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Determination of pre-impact occupant postures and analysis of consequences on injury outcome. Part I: A driving simulator study

Audrey Hault-Dubrulle^{a,b,c,*}, Frederic Robache^{a,b,c,1}, Marie-Pierre Pacaux^{a,b,c,2}, Herve Morvan^{a,b,c,1}

^a Laboratory of Industrial and Human Automation, Mechanics and Computer Science, LAMIH, University of Valenciennes, F-59313 Valenciennes, France

^b University of Lille Nord de France, F-59000 Lille, France

^c CNRS, FRE 3304, F-59313 Valenciennes, France

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ABSTRACT

This paper considers pre-impact vehicle maneuvers and analyzes the resulting driver motion from their comfort seating position. Part I of this work consists of analyzing the driver behavior during a crash. The study is conducted using the LAMIH driving simulator and involves 76 participants. The emergency situation is created by a truck emerging from behind a tractor on the opposite side of the road and tearing along the participant. The driver positioning throughout the simulation is recorded via five video cameras allowing view of the front scene, the driver face, feet and pedals, hands on the steering wheel and global lateral view. Data related to braking force, seat pressure, muscular activity for major groups of muscles and actions on the steering wheel are also collected.

The typical response to this type of emergency event is to brace rearward into the seat and to straighten the arms against the steering wheel, or, to swerve to attempt to avoid the impacting vehicle. While turning the steering wheel, the forearm can be directly positioned on the airbag module at time of crash which represents a potential injurious situation.

These positions are used in Part II to determine scenario of positions for numerical simulation of a frontal collision.

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1. Introduction

In order to assess restraint systems effectiveness, crash tests are performed with ATDs (Anthropometric Test Devices) positioned in a standardized seating posture. Nevertheless, it is widely accepted that vehicle occupants do not maintain exactly the same posture as crash ATDs during normal driving, nor under stressful conditions (vehicle pre-impact maneuvers, emergency braking). Consequently, their posture at the time of impact may significantly differ from those used for restraint system development and evaluation.

Since passenger cars have been widely equipped with airbags, a lot of organizations have reported on the airbag effectiveness for saving lives and reducing serious injuries in frontal crashes. How-

ever, there is still a controversy about serious occupant injuries caused by airbag deployment, mainly attributed to the airbag interacting with the occupant in out-of-positions (OOP).

Common injury situations are encountered when drivers, who are fairly short, position themselves close to the steering wheel. During a crash, as a result of deceleration forces, they move even closer to the steering wheel and can be injured by the airbag punch-out. Another common type of injury occurs when pre-impact braking places unbelted or improperly belted child near the airbag at the time of deployment, or, when a rear-facing child restraint system is installed on the front passenger seat (Kamiji et al., 1998).

In order to evaluate airbag deployment injuries, OOP have been tested. They correspond to extreme postures such as passengers with their feet on the dashboard, unbelted children in close contact with the deploying passenger airbag or unbelted short-stature females sitting very close to the steering wheel (chin on airbag module) (Tylko and Dalmotas, 2001). However, these cases are not fully representative of real world occupant postures.

Furthermore, until the 90s, restraint devices remained non-adaptive, and their functionality was limited to a fixed operation mode related to a fixed value of occupant anthropometry and collision characteristics. Nowadays, many new vehicles offer adaptive or 'smart' restraint systems. These smart restraint systems adjust the force applied to occupant according to information sent to

* Corresponding author at: Laboratory of Industrial and Human Automation, Mechanics and Computer Science, LAMIH, University of Valenciennes, F-59313 Valenciennes, France. Tel.: +33 03 27 51 14 09; fax: +33 03 27 51 13 17.

E-mail addresses: audrey.hault@univ-valenciennes.fr, audrey.hault@orange.fr (A. Hault-Dubrulle), frederic.robache@univ-valenciennes.fr (F. Robache), marie-pierre.lemoine@univ-valenciennes.fr (M.-P. Pacaux), herve.morvan@univ-valenciennes.fr (H. Morvan).

¹ Tel.: +33 03 27 51 14 09; fax: +33 03 27 51 13 17.

² Tel.: +33 03 27 51 13 73; fax: +33 03 27 51 13 16.

