THE ELECTRONIC BELT-FIT TEST DEVICE (*e*BTD): Activity update

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ABSTRACT

The single most effective automotive safety component that has been proven to save lives during a crash is a properly fitted seat belt. Transport Canada introduced the concept of assessing seatbelt fit for occupants in the early seventies. A Beltfit Test Device (BTD) was then developed to measure and assess this fit. Research was sponsored by Transport Canada to quantify the proper limits of certain scales on the device that are considered to represent proper beltfit.

To overcome the deviations of hardware tests and to allow evaluations of belt designs early in design phases, the Alliance of Automobile Manufacturers supported the development of a computer modeling and simulation approach, also known as the electronic Belt Fit Test Device (eBTD), through a Technical Working Group (TWG). That group includes representatives from the automobile manufacturers, Transport Canada and the software developer. The development takes place in close co-operation with the Joint Working Group – Abdominal Injury Reduction (JWG-AIR).

The computer model can be used at the design stage to assess the beltfit criteria developed using the BTD. This model can not only be used as a basis for verifying seat beltfit after the vehicle has been built, but can also be used as an effective design tool for restraint systems.

Recently, the development within the TWG has led to the signing of a Belt Fit Memorandum of Understanding (MOU) between Transport Canada and various automobile manufacturers. This MOU represents the first collaborative effort between a government agency, the Alliance of Automobile Manufacturers and a software company, Human Solutions Inc., to develop an application that evaluates a safety concept, based on computer modeling and simulation in place of a physical measuring device. This paper describes this effort and highlights the results.

INTRODUCTION

The effectiveness of seat belts depends partly on the extent to which their geometric design matches the occupant's anatomical characteristics. Transport Canada determined that, in the past, the requirements of the Canadian Motor Vehicle Safety Standards (CMVSS) 208 and 210, which specify the permissible angle of the lap belt and stipulate the location of the upper anchorage of the shoulder belt, do not ensure that the lap and shoulder belts are positioned to provide the most benefit [3,4,5]. Accordingly, a physical Belt Fit Test Device (BTD) was developed by Transport Canada for the measurement and assessment of static seat belt geometry of automobile seat belts [6]. In essence, the BTD comprises an SAE H-Point Machine with the addition of special torso and lap forms that have been designed to represent a fiftieth percentile Canadian adult (both male and female). The surfaces of the lap and torso forms are marked with scales which facilitate the measurement of seat belt position. When installed and belted on an automobile seat, the device enables lap and shoulder belt position to be read from the scales, for comparison to a specific belt-fit criterion.

Transport Canada has established four limiting criteria with respect to the clavicle, sternum and the outboard and inboard lap scales. Transport Canada believes that belts which meet these criteria should restrain the occupant in a crash, while inducing less serious and fewer injuries to soft tissue and organs from belt forces [7&8].

Although the original intention was to introduce new seat belt fit requirements as part of the 1997 CMVSS 208 amendment, the automotive industry requested that further research be conducted before its use was mandated.

A number of concerns relating to the use of the BTD were raised by the automotive industry. These related to the inherent variability and repeatability problems in positioning the physical device into a vehicle and then placing the lap and torso portions of the seat belt over the body shell to measure the scale contact points for the belt routing (as explained in chapter five of this document). The industry pointed out that these factors made the physical BTD device and its application impracticable and insufficiently objective for a CMVSS certification requirement and test procedure. In response to these concerns, Transport Canada, the Canadian Vehicle Manufacturers Association (CVMA) and the Association of International Automobile Manufacturers of Canada (AIAMC) agreed to participate in a joint working group (the JWG-AIR) to resolve these issues.

In response to the variability issues involved with the BTD as a physical measurement device, verification of the proposed BTD procedure using computer simulation was suggested as an alternative**.** Verification by computer simulation could eliminate differences between different test contractors and operators, to the benefit of both Transport Canada and the vehicle manufacturers. Additional benefits for both Transport Canada and vehicle manufacturers from computer modeling include expanded occupant size models and sensitivity analysis as well as reduced test and travel expenses.

To initiate work on a computer based BTD, Transport Canada funded Genicom, Inc. of Montreal to scan the BTD and develop a computer simulation of belt fit on the BTD.

Computer-Based (eBTD) Program Development

The initial program development effort focused on creating a valid digital representation of the physical device. The approach implemented three parallel spline curves drawn “taut” over the lap and torso shell surfaces of a digital representation of a manikin while connected to known belt anchor points. A frictionless surface was assumed so that the computed forces at each anchor point would pull the belt over the manikin.

Initial validation efforts compared software analyses output from specific landmarks to results from installation of the physical BTD in two vehicle seats. These promising results led to a follow-up validation comparing software results to installations in ten vehicles. Of the 40 measurements taken, 30 software simulation results were within 1 cm of actual data points measured with the physical BTD. Further, 36 of the 40 simulation results were in congruence with the physical criteria results of either pass/fail. The four incongruent results were appreciably close between the first electronic BTD and physical BTD.

