Dynamic models to analyse the influence of the seat belt in a frontal collision

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Abstract. Traffic accidents are influenced by various factors, yet, the highest impacting ones are related to vehicle impact speed and collision type. Also, passive vehicle safety systems play a significant role upon the injuries suffered by vehicle occupants. Under the circumstances, a particularly important aspect to consider when using such systems is the position of the vehicle’s driver and its occupants. In what follows we embark upon an in-depth analysis in order to investigate the contact effects between the seat belt and the driver, under a dynamic regime. We set out to identify the variation of the kinematic and dynamic parameters for both the driver and the seat belt via comparative analyses between the normal position of the driver and some other out of position instances, considered as critical.

1. Introduction

The identification and the analysis of the factors that concur to the occurrence of traffic accidents remains still a highly complex issue, given the large number of disturbing factors, the various traffic situations, and, also, the different behaviour and reactions manifested by each driver. An increased concern with regard to the development and the optimisation of virtual models to analyse the driver’s behaviour at the moment of impact is highlighted within a series of research studies such as in [2,4,6,7]. The dynamic seatbelt simulations as well as vehicle overturning tests are outlined by Taheo et al. in [7], by means of the MADYMO software.

Further research aims regarding vehicle occupant behaviour analysis envisage the proper positioning of the dummy on the driver’s seat have been addressed by a group of researchers from DYNAmore GmbH in [6]. Within this research study, two positioning methods of the dummy were highlighted. The cinematic and dynamic study of the driver’s behaviour in the event of a frontal collision is put forward in [8]. Also, within this research approach, special attention was paid to the identification of an effective method to assess the injuries suffered by the occupant in the head, thorax and pelvis. In order to determine the differences regarding the head injury risk in [8], some vehicle - pedestrian and vehicle - bicycle collision scenarios were investigated.

The most frequently investigated part of the human body following traffic accidents is the thorax area. The research study carried out in [3] highlights the initial steps undertaken to develop a finite element model based on the LS-Dyna code in the event of a collision within the thorax area. In order to validate the results obtained further comparisons to PMHS (post mortem human subjects) tests provided by mainstream literature have been developed. Another reference study in the development of a thorax-area model is set forth in [1]. Based on the MRI images obtained via scanning, an
anthropomorphically correct model of a 5th percentile female-type dummy was developed. Then, the model developed was tested in both lateral collisions (generating results with an increased bio-fidelity) and frontal collisions. The effect of a failed automobile front seat in the case of a rear-end collision and its effects on the occupants was studied in [5]. The design and the developing of two collision tests applied to the same conditions enabled a reliable comparison between a normal seat and a failed one.

The analysis of the influence triggered by the safety belt upon the driver has been and continues to be a focal topic dwelled upon within a series of previously published papers. The abdomen and the thorax are structural elements of the human body that come in contact with the safety belt, thus, most of the studies have been carried out to analyse normal driving positions. However, the novelty put forward in the present paper underpins a close analysis of the dynamic contact for the various positions of the driver in relation to the steering wheel, in order to identify some critical situations with reference to the influence exercised by the safety belt. Moreover, we aim at designing and developing a database encompassing virtual contact dynamic models to carry out a complex analysis upon the influence of the safety belt by reconsidering some material models as well as a series of kinematic and dynamic parameters that define the contact.

2. Methodology
The influence of the safety belt upon the driver’s thorax and pelvis will be investigated by applying two interdependent methods, i.e. virtual prototyping and experimental tests.

The monitoring of the collision, as a kinematic and a dynamic structure, is carried out under the same conditions for both virtual prototyping and experimental tests.

2.1. Virtual prototyping
To design and run the virtual prototyping, we develop a frontal collision model between a medium-sized vehicle and a rigid obstacle, the vehicle speed is set at 50 km/h. The collision simulation is completed via Virtual Crash, dedicated software for traffic accidents modeling and reconstruction. Taking our investigation a step further, we have developed an interface between Virtual Crash and LS-Dyna that enables us to input virtual prototyping data in the LS-Dyna software. The virtual model includes the driver, the seat, the dashboard, and the passive safety systems (airbag and seat belt).

