic crash reconstruction; some strange or not probable findings, such as violent contacts within occupants, or abnormal movements in belted occupants, for instance with dashboard contact, may be partially or totally explained by dislocations in the pre-impact phase, that could also comprise slipping of seat belts from the shoulder and therefore the inefficiency of the thoracic harness.

A better knowledge of what happens just before the crash may provide a coherent solution in apparently contradictory sceneries. Simulated or software-mediated calculations, for instance by Multibody techniques, may be intrinsically misleading if not based on realistic background.

Conclusively, pre-impact occupant movements play a dominant role in determining the trajectory of the inertial post-impact phase, and may significantly affect the practical effectiveness of both active and passive restraint systems, as well the contact patterns within the car passenger compartment.

Of course, the presented sample is based upon a collection of occasional events and not upon a programmed study of crash models; nevertheless, to peep methodically inside real and not simulated nor desired impacts may yield meaningful topics for further speculation and experimental research.

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