The model demonstrated correlation between eBTD and the physical BTD, except where seats, buckles, etc. have deflected the belt from the path that the webbing would take from the anchorage to the BTD.

It was concluded that the seat belt algorithm needed to be refined to include more complex seat belt and restraint system designs (retractable belts, different belt hardware components, seat design elements, etc.). Some work was done to enhance the seat belt algorithm [increasing the number of cross-sections representing the torso and lap surfaces, including tensile force calculations at the end of each belt, allowing user input for seat pan angle, seat height, seat width, buckle hardware parameters, Seating Reference Point (SgRP) and H-point locations]. However, attempts to integrate the module completely into manufacturers’ CAD seat belt design software environments were unsuccessful.

Although this initial effort was unsuccessful, the attempt showed promise for the possibility of developing such a software module.

Subsequently, members of the joint working group were asked to identify possible solutions.

In the fall of 1998, Tecmath of North America, Inc. (now Human Solutions of North America, Inc.) was invited to join the modeling efforts.

Work began immediately on an enhanced prototype version of a software module to include the latest CAD data representation of the H-point machine, the lap and torso surfaces, and user-defined inputs for the location of the H-point, heel point, seat back angle, upper outboard, lower inboard and lower outboard anchor points.

Significant program accomplishments

Seat belt width – A new method was proposed and implemented for simulating the true seat belt width. It was agreed that seat belt width was needed only at the points of interest, i.e., where the belt crosses the various scales. Thus, efforts were focused on simulating realistic seat belt width and curvature over the lap and torso forms that is due to anchor point location and anchor design kinematics at the clavicle, sternum and lap surface areas.

Anchor point kinematics – To model anchor point kinematics, joint working group members collectively agreed upon common types of seat belt anchors, buckles and retractors that represented approximately 95% of seat belt designs. These designs were then analyzed to determine the main parameters that could be used to mathematically model their motion behavior.

Digital data for eBTD – Discrepancies between existing and actual CAD data for the BTD were resolved. The original paper drawings for the BTD were obtained and compared to the current digital drawings. Corrections were made to the digital BTD CAD data to make the torso and lap forms symmetrical along a mid-sagittal line, incorporate the accurate H-point foot dimensions, and insert the appropriate modified seat and back pan dimensions into the model. These pans had originally been created when it was discovered that the original H-point pans interfered with seat belt routing over the lap and torso forms.

Further refinements – Other work performed to enhance the eBTD module included: refinement of the user-interface, increasing the software stability, determining proper measurements when the belt does not contact the surface, inboard lower anchor stiffness model, and inclusion of an error estimate.

Refining the user-interface -This entailed creating windows for accepting user input for the location of the eBTD, H-point, seat back angle, seat pan angle and heel point location. Additions were also made to ease data translation from CAD systems into the module via an Initial Graphics Exchange Specification (IGES) data translator.

Removing various self-limit checks from the original seat belt centerline calculation that were not applicable for the eBTD enhanced software stability. Additional stability was obtained after implementing the correct CAD data for the eBTD device and fine-tuning the algorithm used to calculate the spline curves for the centerline routing.

For instances where the simulated belt width did not come into contact with the torso or lap surface, at least at the measurement scales, methods were implemented to project a perpendicular line from the inner/outer detachment point to the scale. Thus, measures could still be obtained despite there being no contact.

BELT FIT METHODOLOGY

The belt routing calculation is based on three main components that represent beltfit simulation; they are anchor kinematics, the representation of the eBTD manikin, and the interaction, i.e. the contact of the belt with these two components. Once the belt routing calculation is determined, the scale values are computed according to the BTD deployment manual [9].

Basic Concept of Simulation

The belt routing simulation is based on several assumptions:

1. The weight of the seat belt and anchorages is negligible compared to the tension forces.
2. The friction between the seat belt and other contact surfaces is negligible.
3. The tension forces in the seat belt are much larger than inertia forces in the anchors.
4. Environmental considerations such as temperature etc, do not affect the outcome.

Hence the seat belt can be appropriately modeled by a massless object, which is not affected by

friction on the shells. The anchors can be modeled by flexible objects, which are driven completely by the belt and are not obstructed by the environment. Earlier versions of the software had taken into account frictional forces, but the results showed that the influence of the friction to the scale readouts is negligible. Therefore no friction is taken into account in the current version.

The essential concept of the belt routing simulation is to consider the seat belt as a wide, thin rubber band, which is fixed at its ends and is stretched across the eBTD surfaces, as shown in Figures 1 & 2. This rubber band is represented by a simple, dynamic, multi-body system consisting of particles connected with linear springs, called the *spring network*. Neglecting gravity, the simulation calculates the mechanical static force of equilibrium of the spring network subjected to certain constraints. The boundary conditions are the attachment of the network to the overall system with special anchors. Contact between the manikin CAD-Model of the BTD (eBTD) and the belt are also considered within the equilibrium conditions. Since the alignment, with respect to position and orientation of the anchors is not known in advance, the computation also provides corresponding anchor alignments.