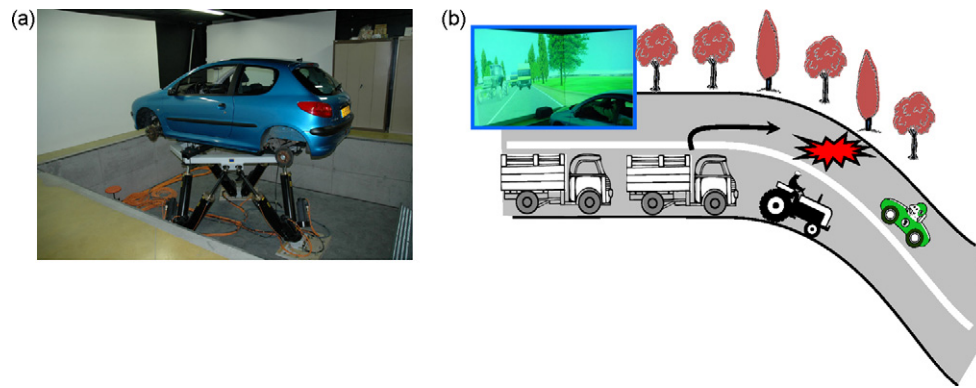


Fig. 1. (a) Dynamic driving simulator. (b) Scenario of the virtual crash.

the computer from sensors located for example in the seat belt retractors and front seats (Occupant Classification Systems (OCS)). Smart restraint systems, which account for occupant characteristics, require assessment of occupant state parameters, including both time-invariant properties like stature and mass as well as time-variant states such as the postural orientation and muscle bracing level.

Accident data provide good information on injuries sustained in specific cases, however it is rare that the pre-impact posture is known or can be determined.

Numerous studies demonstrated that driving simulators are effective tools for road safety research such as investigation on driving speeds (Bella, 2008), lateral positions (Auberlet et al., 2010; Briand et al., 2010), and driving assistant systems (Abe and Richardson, 2005; Chang et al., 2008). Driving simulators have several positive features such as efficiency, low expenses, safety, experimental control and ease of data collection. Previous simulation experiments on driver responses facing an imminent collision demonstrated that it is possible to provoke realistic avoidance behaviors (Morvan et al., 2007; van Schijndel-de Nooij and Wismans, 2008; Couper and McCarthy, 2003; Morris, 2004) and that driver behavior in a virtual driving situation is similar to a real one (Perron et al., 2001; Briand et al., 2010). Thus, an alternative approach to identify pre-crash postural orientation of car occupants is to simulate crashes using a driving simulator.

The objective of this research is to analyze the driver position changes during an emergency situation and to investigate the pre-collision driver posture effects on injury outcome during a collision. The study is split in two parts. This first part reports a driving simulator study aiming at determining how drivers behave during pre-impact events. The second part reports numerical and experimental studies performed to estimate the effect of pre-crash occupant posture on injury outcome; it also proposes a technical solution to reduce driver injury risk in OOP situations.

This first part of the two-part paper begins with a short description of the LAMIH driving simulator and the presentation of the experimental protocol. Then, the results of the experimental drive are presented. Finally, the paper ends with a discussion about the postural changes from comfort driving in such a frontal collision and the determination of pre-crash postures for numerical simulation in Part II.

2. Driver dynamic response study

2.1. LAMIH driving simulator, SHERPA

The study was conducted using the driving simulator of the University of Valenciennes, SHERPA (French Acronym for 'Simulateur Hybride d'Etude et de Recherche de PSA Peugeot Citroen pour

l'Automobile') (left-hand drive simulator vehicle and manual gear box) (Fig. 1a). It consists of an interactive motion-base driving simulator fitted with a whole Peugeot 206. The car is positioned in front of three angled projection surfaces. The central projection surface is located 3.3 m in front of the driver with two peripheral surfaces connected to the central surface at angles of 60°. The entire projection image produces a 180° horizontal × 45° vertical front view of the simulated roadway from the driver position at a resolution of 1280 × 1024 pixels. The central rear view mirror and both wing mirrors are replaced with three small color LCD screens (with resolutions of 800 × 480 pixels). The image refreshment rate is 60 Hz.

