AN ADVANCED 50TH PERCENTILE THOR DUMMY DATABASE

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ABSTRACT

As part of the ADRIA project (Advanced crush Dummy Research for Injury Assessment in frontal test conditions), INSIA-UPM has developed a multibody model with its corresponding database for the new frontal impact dummy (THOR) for use with MADYMO software. Principal new features, i.e. new design and advanced measurement capabilities through new instrumentation, are described in this paper and are also implemented in the THOR model.

For the development of this database and the modeling of the new dummy's features it has been necessary to obtain dummy's properties through special tests and advanced calculation techniques. The effectiveness of new techniques and procedures is explained in the present paper.

As last stage, the database has been validated through a series of component and full dummy tests for which a great number of variables have been recorded. Examples of comparisons between real dummy's response and model's response are shown to appreciate the level of accuracy achieved with the model.

THOR IS AN ADVANCED frontal crash test dummy 50th percentile. THOR is the acronym of Test device for Human Occupant Restraint. The new dummy has been developed in order to create an effective tool for whole-body trauma assessment in a variety of automotive occupant restraint environments. For this objective, improved biofidelic features and significantly expanded instrumentation have been added. In the same way, the design has the purpose of incorporate user-friendly features to facilitate ease of use and maintenance. THOR has been designed and built by GESAC, Inc. under the direction of NHTSA. Foremost advanced features include:

- More humanlike thorax anthropometry and rib contour.
- New rib bonding materials and techniques.
- New high-speed 3D thorax deflection measurement system.
- New dummy posture adjustment system.
- Revised shoulder design with clavicle representation.
- New multi-directional neck design.
- New restorable abdomen design.
- More humanlike pelvic segmentation.

- New compliant femur with improved impact response.
- New restorable load sensing face design.
- Modular construction.
- Enhanced instrumentation (dummy positioning sensors, acetabulum load cells, 3D abdomen penetration measurement, etc.)

Prototypes assemblies have been circulating internationally in test and evaluations trials. Within the framework of the ADRIA project a prototype of the THOR dummy have been tested. ADRIA project started in February 1997 and the following research institutions are involved: TNO, INRETS, TRL, University of Heidelberg, Eindhoven University of Technology and Politechnical University of Madrid.

The specific aim of the project is to develop the necessary knowledge with respect to the limitations of the most widely used dummy, the Hybrid III, and to propose improvements in the frontal impact dummy and its test specifications. The most important limitations of the Hybrid III dummy are:

- The Hybrid III dummy was developed in the seventies based on biomechanical knowledge available at that time and has hardly been changed since then. The new and more relevant measurements to assess injury risk are not implemented in this dummy. The Hybrid III design lacks sufficient bio-fidelity in relation with new biomechanical advances (Cesari, 1990; Thunnissen, 1995; Lowne, 1996).

- The Hybrid III is developed in the United States to assess injury risk for car occupants. Occupant restraints in Europe differ from those in the US. Several studies have indicated that the Hybrid III design is only partly suitable to assess injury risk in European belt conditions (Beusenberg, 1996). It is important to investigate whether the THOR dummy is suitable for use in European restraint conditions.

The project concentrates its first tasks in the injury assessment of foreground body parts: head, face and lower extremities. The last phase is the complete dummy evaluation, i.e. the practicalities and the feasibility of the complete dummy under frontal impact test procedure.

As part of the last phase, INSIA-UPM has developed a THOR database for a multibody model to be used with MADYMO software. This database includes a description in detail of mass properties, geometry of bodies and properties of joints, locations and external geometry contact functions.

To obtain the segment mass properties that compose the THOR database a new modeling technique has been used. This technique presents advantages with respect to the traditional method to obtain properties by experimental means (A review of the advantages in the use of this technique will be included in this paper). Joint properties and the superficial properties have been obtained through specially designed tests for such aims.

In the low velocity range, special tests with servo-hydraulic controller actuators have been used.

In the high velocity range, traditional dynamic impactor tests have been used.

Finally, the accuracy of the developed database has been checked through simulations of component tests and full dummy tests.

NEW FEATURES AND INSTRUMENTATION

New foremost advanced features of the THOR dummy with respect to the Hybrid III include parts with new design and advanced measurement capabilities thanks to new and enhanced instrumentation.

HEAD – Six new uniaxial accelerometers have been added to the instrumentation of the THOR head with respect to the HYBRID III. The face includes five uniaxial load cells for the measurement of contacts with the environment. The model includes the output for the new six accelerometers. The face load cells are not modelled.

NECK - The neck has a new three-dimensional design optimized to reproduce the voluntary test corridors (Wismans, 1983; Thunnissen, 1995; White, 1996). The neck includes upper neck and lower neck load cells as well as another two load cells to measure the front and rear spring compression. In the model, the three neck cables have been included as special components: rear cable, front cable and security cable. The main differences between the THOR and Hybrid III necks are:

- The THOR neck is about 55 mm longer than the Hybrid III neck.
- The cross section shape is ellipsoidal in the THOR neck and circular in the Hybrid III neck, which has larger diameter than the largest one corresponding to the THOR neck.
- The THOR neck has two cables along the rubber column instead of one cable as the Hybrid III has.
- The relative rotation between the head and the upper neck of the THOR is larger than for the Hybrid III in which this rotation is limited due to the stiffness of the nodding blocks. The THOR head can rotate with respect to the neck until either front or aft stop contacts the upper neck load cell.
- The position of the upper neck load cell is different for both dummy necks. The THOR load cell is rigidly connected to the top of the rubber neck column, the Hybrid III load cell is rigidly connected to the head.

The neck has been modelled with three bodies and three joints: bracket, free and spherical. The positions of the joints have been tuned in order to obtain the best correlation between the response of the model and the test results regarding deformations, accelerations, forces and moments. Additionally, neck front and rear soft stops, which limit the turn of the head around Y axis of the neck, have been modelled with contacts between small spheres and planes attached to the head and upper neck load cell segments respectively. These new features of the model allow a very good reproduction of frontal, rear and lateral impacts.