Components of the Seat Belt Simulation

The entire belt simulation essentially consists of the three components:

- Spring network representing the seat belt
- Kinematic link chains representing the seat belt anchors
- CAD-Model of the BTD manikin
- These components are described in more detail in the subsequent sections.

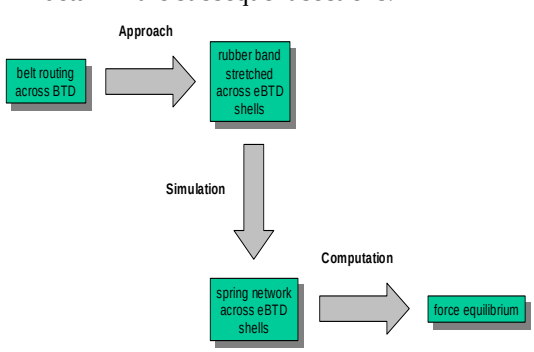

Figure 1: Basic concept of belt simulation

Spring Network – As shown in Figure 2, the seat belt is modeled by a network of massless particles connected by ideal massless linear springs, called the *spring network*. The network is structured as a matrix. The number of particles is calculated so that the longitudinal distance of neighboring particles is set to a default constant value.

An ideal linear spring is characterized by a default length, l_0, and a spring constant, c. For the length, l, of a deflection and the induced spring

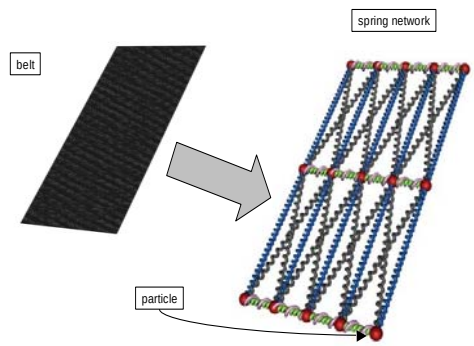

Figure 2: Representation of the seat belt band by a spring network

force, F, is given by

$$F = c(l - l_0) .$$

These springs tend to cause a deflection of a length equal to its default length, l_0. The amplitude of this deflection depends on the spring constant, c.

The particles are connected by four types of linear springs; namely; Longitudinal, Lateral (transversal), Long lateral and Diagonal, as shown in Figure 3.

The stiffness constants for these four types of springs are set so that the final calculated seat belt routing fits to the available experimental seat belt routing data and the computation of the force equilibrium equations for the network is achieved.

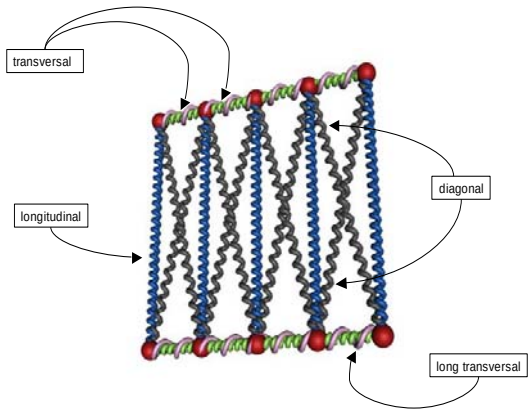

Figure 3: Different springs in the network

Seat Belt Anchors - All seat belt anchor kinematics are represented by kinematic link chains. These link chains are defined by the specification of link lengths and joint properties as degrees of freedom and ranges of motion. These kinematic chains are organized in classes. For each supported anchor class a corresponding link chain is implemented, which can be parameterized by values given by the user.

At the end of each link chain a corresponding seat belt edge is connected to the link chain. The length of this edge is equal to the seat belt width and a border particle row is uniformly fixed to this edge. In particular, particles cannot move across this edge. This means that in the case of the lower inboard anchor, particles do not move from the torso belt to the lap belt and vice versa during the simulation. The same is analogously valid for the upper outboard anchor with respect to the torso and retractor belt. The particles are distributed over the torso, lap and retractor belt in advance, so that approximately the same particle density (particle number per belt length) is achieved in the final belt routing. As an example see Figure 4 for the representation of the upper anchor. While all anchor kinematics can be completely parameterized via the graphical user interface, the lower inboard anchor, defined as anchor class B.2, plays an exceptional role. Unlike any other classes, this anchor possesses a continuous flexible part, which has no direct correspondence in a usual link chain. Hence this part is uniformly discrete and approximated by a fine link chain as shown in Figure 5. Those joints are equipped with one range of motion, whose