Aiming to analyse the influence of the safety belt on the driver, we had first to define the contact between the component parts. Thus, Figure 1 below illustrates the parameter window that we set to define a contact of an Automatic_nodes_to_surface -type. The two contacts were defined between the thorax area of the dummy and the seat belt and between the pelvis and the safety belt. Our selection with regard to this type of contact was based on some of the features (considerations) we had to take into account such as thickness, orientation of segments not needed, the contact from both sides, initial penetrations are detected, possible to change or scale contact thickness, friction and damping available [10].

Figure.1 Defining the seat belt – thorax contact
To establishing the contact model, we took into consideration the type of the component materials as well. Hence, the material used in the thorax area has elastic and visco-elastic properties, of a plastic-kinematic and viscoelastic type. In the pelvis area, the material is of low density foam type. To model the seatbelt we used a seat belt type material, i.e. piecewise linear plasticity, the properties of which are illustrated in Figure 2.

2.2. Experimental tests
The experimental tests, carried out to investigate the frontal collision, have been performed with two vehicles, under polygon conditions, using a dummy, data acquisition systems, sensors and other equipment meant to register acceleration values, force and torque rates. During the experimental test, we positioned the dummy on the driver’s seat observing the procedures applied to reach the objectives set. The vehicle was subject to a frontal collision with another vehicle at a speed of 50 km/h. The restrain systems tested are not correlated with the head, thorax and lower limb transducers, if the biomechanical-based data benchmarks of the injury criteria are exceeded.

In the preliminary test phase, the sensor network, the measuring transducers and related wiring are mounted, observing the required safety and protection measures, hence reducing the disturbing possibilities that might occur during normal vehicle driving. The vehicle is equipped with redundant sensors and the information system selected to measure the variables of interest both on the dummy and on the vehicles involved in the collision. The characteristic points of the collision surface were appropriately marked with reflective cones. The equipment used for the dynamic measurements is of Xsens-type and DSD-PIC DAQ. This equipment is mounted on the vehicle before each test, see Figure 4 and Figure 5. To carry out the tests and to mount the measuring and the recording equipment we rested back the rear seat.
Based on sensitive measurement procedures we set up the experimental polygon and the measuring chains for each controlled variable of interest. The polygon where the collision tests have been carried out was foreseen with a fixed coordinate system, based on which we could measure the dynamic elements. In order to measure the force in the seat belt we used strain gauges, via which, following the calibration procedure, we determined the strains, and, subsequently, by means of equivalent relations, the corresponding forces.

2.3. Results validation
To validate our virtual model, we developed a comparative analysis between the modelling-based results and the results determined experimentally. Figures 6 and 7 indicate the seat belt force variations in the pelvis area and in the thorax area, determined both experimentally and virtually, via the LS-Dyna software.

As indicated in the figures above, the results obtained via a dynamic environment prototyping of the dummy-seat-safety systems assembly are very close to those established following experimental tests, hence validating our model.
Then, in order to analyse the influence of the safety belt on the driver, in a normal position of the dummy, we investigated the graphic representation of the contact forces generated between the seat belt and the pelvis, and respectively the thorax – see Figure 8.

![Figure 8. The contact force between seat belt – thorax – pelvis](image)

In the pelvis area, the maximum contact force is of 18 kN, whereas in the thorax area, the maximum contact force is of 7 kN. Figures 9-12 illustrate the strains and Von Mises equivalent stresses in the pelvis and thorax areas:

![Figure 9. Effective strain – pelvis](image)

![Figure 10. Effective stress Von Mises – pelvis [kN/mm²]](image)

![Figure 11. Effective strain – thorax](image)

![Figure 12. Effective stress Von Mises – thorax [kN/mm²]](image)

A close analysis of Figures 9, 11 and respectively 10, 12, indicates that the strains and the stresses generated by the contact with the seat belt are higher in the thorax area, although the contact force is higher in the pelvis area. Our results are reinforced by the geometric and material characteristics of the component elements, and, also, by the fact that during the impact, the airbag system also impacts upon the thorax area. Although the motions in the thorax are larger (see Figure 13), the analysis of the diagrams in Figure 14 indicates that the pelvis motion bears a more pronounced dynamic character, hence validating the triggering of the submarine phenomenon during the collision.
3. **Driver’s out of position**