THORAX - The dummy's thorax has a new design and includes instrumentation specially designed to evaluate the injuries caused both by safety belts and airbags. The chest deflection potentiometer of the Hybrid III has been replaced by a set of twelve rotary potentiometers distributed in four units (CRUX) at different locations. With the new system it is possible obtain measurements of thorax deflection in the three local cartesian directions. The sternum has an uniaxial accelerometer and also a triaxial accelerometer is included in the CG of the thorax segment. In the model, the ribs are split in two segments: upper ribs and lower ribs. Each ribs block is attached to one spine segment and has a floating design with 6 degrees of freedom with respect to the spine. The rib contour can be modified rotating the upper thoracic segment around the lumbar pit change mechanism as in the real dummy. All the dummy instrumentation features have been included in the mathematical model.

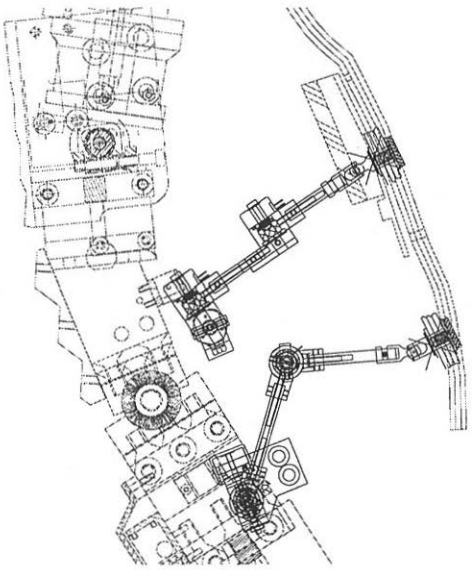

***Figure 1:** THOR dummy CRUX detail.*

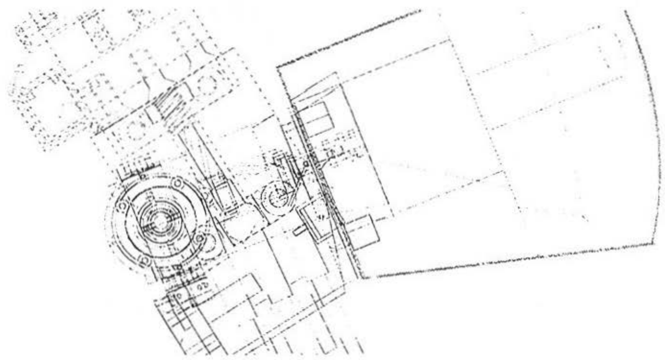

***Figure 2:** THOR dummy DGSP detail.*

SHOULDER – The dummy's shoulder design has been revised with clavicle representation by means of an articulated quadrilateral mechanism, which has been modelled too to simulate the real shoulder behaviour. The clavicle is joined to the superior part of the thorax and to the shoulder yoke. Belt loads are transmitted from the shoulder to the upper thorax. The shoulder model is able to transmit compression and lateral efforts as the real mechanism. In this way better bio-fidelic behaviour is achieved.

SPINE – The spine is equipped with two triaxial accelerometers and a T12 load cell, which is able to measure forces in X, Y and Z directions and moments respect X and Y directions. The spine has been improved with more segments that have been taken into account in the model. The spine has two mechanisms to regulate the angle of its position: lower thoracic pitch change and lower neck pitch change mechanism. These special joints have been included in the developed database. In this way, the model is able to reproduce the different initial dummy positions for each type of test.

ABDOMEN - The dummy's abdomen has been split into two segments, lower abdomen and upper-abdomen. The two parts of the abdomen include measure of deformation and the lower-abdomen, instrumented with two sets of three-dimensional potentiometers (DGSP units). These DGSP allow assessing injuries produced by the steering wheel hoop. In the model, these features have been included and the upper abdomen body is attached to the lower ribs and the lower abdomen is attached to the spine.

PELVIS – The pelvis has a more humanlike segmentation. In this sense the model has been completed. The two sets of acetabular load cells (allow force measurement in X, Y and Z directions) have been represented. The pelvis model reproduces the efforts transmitted through the femur in the pubic area.

FEMUR – The THOR femur includes a compliance joint with one degree of freedom in X direction that reproduces the femur compliance. This feature has been included in the model allowing axial deformation and improved impact response.

EXTERNAL SURFACE AND JOINTS PROPERTIES

The THOR model is composed by 46 rigid solids, linked with their corresponding joints, and a total of 82 degrees of freedom. For each degree of freedom it is necessary to establish its constitutive laws of efforts, the also called joint functions. For the new model the functions of 20 new joints have been established. The database includes 15 locked joints that do not need functions. Rest five dual joints in the arms and lower legs functions included in the database have been obtained from previous MADYMO Hybrid III databases (TNO, 1997).

QUASI-STATIC COMPRESSION TESTS - Surface compliance is dependent on the skin covering thickness and density as well as the compliance of the underlying structure, like e.g. the ribcage. Compression tests were conducted with several penetrating surfaces and for different locations on the dummy's surface: thorax, abdomen and skin pelvis. The static force-deflection characteristics were determined using a digital controlled servo-hydraulic linear actuator of Hidroplus Schenck series. The compression faces were connected to the piston. Triangular and sinusoidal waves were programmed with different frequencies for obtain the dummy's response at several different velocities.

Measurements were performed using external and internal (THOR dummy) instrumentation. A load cell between the piston and the compression face measures the force applied by the actuator. Additionally, the linear displacement of the actuator was recorded for all the tests. The deflection of the THOR surface was measured with the internal CRUX and DGSP units.