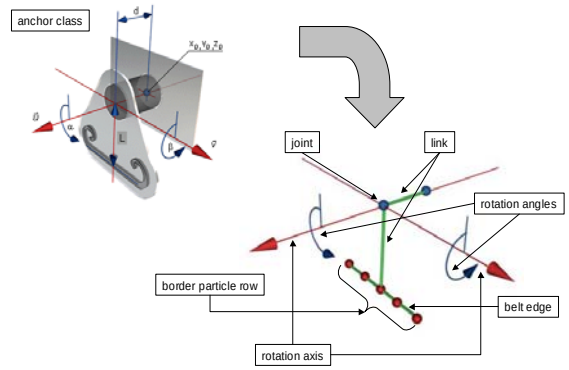

Figure 4: Representation of seat belt anchors

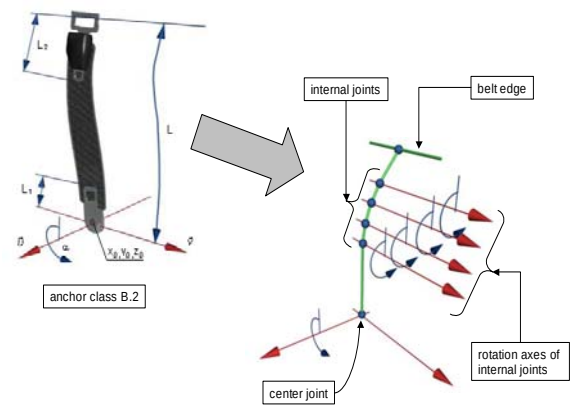

Figure 5: Representation of flexible anchor class parts

amplitude depends on the user specified stiffness parameter. This parameter ranges from soft to stiff to completely cover the full range of anchorage hardware from complete flexible to complete rigid.

CAD Representation of BTD - The CAD-Model of the BTD, was generated in two steps. First CAD surfaces for the torso and lap shell, based on original data from Biokinetics [2], were constructed. In addition, the SAE geometric and kinematic representation of the BTD frame was generated in CAD. As a second step, both surfaces were positioned with respect to the frame. For this procedure several measured fiducial points on the scales of the BTD shell were used to correctly adjust the shells to the frame as shown in Figure 6 & 7.

For the belt routing simulation, the torso and lap shell surfaces are approximated by triangle

surfaces. The density of this triangulation is determined by a compromise between simulation accuracy and computational performance

The above requirements dictate that the triangular surfaces will be an appropriate and smooth representation of the original shell surfaces.

The eBTD is assembled by positioning the overall CAD BTD frame with the shells attached to it. The position of the frame is defined by the following parameters derived from the BTD setup procedure [1]:

1. 3D-Coordinates of BTD H-Point
2. 3D-Coordinates of right BTD Heel Point (y-coordinate automatically adjusted to eBTD dimensions)
3. Inclination of the BTD torso
4. The ankles of the eBTD are rigid.

Computation of Seat Belt Routing - As mentioned above, the final belt routing is simulated as a linear spring network subjected to static equilibrium. Since there is no closed form solution possible for the corresponding equilibrium equations, the solution of those equations has to be calculated numerically using an iterative approach. The nature of the iterative schemes is highly dependent on the initial configuration. Successive iterations of the configurations are calculated until a termination criterion is fulfilled.

Belt Initial Positioning - The method of determining the initial seat belt routing makes use of the position of the eBTD, in particular, of the torso and lap shells, and of the anchor definitions and locations. An initial seat belt routing is then calculated, which is a simple estimation not far from the expected final seat belt routing and runs outside the shell surfaces. Therefore, the initial shape of the seat belt routing is considered as a polygon of three pieces. The middle part of the polygon is determined by certain reference points fixed to the corresponding scales and is connected at its ends to the anchors in their default alignments except for the lower inboard anchor, which is automatically aligned to the middle part of the initial lap belt. The initial retractor belt routing runs linearly from the upper anchor to the car body fixation point. Figure 8 illustrates the initial seat belt routing for the torso and lap belt.