The controls include the steering wheel, the manual gearbox and the pedals (brake, accelerator and clutch) of the original car. Accurate speed and engine data are displayed on the vehicle's dashboard. A force feedback steering wheel is used. The car is equipped with speakers mimicking engine, road tyre and passing traffic noises.

The SHERPA driving simulator uses a 6 degree-of-freedom hexapod motion system. The bump experienced in crash was simulated via this motion system.

2.2. Route and traffic scenario (simulation scenario)

Routes selected for this simulation included rural roads, villages, main roads and highways. Weather and lighting conditions were optimal.

The complete trial began with a 27-km portion on a highway with a 130 km/h speed limit, followed by a 5-km section on a state highway with a 90 km/h speed limit. A regular traffic flow was reproduced so that participants were incited to respect the Highway Code and to adapt their driving to the presence of other cars. Unpredictable events were produced to investigate participant driving behavior (human error, especially traffic rules violation) such as a vehicle cutting up the participant's car on the highway or a slow-driving vehicle on a 2-lane road separated by a white line.

Then the participant drove along a main road crossing a small village with a 50 km/h speed limit. Few meters after entering the village, a car emerged out of a junction on the right-hand side of the road and jumped the stop, thus surprising the participant. This situation was designed to remind participants that unpredictable events might happen at any time as in real life.

Finally, the experimental drive ended with a portion of a rural road and the simulated collision (Fig. 1b). The road was composed of two lanes separated by a white line. The collision occurred in a large bend. Trees along the curving road and an isolate farm concealed the long-rang visual information needed to predict the path of the road ahead and to anticipate future events. In the turn, a lane



Fig. 2. Impacting foam.

of trucks, a tractor followed by 2 trucks, appeared in the opposite lane. The truck just behind the tractor pulled out suddenly to overtake, such that the scenario could not be expected by the participant.

Trees along the road side and trucks on the opposite lane lessened the collision avoidance (Fig. 1b). To improve the realism, a real physical impact was added. At the time of the virtual crash, a large foam rubber block (Fig. 2) impacted the windscreen, a truck horn was emitted and the car body was jerked to simulate the bump experienced in a crash.

The foam rubber block was initially hidden in front of the vehicle, such that it could not be seen by the driver during the experiment. A mechanism fixed on the side of the vehicle produced the motion of the foam rubber block.

The route was 34.3 km long. The participants needed approximately 30 min to complete the scenario depending on the participant's speed.

The participants believed they were participating in a study in ergonomics so they could not predict the occurrence and the location of the collision. Each participant encountered one emergency traffic event during the experimental drive so they could not anticipate the simulated crash.

2.3. Experimental procedure

Participants firstly provided personal information—gender, age, and driving experience. They all read and signed an informed con-

sent document. Experiment directions and safety rules regarding driving tasks and the simulator use were provided.

After a short training session designed for familiarization with the simulator, the true experiment was conducted. No specific requirements were made; participants were asked to drive as they would do in the same real world situation and to adapt their speed to the driving conditions.

At the end of the experimental drive, drivers were asked to fill in questionnaires evaluating their driving characteristics (behavior patterns), their reactions to each separate situation and the realism of the experiment.

2.4. Measurements

2.4.1. Camera set-up

The driver position was recorded throughout the experiment via five video cameras allowing views of the front scene, the driver face, feet and pedals, hands on the steering wheel and a global lateral view (Fig. 3).

2.4.2. Collected data

Data related to braking force, seat pressure and actions on the steering wheel were collected thanks to load cells (Fig. 4).

Data related to muscular activity were recorded for major groups of muscles of the upper and lower limbs (triceps brachii, biceps brachii, trapezius, wrist extensor, quadriceps, soleus muscle, tibialis anterior, ischio) and will be used later in modeling activities.



Fig. 3. Interiors views of video recording during the crash.