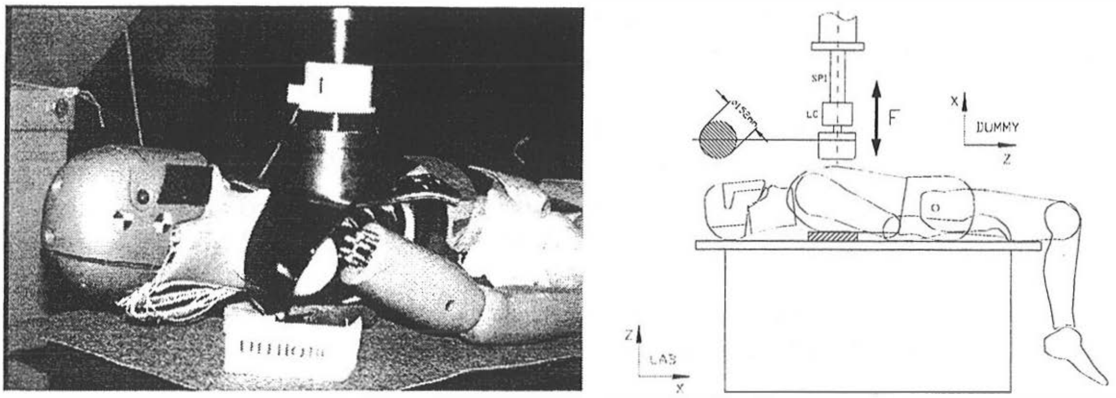

Figure 3: *Thorax compression test*

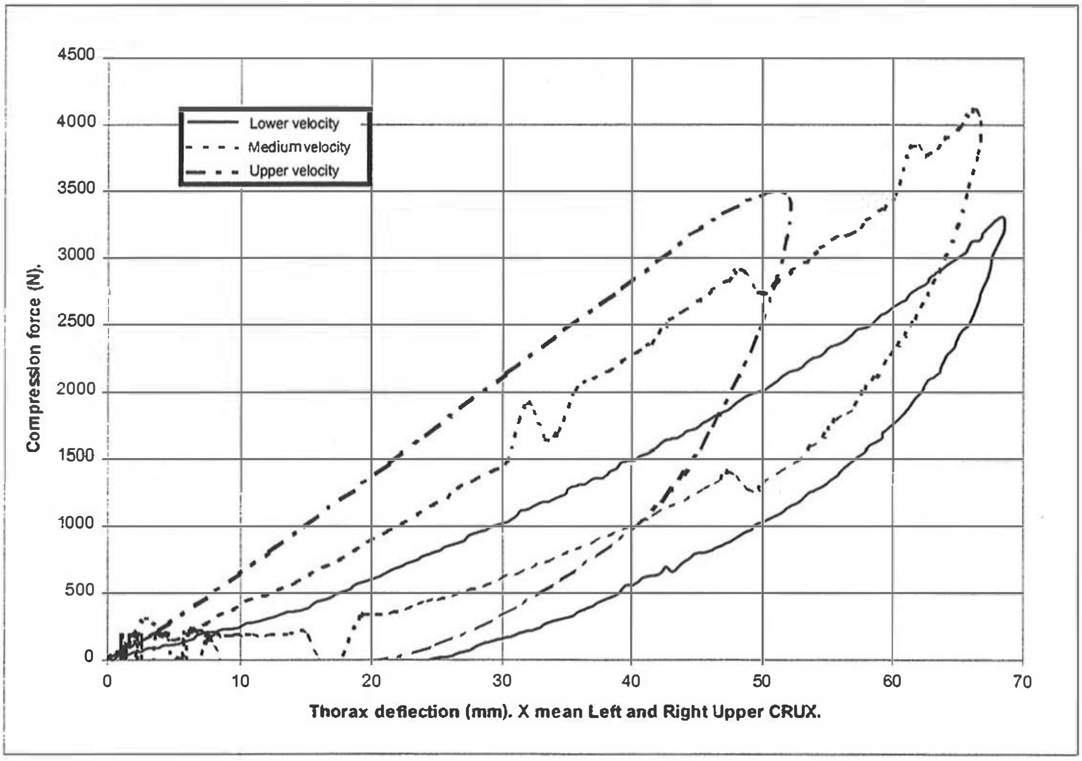

Figure 4: *Force-deflection curves at different velocities.*

JOINT FLEXION TESTS - The stiffness of the connection between the different segments is one of the parameters having a major effect on the movement of the dummy in a crash environment (Philippens, 1991). In this type of tests static joint properties have been determined. The external applied torque as function of the joint rotation is automatically recorded in this test set up allowing a registration of the static joint properties. The tests were performed for several joints: upper thoracic joint, lumbar joint, hip joint and shoulder joints.

Measurements were performed using external and internal (THOR dummy) instrumentation. A load cell between the wire and the traction system measures the force applied. Joint rotations were obtained through linear displacements of several points of the dummy measured with string potentiometers. Additionally, internal T12 spine load cell was used to measure force and moment in lumbar joint flexion test.

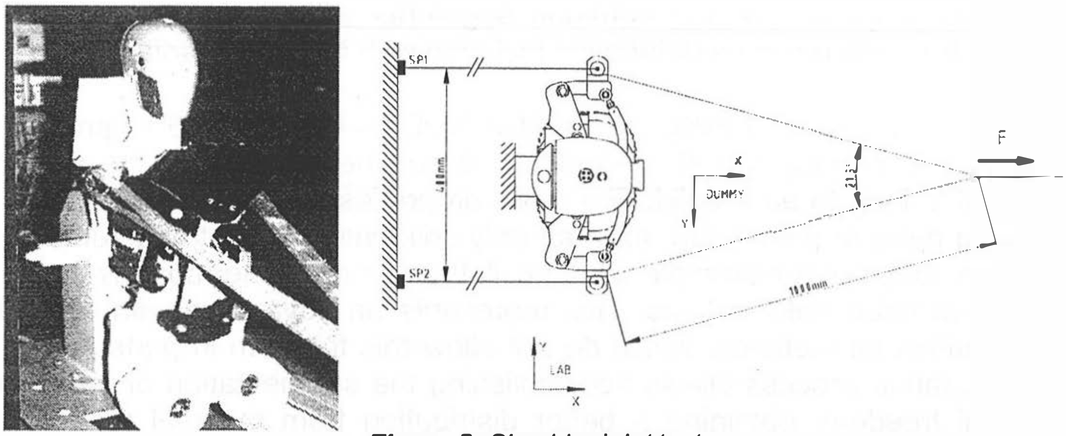

Figure 5: Shoulder joint test

MASS PROPERTIES AND SEGMENTATION

INSIA has concentrated its database development efforts in the parts that are different in the THOR dummy respect to the Hybrid III. One principal difference of THOR is the increase of sensors respect to the Hybrid III. The THOR spine, abdomen (with two different parts lower and upper abdomen), neck, head, thorax and shoulder have a new design. With the objective of develop a database that allows the modelling of the new performances of the THOR dummy, a quite new segmentation respect to the Hybrid III has been chosen (Happee, 1996). The new segmentation allow to calculate at least the same number of signals that dummy records.

To obtain the inertial properties and the geometrical description of the segments as well as joint positions the INSIA-UPM has used the technical drawings of the THOR dummy. Based on the data included in these drawings INSIA-UPM has constructed a 3D geometrical model of the THOR that include all the dummy parts. Within this model the density properties of each material are included. Using CAD software with this 3D model INSIA-UPM has obtained the inertia matrix for each segment and positions of centers of gravity. Using this procedure it is possible to divide the dummy in segments with more accuracy than using experimental measurements because the dummy parts can be divided in portions without to break the real dummy parts.