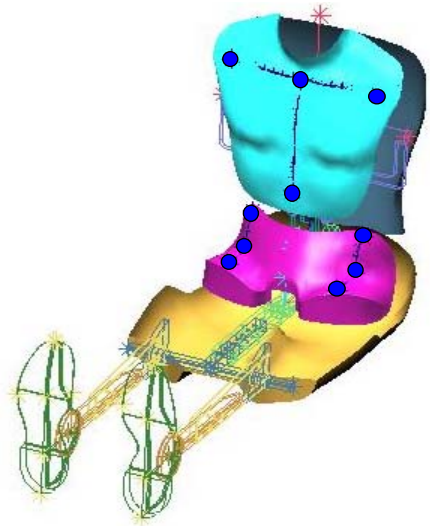

Figure 6: Fiducial points on BTD scales

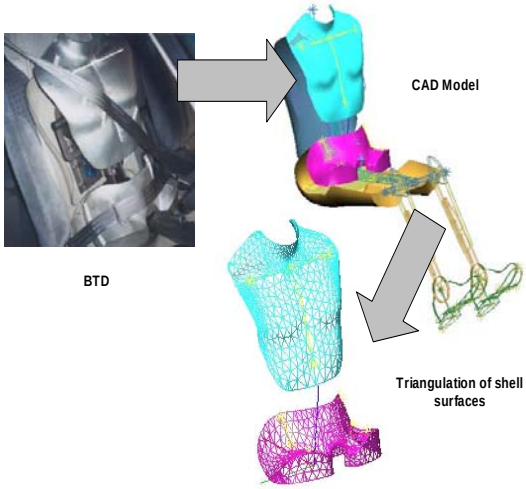

Figure 7: eBTD: CAD representation of BTD

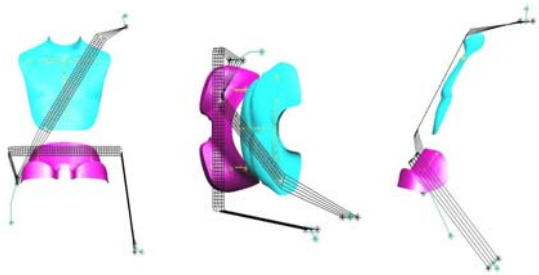

Figure 8: Initial positioning of seat belt.

ITERATIVE APPROACH:

Equilibrium conditions - The calculation of the static mechanical equilibrium of the spring network primarily affects the position of the particles. Since the border particles are fixed to the link chains representing the anchors, the particle positions affect the alignment of the anchors.

Rigid particle equilibrium - In each iteration step, all current forces induced by the springs are calculated, in particular the total resulting force in each particle:

$$F_{result} = F_{longitidual} + F_{lateral} + F_{longlateral} + F_{diagonal}.$$

Depending on the total resulting forces, the particles are moved towards the static equilibrium configuration (Figure 9). This results in new positions where the resulting forces are smaller than in the current positions. There are no moments due to the structure of the spring network and therefore are not considered in the equilibrium equations.

Small resulting forces in all particles indicate that the equilibrium configuration is reached. Hence the termination criteria consist of checking the resulting forces and movement steps of the particles respectively against a given tolerance. The simulation process stops, when a given number of iteration steps is reached or termination criteria are fulfilled.

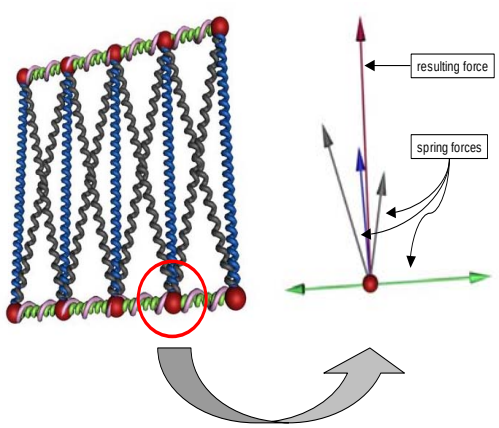

Figure 9: Movement of the belt representing particles

Anchorage simulation - The movement of the particles described above is free and unrestricted in space. But all border particles fixed to the anchors are subjected to the range of motions in conjunction with the link lengths of the kinematic chains modeling these anchors, i.e. they have to be located on the reach envelopes of the link chains. Hence the movement of these particles in space induced by the static mechanical equilibrium has to be transformed into joint rotations. This is done with moments that are induced in each joint by the spring forces in the border particles. Internal inertial forces of the anchors do not affect these moments. The moments are projected to the current rotation axes of the joint and transferred into joint rotation angles (see Figure 10). All rotation angles combined define the new alignment of the anchor, whereby these angles are restricted to the range of motion given by the user.

Small rotation angles in all joints indicate that the equilibrium configuration is reached. Hence the termination criteria consist of checking the rotation angles of the joints against a given tolerance. Moreover, these criteria are combined with the corresponding ones given above.

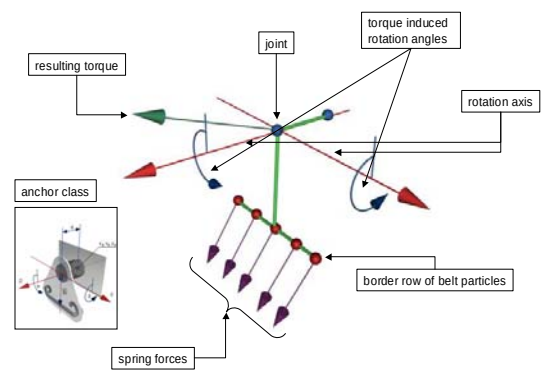

Figure 10: Rotation of anchor

Contact between different components - The movement of the belt is only restricted by the anchors. The torso and lap shells are considered by a separate contact algorithm between the particles and shell the surfaces.

The anchors are assumed not to be obstructed by environmental objects. Hence there is no contact control of the anchors except for the seat belt

edge, which is implicitly checked for all the particles in the vicinity of the edge surface.

Contact check - All particles of the spring network have either the status *free* (positioned free in space) or the status *contact* (positioned on a shell). At the beginning of the calculation all particles of the initial seat belt routing have the status *free*.

The movement for all *free* particles is calculated as explained above. Before the particles are moved to the new positions, the algorithm checks if particles would penetrate triangles of the shells. In that case the corresponding movement is restricted and the particle is placed on the intersection point on the shell and gets the status *contact*.