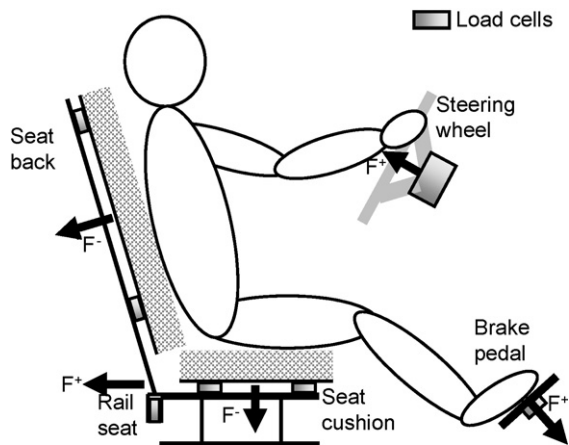


Fig. 4. Sensor positions.

Table 1
Characteristics of participants.

	Driving simulator study
Sample of participants	76
Women	20
Men	56
Age (range)	18–52 years
Average Age (standard deviation (SD))	26.8 (7.3)
Driving experience (range) (years)	0–29 years
Average kilometers driven per year (SD)	12,910 (9748)
Kilometers driven per year	300–40,000

* The participant obtained the driving license from some months.

The driver-vehicle-environment interaction parameters were measured, such as impact velocity, time of crash, steering wheel position, state of the pedals, gear lever position and vehicles' position on the road.

2.4.3. Volunteer data

Participants were students and staff at the University of Valenciennes and people recruited locally.

Participants were asked to own a valid driving license and to have a normal or corrected vision. No selection criteria were made in terms of gender, age, height or weight in the participant selection.

Two people already used the driving simulator before but not in a similar experiment.

Table 1 lists the participants' demographic and driving information.

The sample was composed of 20 women and 56 men, with an average age of 26.8 years (18–52, SD 7.3). Seventy of the participants were under 40 years old and only 6 participants were over 40. The participants owned their driving license from few months to 29 years. The yearly kilometer average reported by the participants was 12,910 km, ranging from 300 to 40,000 km (SD = 9748 km).

Table 2
Height and weight of simulator study participants (distinction men and women).

	Weight (kg)			Height (cm)		
	All	Men	Women	All	Men	Women
Maximum	122	122	100	190	190	176
Minimum	46	49	46	156	158	156
Mean	74	76.3	67.5	175.1	178.1	166.5
Standard deviation	14.1	12.8	15.7	8.3	6.8	5.7
5th percentile	52	55	46	160	168	156
50th percentile	72.5	73	62	175	179	166
95th percentile	99	96	92	188	188	175

Table 3
Height and weight of French drivers from Rebiffé et al. (1982) study.

	Weight		Height	
	Men	Women	Men	Women
Mean	74.1	59.5	171.6	160.2
Standard deviation	11.0	10.0	6.8	6.1
5th percentile	58.2	46.5	160.7	150.7
50th percentile	73.2	58.0	171.9	160.4
95th percentile	94.6	78.0	183.0	170.5

2.4.4. Physical data

For each participant, anthropometric data were measured in a calibrated space to allow a postural reconstruction method (Hetier et al., 2004, 2005). Table 2 provides the height and weight statistic data for all participants and for women and men separately.

An anthropometric survey was conducted on 3252 French drivers (1587 females, 1665 males) by Rebiffé et al. (1982). The main results in height and weight are reported in Table 3 for men and women.

From these results, it can be seen that the participants selected for the current study were quite representative of the French driver population.

3. Results

3.1. Simulation realism

Subjective and objective data were collected to evaluate the realism of the experiment. Subjective data included both the driver's verbalizations and their answers to questions evaluating their driving behavior and their reactions. Objective data included 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 maneuvers provoked by the truck passing. Regarding the results, it can be supposed that most of the participants have reacted as they would have done in the real life.

3.2. General driving characteristics

All participants reacted to the traffic accident by actions on pedals and/or steering wheel. Six persons avoided the frontal crash but hit the truck laterally or collided with trees. General driving performances are presented in Table 4. The participants who avoided the frontal collision with the truck were not included in these statistical data. Men and women had the same performance, so no distinction was made according gender.

The average speed in town was calculated from the host vehicle speed at 50 m after the town enter panel and its speed at 50 m before the town exit panel.

The accelerator release time corresponded to the period between the overtaking event and the release of the accelerator. The braking reaction time was defined as the time period between the overtaking event and application of the brakes.