During THOR testing period INSIA-UPM has obtained measurements of weight of 48 THOR individuals parts and subassemblies to check the results obtained with the above segment mass properties calculation procedure and also to obtain certain material densities like foam rubber which were unknown. When the mass properties calculation finished, the total obtained dummy mass is 78.72 Kg. The real mass of dummy is 79.6 Kg. The accuracy of calculation is 99%. No adjustment to correct this 1% difference is made in the database. Differences between real dummy mass and value obtained by calculations are due principally to the bolts that are not included in the CAD model.

THOR dummy has the same lower legs and arms than the Hybrid III dummy. The mass properties of the common segments with the Hybrid III can be obtained from the previous databases included with MADYMO software.

ATTACHED PARTS LINKED TO EACH BODY - Once the 46 segments that compose the dummy model are defined, it can be established the individual parts that belong to each solid. The mass properties calculation process allows assigning parts of pieces that form an only solid into different segments of the dummy model, like for example a load cell, the ribs and other dummy parts that experiment large deformations. This represents an advantage with respect to the experimental methods, which do not allow this freedom in parts assigning. The calculation process allows accomplishing the segmentation of the dummy with total freedom, obtaining a better distribution from the real mass of the dummy in its different segments.

MASS PROPERTIES CALCULATION

3-D model - From the 2-D technical drawings every body of the THOR dummy was modelled in 3-D with CAD software. These 3-D models were used to calculate the properties of each body:

- Density.
- Position of centre of gravity (CG).
- Tensor of inertia.

A table with the list of bodies that compose the THOR dummy along with inertial property data can be found in Appendix A.

Densities - The bodies can be classified in two groups:

- Bodies made of only one material, i.e. iron, aluminium, rubber, etc. In this case, the calculation of density is very easy and only a table of material densities is needed.
- Bodies composed by two or more different materials. Firstly, it is necessary differentiate between each part made of only one material. Then the volume of each homogeneous part is calculated. When volume and density are known, the mass of this part can be calculated. Adding the mass of all parts and dividing by the global volume, the apparent density is obtained. Another possibility is to weigh the piece and to calculate its volume, using these data the density is obtained.

Tensor of inertia and center of gravity (CG) - In this stage the following steps have been followed:

1. Development of a 3-D model for each body using the technical drawings and by means of CAD software.
2. Each body is divided in different parts, each one composed by only one material or composed by commercial parts as accelerometers, load cells, etc. This process is necessary since the CAD software uses only one

density of 1 gr/cm^3 for all solids of a body. The CAD software performs geometrical calculations for the Inertia tensor of each solid. With these volumetric results, total mass and inertia tensor can be obtained multiplied CAD results by the respective density of each set of homogenous parts.

3. Calculation of the mass and CG position for each body adding the individual results for each homogenous part of the body.
4. Calculation of the tensor of inertia for each body, The tensor of inertia is obtained multiplying the components of the geometrical inertia tensor obtained with the CAD software by the density of each homogenous part. All these individual tensors are referenced and calculated respect the same reference system located in the joint. The global tensor of each body respect the joint reference system is calculated adding all individual inertia tensors. The inertia tensor of each body with respect its centre of gravity is calculated applying the extended Steiner formulas.

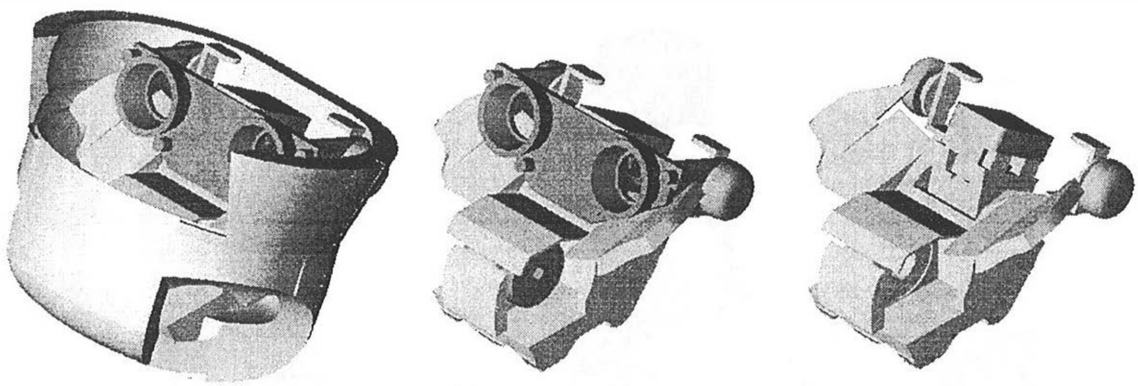

Figure 6: *Pelvis*

The process describes in points 2, 3 and 4, implies a great amount of operations being necessary to develop specific software for these calculations. This software generates, from a set of inputs files provides by the CAD software of each homogenous part of a body, an output file with the global results for the body in process, (total mass, centre of gravity location, inertia tensor respect joint reference system and inertia tensor respect to global CG).

Figure 6 is an example of the different parts of a 3-D model corresponding to the pelvis body.

The final data for each body are:

- Joint number to which the body is referenced.
- Position (m) of its CG respect to the local reference system corresponding to its associated joint.
- Mass associated (Kg.).
- Principal moments of inertia (Kg m^2).
- Orientations (rad) of the principal directions of inertia respect to local reference system. These rotations should be applied in next order: Z rotation, Y rotation and finally X rotation.

EXTERNAL GEOMETRY

Once the definition of joints and solids is finished, next step is to develop the external geometry of THOR dummy for include them into Madymo. This geometry has been modelled using ellipsoids (with degree two, three and four). Each ellipsoid is linked to a body and it is located and oriented respect to the local body reference system. In the modelling of each body a different number of ellipsoids are used. An ellipsoid is defined by its geometry (semiaxes distances a, b and c), the position of its centre, its degree, its orientation, its contact functions in load and unload and its hysteresis slope. A total of 80 ellipsoids are used to define the external geometry of the THOR dummy. Parameters for the definition of the ellipsoids have been obtained with the data included in the technical drawings of the dummy.