The movement for all *contact* particles is calculated as described below. Before the particles are moved to the new positions the algorithm checks if particles would leave the triangles of the shells. In that case the particle gets the status *free* again.

Figure 11 illustrates the movement of one particle, which changes from *free* to *contact* and back to *free* movement.

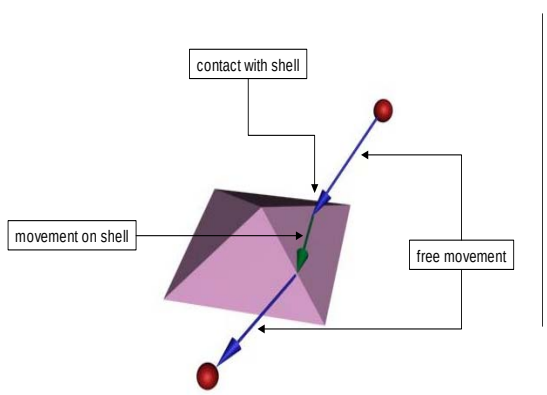

Figure 11: Particle movement relative to shell

Rigid particle Movement - As a particle is located on a shell, in particular on one triangle of the shell, the calculation of the movement is adapted to the new situation. In a first step the movement is determined and in a second step the resulting force is projected onto the triangle where the particle is located, if the force direction is to the inner side of the triangle and the shell respectively. This projected force is assumed to be not affected by friction forces caused by the shells. Depending on this modified force the particle is moved towards the static mechanical equilibrium configuration. During a single iteration step a particle on a triangle moves at most to the border of the triangle, while longer steps are cut at the border. A simple example of a movement on a triangle is shown in Figure 12.

Determination of Scale Values - The scale values of the final belt routing are determined according to the BTD manual [8]. First all elements, comprising the eBTD with scales and the belt routing, is projected onto an xz-plane. Second, the relevant belt edges are intersected with the corresponding scales (torso belt: lower edge, lap belt: upper edge). Third, the scale readouts are determined (Figure 13). Moreover, the algorithm checks whether at least one edge of the seat belt band touches the scale of the scale readout. Using this information together with the pass/fail criteria, the algorithm provides the values of the scale readouts and indicates by green/red colors whether the pass/fail criteria are fulfilled. If no seat belt edge touches the scale, the corresponding scale readout is automatically marked by *fail* and no value is displayed.

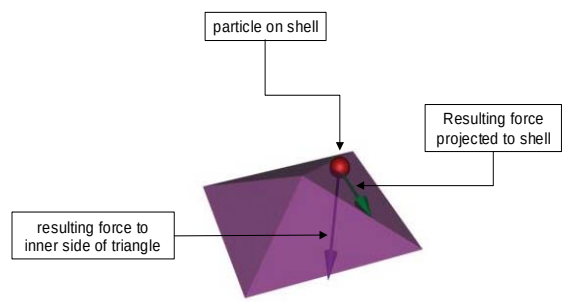

Figure 12: Projected force on shell

***e*BTD EVALUATION –** The issue of variability of physical measurement is commonly known in all engineering endeavors that involves modeling and simulation of a physical quantity. The eBTD model is no exception. Verification and Validation (V&V) of such model has been an essential development objective of the software. A software developer performs software V&V to ensure code correctness, reliability and robustness.

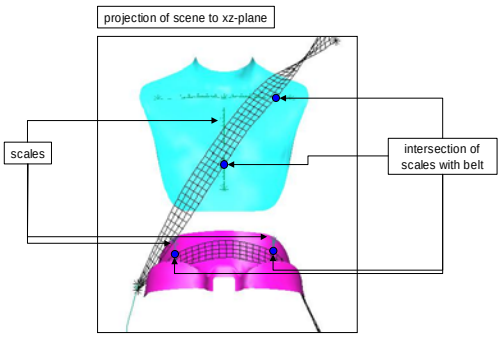

Figure 13: Determination of scale values

The objective of the eBTD model V&V is to ensure that the end product is a predictive model based on fundamental physics of the problem being solved.

eBTD VERIFICATION AND VALIDATION PROCESS

Since the eBTD is intended to be used as a simulation tool in the design process as well as a virtual certification tool, a V&V process is required to quantify the level of confidence in the predictions made with the models built using this software. The expected outcome of the V&V process is the ability to quantify the level of agreement between experimental and predicted results, as well as quantify the accuracy of the numerical models when used in a predictive mode.

The Verification and Validation definitions used in this report are adopted from [11] as follows:

- ***Verification*** is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution approach.
- ***Validation*** is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

Verification and Validation are processes that collect evidence of a models correctness or accuracy for a specific set of parameters; thus, V&V cannot prove that a model is correct and accurate for all possible conditions and applications, but rather provide evidence that a model is sufficiently accurate. Therefore, V&V are ongoing activities that end when the desired sufficiency is reached.

Verification is concerned with identifying and removing errors in the model by comparing numerical solutions to analytical or highly accurate benchmark solutions.

Validation, on the other hand, is concerned with quantifying the accuracy of the model by comparing numerical solutions to experimental data.