Table 4
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 150 m before crash (km/h)	76.3	50.7	96.1	10.3
Speed at truck overtaking (km/h)	73.8	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 at truck overtaking (m)	29.6	18.3	39.0	4.7
Deceleration from truck overtaking to crash (m/s ²)	1.6	3.8	−0.4 (Acc.)	1.0
Accelerator release time (s)	0.37	0.05	1	0.24
Braking reaction time (s)	1.06	0.25	2.25	0.42

The collision occurred on a main road segment. The average driving speed of the participant vehicle was 76.3 km/h. The speed seems realistic, considering the type of road, which was the beginning of a wide turn. This speed was quite steady until the truck appeared in the opposite lane (the truck was visible at 150 m). When the truck pulled out, most of participants braked. The average deceleration rate was 1.6 m/s². The mean overlap of the vehicles during the impact was 61.8% and the angle between the truck and the host vehicle varied from −18.8° to 5.1°.

3.3. Force analysis: pre-event and event data.

The Fig. 4 indicates the position and the direction of force sensors.

The forces applied on the seat (cushion and back), the seat adjustment rail, the steering wheel and brake pedal were recorded for 26 drivers only, due to technical problems with the acquisition system. The evolution of these forces from pre-event to event data was analyzed.

Four periods are defined

1. *Quiet period*: As the collision occurs in a wide turn, the tractor and the trucks are not immediately visible. The trees along the curving road and an isolate farm conceal the visibility of the road ahead.

The quiet situation corresponds to the time period before the tractor and trucks are visible.

The mean forces during the quiet situation are computed at a time interval going from −50 s to −5 s before the time that the trucks are visible. The time interval is chosen such that forces are constant for all drivers during this period.

2. *150 m before crash period*: The reference time for this period is chosen as the time at which the driver arrives at a distance of 150 m from the crash location. This corresponds globally to the onset of visibility of trucks (tractor followed by trucks) on the opposite lane. It depends on the driving speed of the occupant.

The mean forces for this period are computed at an interval of 1 s centered on the reference time.

3. *Truck overtaking period*: The truck overtaking onset time corresponds to the time the truck crossed the white line.

The mean forces for the truck overtaking period are computed on an interval of 1 s centered on the truck overtaking onset time.

4. *Crash period*: This is the time period of the collision (the vehicle hit the truck).

The extreme values of forces are computed on an interval of 1 s centered on the collision time.

At the end of the experiment, when the simulation was stopped, participants were asked to push the steering wheel with hands placed in a 10 and 2 o'clock position, pushed back the upper torso against the backseat and pushed the pedals with maximal voluntary

forces (Table 5). The forces measured in the seat, the steering wheel and the pedals were denoted Ffull. The same experiment was reproduced but with pulling the steering wheel. The values of Ffull were used to normalize forces measured during experiment. If the driver applied an axial compressive load on the steering wheel during the crash, the Ffull efforts measured during pushing out were used to normalize the values. If the driver applied an axial traction on the steering wheel during the crash, the Ffull efforts measured during the pulling on were used to normalize the values. This normalization allows the comparison among driver efforts independently of their morphological variability.

The normalized forces on the seat (cushion and back), rail, steering wheel and brake pedal are illustrated in Figs. 5, 6 and 7, respectively.

Drivers realized that a crash was imminent when the truck crossed the white line. Until this moment, global positions of the drivers remained quite steady with some small perturbations due to the type of road; such that participants replacing their hands on the steering wheel at the beginning of the bend. Then, significant altering in postural orientation was observed at the moment of crash.

During the quiet situation, no force was applied on the brake pedal. At imminent collision, drivers braked suddenly. As a consequence of bracing and braking, the participants pushed the pelvis back into the seat and leant backward. Contact occurred between the seat back and the upper portion of the torso, around the shoulder area. An increase of seat back and rail seat forces and a decrease of seat cushion efforts were induced. Only one person pushed down in the cushion seat (increase of cushion seat force). Participants also strengthened arms and legs. Consequently, increased forces on the steering wheel and brake pedals were induced.

Some people developed forces during crash over the maximum voluntary efforts. This can be explained by the fact that Ffull efforts are sustained efforts while driving efforts during crash are instantaneous efforts.