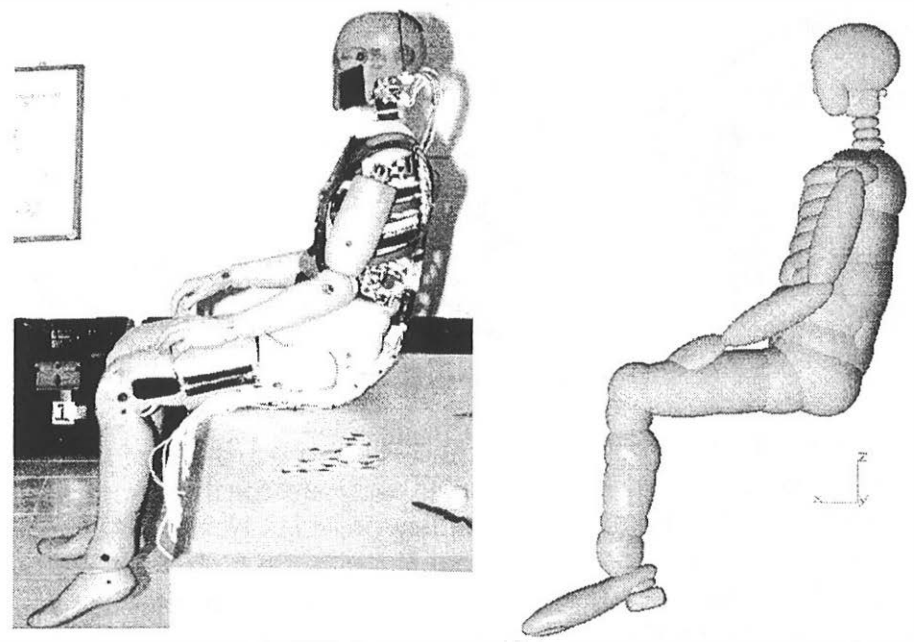

Figure 7: *THOR dummy and MADYMO THOR model side view.*

DATABASE VALIDATION

Data obtained from the tests has been converted in functions that MADYMO software requires (See MADYMO User's Manual). These functions have been used as start point for the validation process. Some of these functions have been modified in order to obtain a better correlation between the model's response and the real dummy's response.

THOR database has been validated and tuned through a series of component tests and full dummy tests.

HEAD NECK SLED TESTS - The HyGe sled tests, performed by TNO with the head-neck subassembly, have been used to validate the response of the same subassembly in the database developed for the THOR dummy. HyGe sled tests were conducted with an isolated head-neck system reproducing the tests described in (Thunnissen, 1995 and Wismans, 1984). For each test, the THOR dummy neck was placed on a HyGe sled. The head-neck subassembly validation has been made through the reproduction of the HyGe tests.

The same geometrical initial configuration of the head-neck subassembly has been used for each test. The system has been subjected to an excitation corresponding to the real acceleration measured by the sled accelerometers. Nine different tests were considered, in three impact configurations: frontal, rear and lateral impact under specific conditions. The dummy head-neck system was mounted on the sled such that it was either accelerated in frontal, lateral or backward direction.

A comparison between the real response and the model response has been performed. Besides the variables recorded by the head-neck sensors a series of angles and trajectories corresponding to a certain control points have been obtained through the photograms filmed by a high-speed video system (Hoofman, 1998). The validation includes the following types of response:

- Trajectories, positions and angles
- Accelerations
- Forces and moments

Table 1 - Validated variables in Head-Neck Sled Tests.

FRONTAL AND REAR TESTS	LATERAL TESTS
Linear head center of gravity X-acceleration	Linear head center of gravity X-acceleration
Linear head center of gravity Z-acceleration	Linear head center of gravity Y-acceleration
Linear head center of gravity Resultant-acceleration	Linear head center of gravity Z-acceleration
Trajectory OC joint target respect to inertial space X-direction	Linear head center of gravity Resultant-acceleration
Trajectory OC joint target respect to inertial space Z-direction	Trajectory A point with respect to inertial space X-direction
Head angle with respect to inertial space	Trajectory A point with respect to inertial space Z-direction
Upper neck load cell angle	Trajectory B point with respect to inertial space X-direction
Front spring load cell force	Trajectory B point with respect to inertial space Z-direction
Rear spring load cell force	Head angle with respect to inertial space
Upper neck force in X-direction	Front spring load cell force
Upper neck force in Z-direction	Rear spring load cell force
Upper neck torque about Y-axis	Upper neck force in X-direction
Lower neck force in X-direction	Upper neck force in Y-direction
Lower neck force in Z-direction	Upper neck force in Z-direction
Lower neck torque about Y-axis	Upper neck torque about X-axis
Linear acceleration measured by uniax HTX1 in X-direction	Upper neck torque about Y-axis
Linear acceleration measured by uniax HRZ1 in Z-direction	Upper neck torque about Z-axis
	Lower neck force in Y-direction
	Lower neck torque about X-axis
	Linear acceleration measured by uniax HTX1 in X-direction
	Linear acceleration measured by uniax HTY1 in Y-direction
	Linear acceleration measured by uniax HRY1 in Y-direction
	Linear acceleration measured by uniax HRZ1 in Z-direction
	Linear acceleration measured by uniax HSX1 in X-direction
	Linear acceleration measured by uniax HSZ1 in Z-direction

KROELL TESTS. - The objective of these tests is to determine the dynamic upper ribcage response by means of a rigid flat impactor assembled in a pendulum. The principal response corridors required to be met by THOR are the traditional Kroell corridors for rigid disk impact at 6,7 m/s and 4,3 m/s at the upper ribcage (Kroell, 1971).

The THOR dummy was set up in a sitting position, with no back support and the arms raised (suspended with strings). The dummy was positioned in front of the impactor such that the centre line of the impactor was at the vertical level of the middle of dummy rib #3, and positioned over the mid line of the sternum. This position would be at the middle of the line connecting the attachment nuts of the two upper chest deflection measurement systems (CRUX). The impactor face was parallel to the chest at this location. For this purpose it was necessary to position the lower thoracic spine at about 4° relative to vertical.

All the measurements were conducted by using external (accelerometer at the rear face of the impactor) and internal (THOR dummy left and right upper CRUX) instrumentation.

Two impact speeds were considered for the tests performance and database validation: 4.3 m/s. and 6.7 m/s. The measurements include the impact force measured at the impactor by means of an accelerometer and deflections measured by the two Upper CRUX systems. The average of the right and left X deflections was used as the measure for thorax deflection.