Because modeling and/or mathematical errors can cancel, giving the impression of correctness (right answer for the wrong reason), verification must be performed before the validation activity begins.

Following the above logic, the software developer (Human Solutions Inc.) followed a mathematical based ***verification*** approach, to assure that the mathematical model perform as formulated. Therefore, it thought a **D**esign **O**f **E**xperiment (DOE) approach to take into account the effect of the greatest number of variables that affect the results. This approach enables the analysis to be carried out of the effects of different errors on the computations and as such, seeks to address as many sources of variability as possible. Since the determination of the error bounds is a mathematical objective of the eBTD model development, it was logical to rely on a DOE approach to assess these errors. Accordingly variability had to be dealt with as an outcome of the DOE approach. Human Solution's evaluation approach was designed such that the necessary input parameters were measured or deduced out of measurements in real vehicles. The idea behind this approach is to eliminate the manufacturing tolerances and to consider the real position of the eBTD in the vehicle of interest, i.e. the scenario is reconstructed in the simulation software exactly as it can be observed in reality. The resulting calculated scale values were compared with values taken from experiments with real vehicles of the corresponding make and model. From the available 34 data sets, 15 vehicles were considered for comparison. The mean differences for the individual belt fit scales using data corrected to match the position of the eBTD were in the range of -0.2 cm and -0.7 cm with corresponding standard deviations of 0.8 cm and 2.5 cm. With corrections to the anchorages, then the mean differences range from 0.1 cm and -0.3 cm with corresponding standard deviations of

0.3 cm depending on the specific interpretation of the tests [13].

The above verification effort was followed by a number of physical tests by Biokinetics [12] with the objective of ***validating*** the physical phenomenon. In these tests, it was necessary to follow an approach that seeks to reduce, and perhaps eliminate the sources of variability and errors. Biokinetics used design data as input parameters to run the belt routing simulations. Design data in this context corresponds to parameters that are measured or derived from CAD drawings. Vehicle manufacturers for the vehicles tested provided these data. The resulting calculated belt score values were then compared with values measured in experiments with real cars of the same make and model. The deviations between the measured and the calculated scales were in the range of -7.0 cm and 3.0 cm. While the discrepancies are large, a statistical test that compares the average deviation between measured and calculated scale values could not be conducted since the evaluation was based on four vehicles only.

These promising results led to a follow-up validation comparing software results to the physical BTD installations in vehicles. Thirteen passenger vehicles participated in a workshop to evaluate the use of the eBTD simulation module as an alternative to the physical measurement device. Simulations were completed for only 9 vehicles, due to lack of design data.

Differences were calculated between the score predicted by the eBTD (Design based) simulation and the score measured with the physical device. The absolute values of these differences are presented in Table 2. Each scale and vehicle is listed and for those vehicles for which the simulation was not completed, an n/a is recorded.

The average variation for each scale is computed and presented in **Table** 2. Previous work found that the expected maximum standard deviation from physical measurements is 0.6 cm (Anctil, 2001). This deviation is based on data from both lap and torso forms, several seat locations, a total of 10 samples per seat and a test matrix of vehicles.

Correlation Coefficients

Correlation coefficients were used to determine the relationship between two different sets of eBTD scores. The range of a correlation coefficient is 0 to 1, where 1 represents an exact correlation. The correlation coefficient is computed using the following equation:

$$\rho_{x,y} = \frac{Cov(X,Y)}{\sigma_x \sigma_y} \quad -1 \le \rho_{xy} \le 1$$

$$\text{And:} \quad Cov(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)$$

Where **:** σ = standard deviation

and μ = mean.

The correlation coefficients were computed to compare the BTD scores resulting from the physical measurements and several eBTD simulations. The results, presented in Table 3, include only the nine vehicles for which the simulations were successfully completed.

An additional scenario is included in which the effect of the B2 anchorage stiffness parameter is investigated.

Table 2 - Variation of eBTD and BTD Scores

Vehicle No.	**Outboard (cm)**	**Lap, Inboard (cm)**	**Sternum (cm)**	**Clavicle (cm)**
1	0.4	1.3	0.5	0.2
2	0.0	0.3	0.1	0.4
3	0.5	0.5	0.2	1.3
4	0.3	0.1	3.0	0.7
5	n/a	n/a	n/a	n/a
6	n/a	n/a	n/a	n/a
7	0.1	0.4	0.1	1.2
8	0.4	2.7	1.7	0.4
9	0.1	0.8	1.3	0.2
10	n/a	n/a	n/a	n/a
11	0.9	0.3	0.3	0.6
12	0.2	0.3	0.4	0.9
13	n/a	n/a	n/a	n/a
Average:	**0.3**	**0.7**	**0.8**	**0.7**

In this scenario, the design simulation was repeated using the measured stiffness for the four vehicles in which the design stiffness was considerably different from the measured stiffness.

The results show that the lap inboard score has a lower correlation in all scenarios. This score can be greatly affected by the anchorage stiffness. The means by which the stiffness parameter is measured or defined can highly affect the results. It is shown that the correlation improves between the design simulation and the measured scores when the measured stiffness parameter is used (scenario 4).