3.4. Postures: comfort posture to pre-crash posture

Videos were analyzed for the seventy participants who did not avoid the frontal collision. Results suggest that most of drivers had

Table 5
Maximum voluntary efforts.

	Mean	Min	Max	SD
Seat back	−811.90	−407.00	−1428.50	259.10
Cushion seat	−509.85	−334.18	−834.41	104.46
Rail seat	520.37	279.75	752.53	121.98
Steering wheel	−175.34	−36.38	−561.14	152.16
Brake pedal	529.03	207.47	979.63	241.55

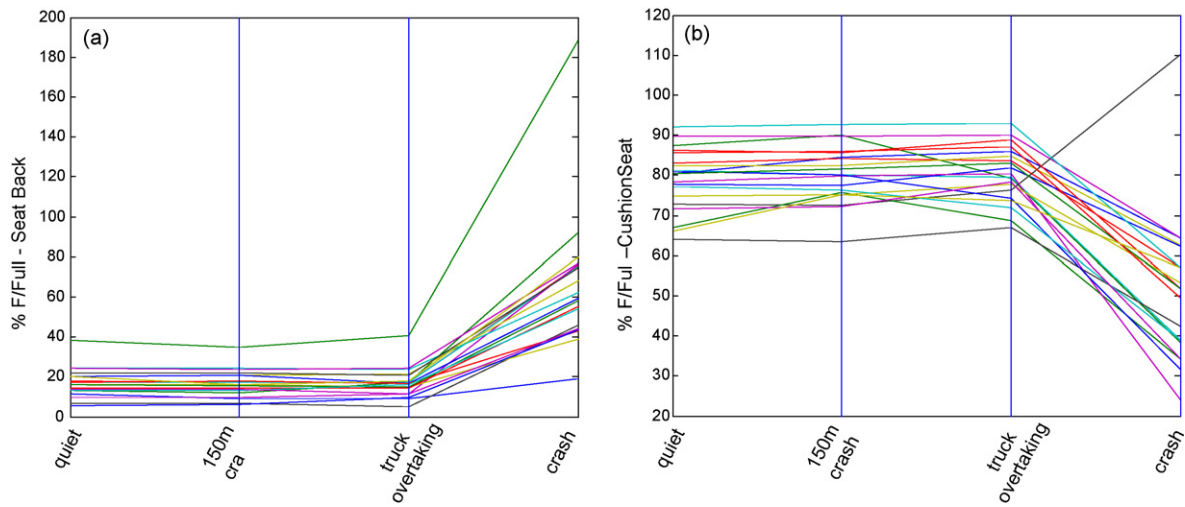


Fig. 5. Evolution of seat efforts for participants until crash. (a) Backseat and (b) cushion seat.

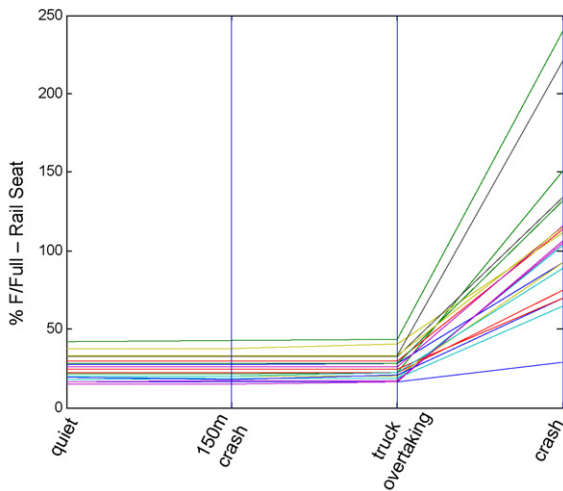


Fig. 6. Evolution of seat rail efforts participants until crash.

sufficient reaction time to anticipate the imminent collision that led to significant altering in postural orientation.

The typical response to this type of emergency event (frontal collision with a truck) was to brace rearward into the seat and

to straighten the arms against the steering wheel and/or the gear lever, or, to turn the steering wheel to swerve around the vehicle.

Three positions during crash are highlighted in this part of this study illustrating video observations (Figs. 8–10).

In Fig.8, the bracing driver in pre-impact situation tended to extend elbow and knee joints, and consequently pushed the pelvis back into the seat and lean backward. A considerable straightening of the arms was observed but the elbows remained bent at approximately 90°. This position accounted for 52.86% of participants.