RIGID SEAT SLED TESTS - Ten sled tests were performed with rigid seat (for the validation of the multibody model) and flexible seat (for the analysis of the dummy's response under European accident conditions), (Martínez, 1998). The validated THOR database allows the numerical analysis of anchorage sensitivity on the dummy's response. In the tests, rigid and flexible seats have been used. The positioning of seat belt anchorages was determinated by studying a database made with configurations of seat belts of vehicles fabricated between 1992 and 1997. Two configurations for three doors vehicle body, two configurations for five doors vehicle body and a subabdominal configuration were considered. In all tests, impact speed was 50 Km/h except in subabdominal seat belt that was reduced to 25 Km/h.

Since only rigid seat tests have been considered for the validation, seat modelling has been carried out using planes instead of ellipsoids, selecting appropriate contact functions. Flexible seats have not been modelled in order to simplify the seat modelling and to identify and interpret in a clearer way the results of dummy's response.

Table 2 - Validated variables in Rigid Seat Sled Tests.

Head CG Accelerometer (X axis) (m/s^2)	Spine Thoracic Force (Z axis) (N)
Head CG Accelerometer (Y axis) (m/s^2)	Upper Neck Moment (X axis) (Nm)
Head CG Accelerometer (Z axis) (m/s^2)	Upper Neck Moment (Y axis) (Nm)
Head CG Resultant Accelerometer (m/s^2)	Upper Neck Moment (Z axis) (Nm)
Head Vertex Accelerometer (X axis) (m/s^2)	Lower Neck Moment (X axis) (Nm)
Head Vertex Accelerometer (Y axis) (m/s^2)	Lower Neck Moment (Y axis) (Nm)
Head Occipital Accelerometer (Y axis) (m/s^2)	Lower Neck Moment (Z axis) (Nm)
Head Occipital Accelerometer (Z axis) (m/s^2)	Spine Thoracic Moment (X axis) (Nm)
Head Temporal Accelerometer (X axis) (m/s^2)	Spine Thoracic Moment (Y axis) (Nm)
Head Temporal Accelerometer (Z axis) (m/s^2)	Head rotation (rad)
Pelvis CG Accelerometer (X axis) (m/s^2)	Upper Right Thorax Disp. (X axis) (m)
Pelvis CG Accelerometer (Y axis) (m/s^2)	Upper Right Thorax Disp. (Y axis) (m)
Pelvis CG Accelerometer (Z axis) (m/s^2)	Upper Right Thorax Disp. (Z axis) (m)
Pelvis CG Resultant Accelerometer (m/s^2)	Upper Right Thorax Distance Change (m)

Lower Spine Accelerometer (X axis) (m/s^2)	Upper Left Thorax Disp. (X axis) (m)
Lower Spine Accelerometer (Y axis) (m/s^2)	Upper Left Thorax Disp. (Y axis) (m)
Lower Spine Accelerometer (Z axis) (m/s^2)	Upper Left Thorax Disp. (Z axis) (m)
Lower Spine Resultant Accelerometer (m/s^2)	Upper Left Thorax Distance Change (m)
Thorax CG Accelerometer (X axis) (m/s^2)	Lower Right Thorax Disp. (X axis) (m)
Thorax CG Accelerometer (Y axis) (m/s^2)	Lower Right Thorax Disp. (Y axis) (m)
Thorax CG Accelerometer (Z axis) (m/s^2)	Lower Right Thorax Disp. (Z axis) (m)
Thorax CG Resultant Accelerometer (m/s^2)	Lower Right Thorax Distance Change (m)
Upper Spine Accelerometer (X axis) (m/s^2)	Lower Left Thorax Disp. (X axis) (m)
Upper Spine Accelerometer (Y axis) (m/s^2)	Lower Left Thorax Disp. (Y axis) (m)
Upper Spine Accelerometer (Z axis) (m/s^2)	Lower Left Thorax Disp. (Z axis) (m)
Upper Spine Resultant Accelerometer (m/s^2)	Lower Left Thorax Distance Change (m)
Neck Front Load Cell Force (N)	UASP (m)
Neck Rear Load Cell Force (N)	Lower Abd. Right Disp.(X axis) (m)
Outer Lap Seat Belt Load Cell (N)	Lower Abd. Right Disp.(Y axis) (m)
Upper Shoulder Seat Belt Load Cell (N)	Lower Abd. Right Disp.(Z axis) (m)
Upper Neck Force (X axis) (N)	Lower Abd. Left Disp.(X axis) (m)
Upper Neck Force (Y axis) (N)	Lower Abd. Left Disp.(Y axis) (m)
Upper Neck Force (Z axis) (N)	Lower Abd. Left Disp.(Z axis) (m)
Lower Neck Force (X axis) (N)	Head trajectory (X axis) (m)
Lower Neck Force (Y axis) (N)	Shoulder trajectory (X axis) (m)
Lower Neck Force (Z axis) (N)	Elbow trajectory (X axis) (m)
Spine Thoracic Force (X axis) (N)	Arm trajectory (X axis) (m)
Spine Thoracic Force (Y axis) (N)	Knee trajectory (X axis) (m)
Spine Thoracic Force (Z axis) (N)	Foot trajectory (X axis) (m)
Upper Neck Moment (X axis) (Nm)	Head trajectory (Z axis) (m)
Upper Neck Moment (Y axis) (Nm)	Shoulder trajectory (Z axis) (m)
Upper Neck Moment (Z axis) (Nm)	Elbow trajectory (Z axis) (m)
Lower Neck Moment (X axis) (Nm)	Arm trajectory (Z axis) (m)
Lower Neck Moment (Y axis) (Nm)	Knee trajectory (Z axis) (m)
Lower Neck Moment (Z axis) (Nm)	Foot trajectory (Z axis) (m)
Spine Thoracic Force (X axis) (N)	
Spine Thoracic Force (Y axis) (N)	

RESULTS OF VALIDATION – Figures 8, 9 and 10 are examples of some variables for which a comparison between the test results and the simulations are developed.