Another reason that the lap inboard score is not expected to correlate well between simulations and physical measurements has to do with the thickness of the buckle.

Table 3 - Correlation Coefficients for BTD Scores

		Lap Outboard	Lap Inboard	Sternum	Clavicle
1.	Design Simulation vs. Physical BTD	0.78	0.39	0.81	0.87
2.	Measured Simulation vs. Physical BTD	0.83	0.48	0.92	0.91
3.	Design vs. Measured Simulations	0.62	0.20	0.88	0.91
4.	**Design (modified) vs. Physical BTD**	**0.84**	**0.53**	**0.86**	**0.79**

Currently, the simulation does not take the thickness into account and, if the buckle is resting against the seat or the physical BTD, the detachment points of the belt with the buckle can differ between the simulation and the physical device

Pass/Fail Prediction

Perhaps more important than the score itself, is whether or not the simulations can predict the pass/fail outcome of the seatbelt fit based only on the design data. Considering the 9 vehicles for which both the BTD and eBTD scores are available, the eBTD predicted the same pass/fail outcome for the lap outboard in all cases. For the lap inboard, sternum and clavicle scores, the eBTD predicted 8 out of 9 pass/fail outcomes for each category correctly. Overall, that is 33 out of 36 (or 92%) correctly predicted outcomes.

It is known that the specified design stiffness for 4 vehicles is incorrect and considerably different from the measured stiffness. For vehicle 8, this difference is sufficient to change the pass/fail outcome. When these simulations are repeated using the design data for the geometry and the measured data for the stiffness, the eBTD predictions for vehicle 8 are the same as predicted by the physical BTD. This raises the eBTD prediction success rate from 92% to **over 97%.**

It should be noted however, that almost all of the scores recorded during this workshop were passing scores. To better evaluate the prediction success of the eBTD module, it would be desirable to have a larger representation from vehicles that would provide a failing BTD score.

Of the 40 measurements taken, 30 software simulation results were within 1 cm of actual data points. Furthermore, 36 of the 40 simulation results were in congruence with the physical criteria results of either pass/fail. The four incongruent results were appreciably close between the first electronic BTD and physical BTD. The eBTD simulations were able to predict the correct pass/fail result for 92% of the reported scores and the average difference between the scores ranged from 0.3 to 0.8 cm for the different scales.

The validation results demonstrated correlation between eBTD and the physical BTD, except where seats, buckles, etc. have deflected the belt from the path that the webbing would take from the anchorage to the BTD.

ENHANCEMENT OF SIMULATION – To enhance the current simulation further developments are underway. For example, an extension of the anchor kinematics library will enlarge the use of the simulation software by enabling the coverage of a higher number of scenarios. Here two principal approaches are conceivable: To incorporate the kinematic properties of existing anchors or to provide a

parametric approach that enables the user to define own anchorages.

In an early design phase the principal package of the occupant compartment is known but often not necessarily the details of the interior design that could possibly influence the belt routing significantly. Examples are the contours of the seat pan and the back rest in case a contact between the belt and the upholstery occurs. Consequently a generic seat with morphing functionalities to adapt to the seat is of great potential.

TRANSFER OF TECHNOLOGY ONTO HUMAN MODELS – Since the BTD represents one anthropometric type in one position benefits may result from transferring the described technology to human models representing occupants of different size and gender. Thus whole populations represented through manikins with different anthropometric properties in many postures can be analyzed. The belt routing can be assessed in a general sense, i.e. whether the belt lies too close to the neck or too close to the shoulder or even on the upper arm (Figure 14). Additional checks can be performed in the case where the human model represents a bony structure, i.e. the basis for the original BTD criteria, or where the belt stretches over the bony structures of the torso (Figure 15).

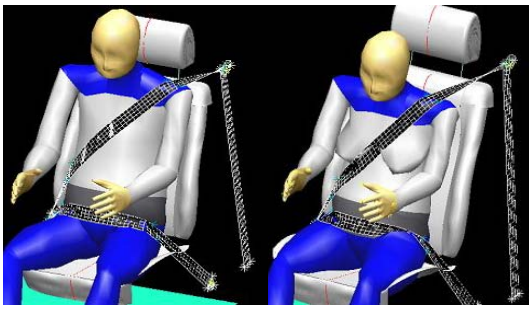

Figure 14: Belt routing for different RAMSIS

USAGE IN RELATED AREAS – There are many fields of application in which a realistic 3-dimensional model can be used. Besides testing an existing belt restraint package with given seat travel path and given anchor kinematics and applicable adjustments, the belt routing module can be used to find optimal locations, types, and adjustments of anchors.

Figure 15: Belt routing and bony structure of RAMSIS

Secondly, it is conceivable to use the simulation results to provide a first estimate of the perceived comfort. Here, contact surface detachment points from the torso, and angles in which the belt leaves the human body could be used as input parameters for future simulation models.

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