In Fig. 9, the participant drove with the two hands on the steering wheel at the beginning of the turn. During the emergency event, he moved much further away and put his right hand on the gear lever. Considerable straightening of arms was observed. This position at impact was observed for 35.71% of participants.

In Fig. 10, the participant braced and gave a sharp turn of wheel to try to swerve around the truck during emergency event. This position was highlighted since in this configuration the forearm was placed in front of the steering wheel.

A particular attention is paid to arm and hand position on the steering wheel since airbags can inflict injuries when upper extremities are close to the air bag module at the time of impact (Huelke et al., 1995; Marco et al., 1996).

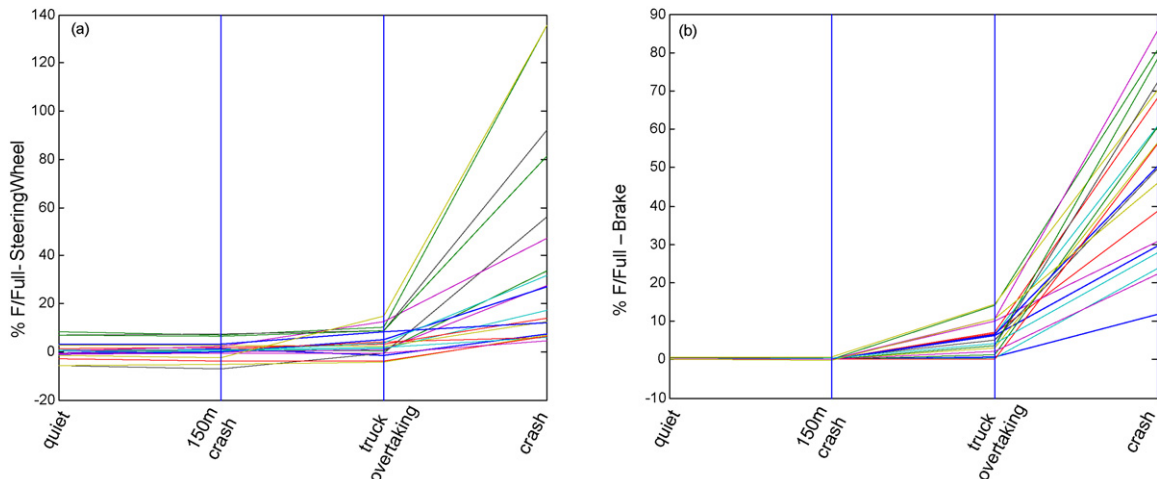


Fig. 7. Evolution of efforts for participants until crash. (a) steering wheel (compression) and (b) brake.



Fig. 8. Normal position to moving further, straightening arms.



Fig. 9. Normal position to moving further, touching gear lever.



Fig. 10. Normal position to moving further, steering.

3.5. Hand and arm positions

Videos were analyzed to establish drivers' hand location at the time of impact. Standard clock face nomenclature was used to describe the positions.

At the beginning of the experimental drive, participants adopted a 10 and 2 o'clock position or 9 and 3 o'clock position. Comfort positions were observed after only 20 min. For the left arm, participants often rested their arm by leaning their elbow on the window sill or the forearm on their thigh. For the right arm, drivers often rested their arm by laying their right hand on the gear lever or the forearm on their thigh. Participants regularly came through one comfort position to another one. Then, when drivers realized a crash was imminent, they modified their posture.

First, both hands were examined together. At the point of impact, the most common position (Table 6) for the drivers was to have both hands on the steering wheel (52.86%). The next common position for the driver was to have the left hand on the steering

Table 6
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	Off ^a	7.14
4	On the steering wheel	On the handbrake	1.43
5	On the steering wheel	On lap	1.43
6	Off	On the steering wheel	1.43

^a For example when the participant tries to take the gearshift.