For the first situation analysed we considered a normal position of the dummy, thus, the Hybrid III - 5th female percentile dummy was positioned with the thorax centered on the steering wheel at a distance of about 350 mm from the steering wheel. To position the dummy, the knee joint was set at an angle of -30 °, and the hands were placed on the steering wheel by modelling the elbow joint at an angle of -60 °. During subsequent tests we focused on the out of position (OOP) by changing the position of the dummy, both in terms of the distance from the steering wheel and the dummy’s angular position in relation to it. In all the 11 analysed situations, the dummy was considered to be fixed by means of a three-point seat belt restraint system. Starting from the normal position of the dummy, in the first test scenario, for the first four OOPs, we reduced the distance between the thorax and the steering wheel to a minimum of 150 mm. Starting with the OOP5 position, we rotated the dummy from the H point (dummy’s mass center) in relation to the steering wheel by 5, 10 and 15 degrees, first to the left and then to the right.

As illustrated in Figure 15, we can notice that the maximum value of the contact force recorded in the pelvis area was obtained for the OOP6 case, i.e. the rotating of the dummy’s mass center to the left, hence causing stains, and implicitly leading to lesions on the right side of the pelvic area.

![Figure 15. The contact force between seat belt and pelvis for the out of position](image1)

As illustrated in Figure 15, we can notice that the maximum value of the contact force recorded in the pelvis area was obtained for the OOP6 case, i.e. the rotating of the dummy’s mass center to the left, hence causing stains, and implicitly leading to lesions on the right side of the pelvic area.

![Figure 16. Effective strain – pelvis – OOP6](image2)

![Figure 17. Effective stress Von Mises – pelvis – OOP6](image3)
Figure 18. The contact force between seat belt and thorax for the out of position

Also, the maximum value of the contact force recorded in the thorax area was obtained in a dummy-out of position case, by rotating its mass center towards the left. Thus, we could identify the maximum stresses and strains values, recorded in the central-right area of the thorax, i.e. in the seat belt contact area.

Figure 19. Effective strain – thorax – OOP5     Figure 20. Effective stress Von Mises – thorax – OOP5 [kN/mm²]

4. Results

Following our research study, we could determine the time-related variation laws for the kinematic and dynamic parameters that allow for the monitoring of the driver’s motion during the collision. Also, we established the motions, the strains and the stresses in all areas affected by the driver’s seat belt, hence enabling us to identify the critical positions induced by the dynamic flexibility of the seat belt.

The variation of the dynamic parameters (contact forces, reactions) were analysed by means of comparison, applying the two methods previously mentioned, i.e. the numerical modelling and simulation and the experimental analysis.

The results obtained subsequent to our virtual prototyping were validated by the analysis and experimental tests, carried out mainly to investigate the driver’s normal position. Thus, we were able to widen our modelling and numerical simulation of the frontal collision phenomenon as applied to different front positions of the driver in relation to steering wheel.

Although, the experimental testing of the collision phenomenon between two vehicles in the polygon is essential for the further development of the analysis, the quality of such trails in terms of results accuracy implies rather higher costs. Therefore, the virtual prototyping on a complete model, designed as a structure, enabled us to develop a complex approach to different types of collision.
5. Conclusion
Our analysis on the influence of the safety belt upon the driver was carried out via two methods, virtual prototyping and experimental tests. The experimental tests, carried out under polygon conditions, implied the monitoring of a frontal collision between two medium-class vehicles, aimed at identifying the kinematics and dynamics of the dummy’s behaviour during the impact.

The virtual prototype entailed the design of the virtual model for the assembly: dummy - dashboard - seat - passive safety systems, while defining the dynamic contact between the components of the dummy (thorax, pelvis) and the seat belt, as well as the airbag system. Several dynamic models have been developed for the contact between the dummy and the passive safety systems, mainly the safety belt. The dynamic analysis and the results comparison between the virtual and the experimental models were carried out to investigate the normal position of the dummy in relation to the steering wheel, hence validating our virtual model. Next, our research was extended to monitor the dynamic response of the dummy’s motion during a frontal collision for several out of position instances (OOP), identified as critical.

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