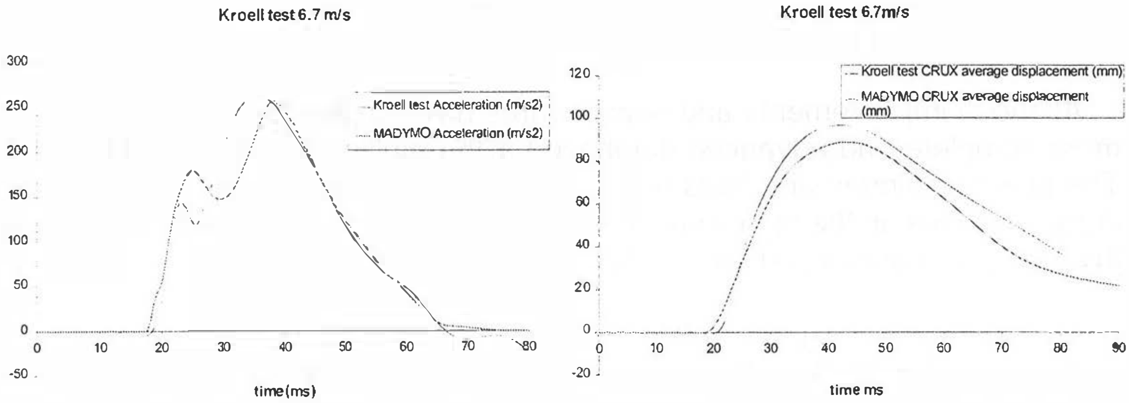

Figure 8: *Kroell test (6.7 m/s) impactor accel. and CRUX average displacement validation.*

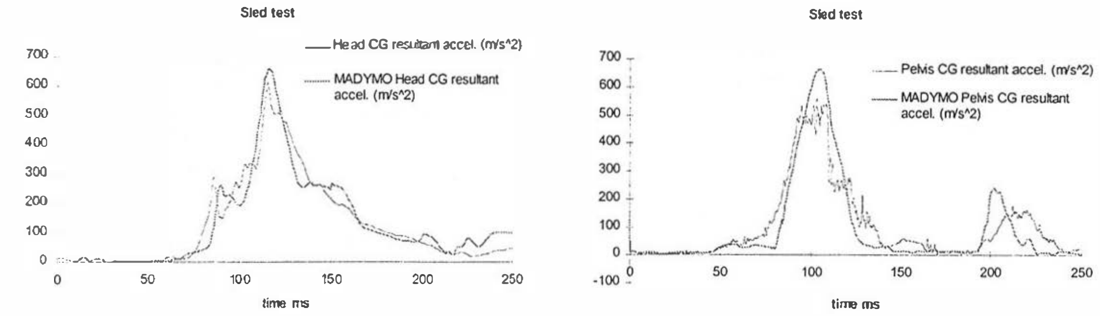

Figure 9: *Sled test head and pelvis resultant acceleration validation.*

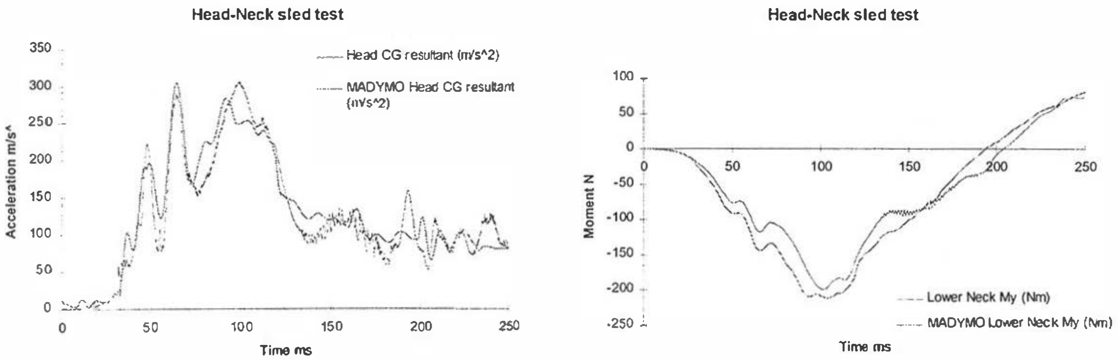

Figure 10: *Head-Neck sled test head resultant acceleration and lower neck Y axis moment.*

CONCLUSIONS

THOR dummy incorporates a large amount of instrumentation, specially in the thorax and abdominal region, that allows new and more complete measurements capabilities. Additionally some parts like neck, spine and ribcage have a new designs that make the dummy more bio-fidelic. These facts make the THOR dummy more complex with respect to the Hybrid III dummy but reflects better the current knowledge on frontal human body crash behaviour.

All these improvements and new features have implied the development of a more complete and advanced database for the multibody model for MADYMO. The new techniques and tests used for obtain physical properties of the THOR dummy as well as the high level of accuracy achieved for the database converts the model in a useful and precise tool for automotive research.

The adequate experimental and mathematical methods selected have guaranteed the good results obtained. To obtain reliable data in relation with dummy's properties, the developed tests have followed the sequence: quasi-static (with increasing speed configurations), dynamic and validation. Kinematic and dynamic variables have been taken into account for the tuning of the model. The model satisfies these two conditions.

All available tests of the THOR test programme, within the ADRIA project, have been used for the validation process. The model's response for different impact test conditions (different angles, use of airbags, etc.) has not been possible to check. We expect that in the future can be developed new THOR tests in order to check and tune the model for different conditions.

The authors think that the excellent results obtained during the validation of the THOR model are due to the following reasons:

- The joint positions of the model have been obtained with high precision. Some joint positions have modified during the validation phase to obtain a better correlation between tests and simulations.
- The mass properties of the dummy are calculated with high precision. The methodology used is a promising tool that can be applied in built dummies and also during the design phase of new dummies.
- Special attention has been applied to include all the special components of the THOR dummy like the neck cables.
- The tests performed with THOR dummy have been allowed to obtain the compliance properties of the dummy at component level with high precision.

The results obtained by the database are good and correlate with high accuracy with tests. It can be concluded that the developed database is a good mathematical model to predict the injury criteria measures for the 50th percentile THOR dummy.

ACKNOWLEDGEMENTS

This study was supported by the European Community under contract number PL96-1074. All opinions given in this paper are those of the authors and not necessarily those of the EC. The authors wish to express their special thanks to NHTSA and GESAC for providing them with the possibility to test the THOR dummy and for their support during testing and analysis. Also to the TNO road vehicles members staff for providing with the tests results of the THOR head-neck assembly.