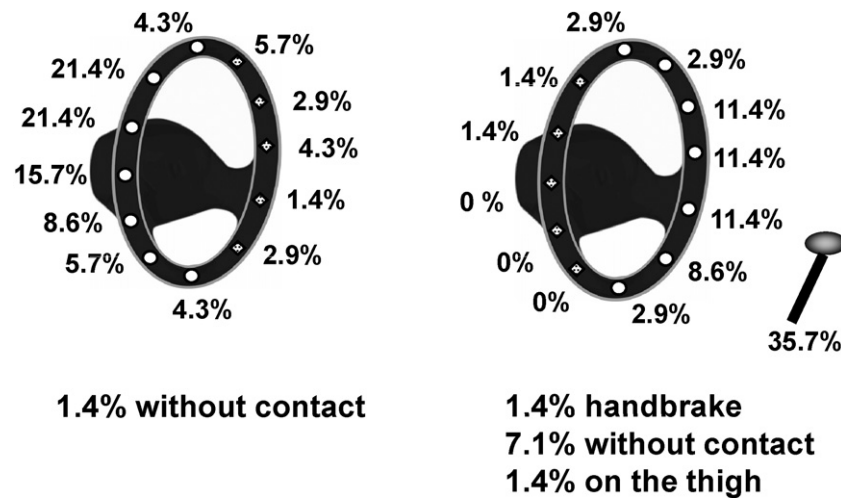


Fig. 11. Percentage of participants' left and right hand positions on steering wheel.

wheel and the right hand on the gear lever (35.71%). Five participants (7.14%) had the left hand on the steering wheel and the right hand off the wheel. This mainly corresponded to drivers that brought their right hand down from the steering wheel or thigh to the gear lever. Unusual cases were driver with the left hand on the wheel and the right hand on the handbrake or the thigh, and driver with the left hand off and the right hand on the wheel.

Prior to impact, 100% of the participants braked and 54.26% declutched. This can be related with the fact that 35.7% of the participants had their right hand on the gear lever. Indeed, a strong braking is often associated with declutching.

Then, each hand position was examined separately. The distribution of hands' positions on the steering wheel is presented in Fig. 11.

In 17.2% of cases, the left hand was in a 1–5 o'clock position. For 2.8% of cases, the right hand was in a 10 or 11 o'clock position. These cases were due to participants giving a sharp turn of wheel in an attempt to swerve around the truck. The forearm or the hand was then in close proximity to the airbag module and was likely to sustain injuries during the airbag deployment.

Furthermore, the results showed that 21.4% of participants had their left hand in a 10 o'clock position, 11.4% had their right hand at 2 o'clock, but only 7.14% of participants were in a 10 and 2 o'clock position as the standardized hand posture of ATD in a frontal impact.

4. Conclusions and discussion

Changes in driver posture were determined during a simulated frontal collision on the LAMIH car driving simulator. It integrated a real vehicle (Peugeot 206, left-hand drive simulator vehicle and manual gear box); a 6 degree-of-freedom hexapod motion platform that generated motion experienced under normal acceleration, braking and steering; accelerator pedal, brake pedal and steering wheel with force feedback; a virtual reality-based visual and audio system.

The main conclusions from this study can be summarized as follows:

- An unavoidable crash was reproduced to provide insight on driver postural orientations during emergency vehicle maneuvers. The realism of the simulator study was verified to ensure the validity of the results for a frontal collision. Results from videos suggested that most drivers had sufficient reaction time to anticipate the imminent collision that led to significant altering in postural orientation.

- The typical response to this emergency event (frontal collision with a truck) was to brace rearward into the seat and to straighten the arms against the steering wheel and/or the gear lever, or, to turn the steering wheel to attempt to avoid the impacting vehicle.
- Giving sharp turn of wheel led 20% of the participants to have one arm in front of the steering wheel at the time of crash. Since airbags are usually mounted in the hub, this may represent a rather risky position.

Based on these conclusions, an OOP is identified from this car driving simulator study based on incidence and potential severity. This OOP corresponds to a driver seating with the left arm in front of the steering wheel. Numerical simulations and experiments are then performed to investigate the influence of this identified driver pre-collision posture on injury outcomes. This is the object of the second part of this article.

However, a limitation of the study is that the participants are relatively young. While older drivers have become a larger part of the driving population and will continue to do so as the baby boomers reach retirement age (Lyman et al., 2002), the findings of the study cannot be applied to older drivers who may have slower reactions.

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