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APPENDIX A. MASS AND INERTIAL PROPERTIES

Nº	BODY	CENTRES OF GRAVITY (m)			MASS (Kg)	PRINCIPAL MOMENTS OF INERTIA (Kg m^2)			Principal moments of inertia ORIENTATIONS (rad)		
		X axis	Y axis	Z axis		Ixx	Iyy	Izz	Rot Z axis	Rot Y axis	Rot X axis
1	Pelvis	-0.0455	0.0001	0.0339	11.13	0.0923	0.0767	0.0699	0	0.04472	0
2	Lower Abdomen	0.0228	0	-0.0049	1.18	0.0063	0.0077	0.012	0	-0.0587	0
3	Lower Lumbar	-0.0038	0	0.0472	1.76	0.0011	0.0015	0.0014	0	-0.4348	0
4	Thoracic T12 LC	0	-0.0022	0.0253	1.75	0.0012	0.0009	0.0013	0	0	0.0616
5	Lower Thoracic	0.0225	0.0007	0.021	4.86	0.0268	0.0203	0.0126	-0.0024	0.4964	-0.0239
6	Lower Ribs	0.1814	0	0.0101	0.9	0.0113	0.0024	0.0109	0	-0.1595	0
7	Upper Th Spine	-0.0043	0	0.0571	4.55	0.0215	0.0095	0.0191	0.0049	-0.0829	0.0127
8	Neck Change Pitch	0	-0.0032	0.0178	0.52	0.0002	0.0002	0.0003	0.0035	0.004	-0.3074
9	Lower Neck LC	-0.0028	0	0.0166	0.79	0.0002	0.0002	0.0002			0
10	Neck	-0.0028	0	0.0447	0.69	0.0043	0.0042	0.001	0.0061	0.045	0
11	Upper Neck Plate	0	0	0.0233	0.93	0.0022	0.0022	0.0003	0	0	0
12	Upper Neck LC	0	0	0.0137	0.26	0.0002	0.0002	0.0002	0	-0.1813	0
13	Head	0.0108	0	0.0447	3.9	0.0144	0.0131	0.0103	0	-0.896	0
14	Sh support Left	-0.0191	0.04	0.0123	1.03	0.002	0.0011	0.0028	-0.011868	-0.67998	-0.3564
15	Sh support Right	-0.0191	-0.04	0.0123	1.03	0.002	0.0011	0.0028	0.011868	-0.67998	0.3564
16	Sh yoke Left	0.0401	0.0058	-0.0162	0.16	0.0001	0.0002	0.0001	0.0637	-0.05236	-0.051836
17	Sh yoke Right	0.0401	-0.0058	-0.0162	0.16	0.0001	0.0002	0.0001	-0.0637	-0.05236	0.051836
18	Clavicle Left	0.0213	-0.0617	-0.0028	0.24	0.0005	0.0001	0.0005	0.148	0.602837	0.149924
19	Clavicle Right	0.0213	0.0617	-0.0028	0.24	0.0005	0.0001	0.0005	-0.148	0.602837	-0.149924
20	Upper Arm Left	0.0009	-0.0025	-0.1323	2.06	0.0122	0.0125	0.01	0	0	0
21	Upper Arm Right	0.0009	0.0025	-0.1323	2.06	0.0122	0.0125	0.01	0	0	0
22	Lower Arm Left	-0.0013	-0.0017	-0.0885	1.71	0.0133	0.0153	0.01	0	0	0
23	Lower Arm Right	-0.0013	0.0017	-0.0885	1.71	0.0133	0.0153	0.01	0	0	0
24	Hand Left	0.0035	0.0017	-0.0547	0.6	0.01	0.01	0.01	0	0	0
25	Hand Right	0.0035	-0.0017	-0.0547	0.6	0.01	0.01	0.01	0	0	0
26	P. Ac. LC Left	-0.0014	0.0291	0.0018	1.53	0.001	0.001	0.0012	1.3408	0.3927	-0.6018
27	P. Ac. LC Right	-0.0014	-0.0291	0.0018	1.53	0.001	0.001	0.0012	-1.3408	0.3927	0.6018
28	Up. Femur Left	0.0658	0.0119	0.0214	4.81	0.0068	0.0164	0.0159	0.0243	0.0635	0.377
29	Up. Femur Right	0.0658	-0.0119	0.0214	4.81	0.0068	0.0164	0.0159	-0.0243	0.0635	-0.377
30	Middle Femur Left	0.0665	0	0	2.06	0.0036	0.0048	0.0048	0	0	0
31	Middle Femur Right	0.0665	0	0	2.06	0.0036	0.0048	0.0048	0	0	0
32	Knee Left	0.0523	0.0047	-0.0036	1.71	0.01	0.0144	0.0143	0	0	0
33	Knee Right	0.0523	-0.0047	-0.0036	1.71	0.01	0.0144	0.0143	0	0	0
34	Upper Tibia Left	-0.0029	0	-0.0201	1.31	0.01	0.009	0.01	0	0	0
35	Upper Tibia Right	-0.0029	0	-0.0201	1.31	0.01	0.009	0.01	0	0	0
36	Middle Tibia Left	0	-0.0003	-0.11	2.12	0.03	0.0271	0.01	0	0	0
37	Middle Tibia Right	0	-0.0003	-0.11	2.12	0.03	0.0271	0.01	0	0	0
38	Lower Tibia Left	0.0112	0.0003	-0.0347	0.71	0.01	0.006	0.01	0	0	0
39	Lower Tibia Right	0.0112	-0.0003	-0.0347	0.71	0.01	0.006	0.01	0	0	0
40	Foot Left	0.0518	0	-0.0302	1.48	0.002	0.0064	0.0064	0	0	0
41	Foot Right	0.0518	0	-0.0302	1.48	0.002	0.0064	0.0064	0	0	0
42	Upper Ribs	0.16	0	0.0306	1.66	0.0153	0.0063	0.0102	0	0.433016	0
43	Upper Abdomen	-0.0306	0	-0.0103	0.38	0.0009	0.0011	0.0012	0	-0.1192	0
44	Shoe Left	0	0	0	0.643	0.002	0.007	0.007	0	0	0
45	Shoe Right	0	0	0	0.643	0.002	0.007	0.007	0	0	0
46	Mid Sternum	-0.0147	0	0.0149	0.4	0.0004	0.0003	0.0001	0	-0.01571	0
				TOTAL	**80.006**						