Technical Paper

Applications of Occupant Safety Simulation using MADYMO

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In recent years, simulation based on the combination of vehicle and human body CAE models has become possible to predict and assess occupant behavior and injury in vehicle collision or rollover. Human body CAE modeling can roughly divided into two types: one using multi-body techniques and the other using finite element techniques. The multi-body modeling offers simple, easy analysis and is thus more practical as dimensions, posture and dynamic properties can be changed relatively easily and calculation takes less time. This paper attempts to briefly present techniques to simulate dynamic seatbelt and vehicle rollover tests on a computer using MADYMO, the occupant safety simulation software that is mainly based on multi-body techniques.

1. Introduction

In machine structure design, development time reduction and quality improvement can be expected through the use of computer-aided engineering (CAE) techniques in the design phase, such as stress analysis (Finite Element Analysis: FEA), fluid analysis (Computational Fluid Dynamics: CFD) and mechanism/motion analysis (Multi Body Dynamics: MBD). Some types of machine structures, including construction machinery and vehicles, require human operators who ride on and drive them. These types of machine structures, on the other hand, have the danger to collide or roll over depending on driving and other working conditions. While machine design has seen improvement in durability, noise reduction and other areas thanks to CAE and other techniques, occupant safety has not been a major target for computer simulation. This appears to be due to human body, a biological structure, being perceived as something alien to the existing CAE modeling (discretization into elements etc.). Despite such a perception, thanks to the rapid advance in computer technology of today and the development of human body modeling techniques, CAE models that faithfully represent human body movement have been released for practical applications mainly in the automotive industry (See **Fig. 1.1**). With these practical human models, it is now possible to predict and assess, for example, the severity of damage to various parts of human body in a collision and to plan and implement a range of countermeasures prior to collision testing. Compared with the simple assessment based on the amount of structural deformation or acceleration, human body modeling enables more realistic judgment, and improves the efficiency in occupant safety assessment.

This paper describes the technical aspects and some examples of the occupant safety simulation which uses the globally renowned occupant safety simulation software MADYMO.
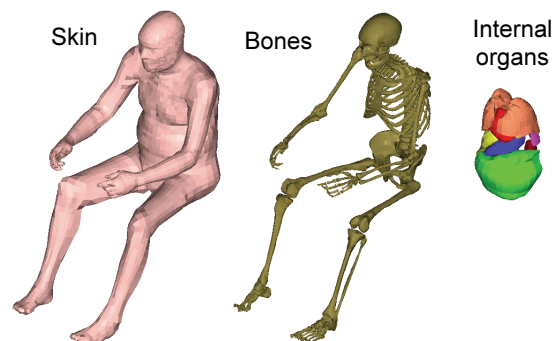

Fig. 1.1 Example of Human Body CAE Model (MADYMO Finite Element Model)

2. MADYMO Occupant Safety Simulation Software

The MADYMO (MAthematical DYnamic MOdel) occupant safety simulation software was developed by TNO Automotive Safety Solutions (TASS) BV of the Netherlands and consists of the solver, a database of crash dummy and human body models, the pre- and post-processors and other components.

2.1 Solver

Three-dimensional models used for occupant safety simulation can be roughly divided into multi-body models and finite element models. Multi-body models are capable of efficiently simulating three-dimensional motion of a dynamic system consisting of complicated kinematic interconnected bodies. Finite element models are capable of simulating not only three-dimensional motion of finite elements but also local structural deformation and stress distribution in finite elements. Compared with multi-body models, finite element models often take longer to be created and require far more time for calculation to execute simulation. The MADYMO solver is compatible with both multi-body and finite element models. In initial design, multi-body models' feature of requiring less time for calculation can be exploited for optimization study including many design parameters. In addition, the MADYMO solver supports the coupling function with other finite element programs (LS-DYNA, Pam-Crash, Radioss, ABAQUS) for simulation. This feature can be utilized in detailed design for close examination with respect to vehicle deformation.

2.2 Database of crash dummy and human body models

Among human body CAE models, some are numerical models of crash dummies, such as the Hybrid III and EuroSID, used in automotive collision testing while others are numerical models based on the actual human body structure. On crash dummy CAE models, the dummy's response characteristics are reproduced by entering relevant data such as the dummy's dimensions, mass, moment of inertia, movable joint angles and surface contact load characteristics.

MADYMO is supported by a various database of multi-body crash dummy CAE models. There are two types of the multi-body crash dummy model: the ellipsoid and facet models (**Fig. 2.2.1**). These models are verified for correct representation of crash dummies, in simulation (impact and sled testing) of calibration and other testing conducted on crash dummies.
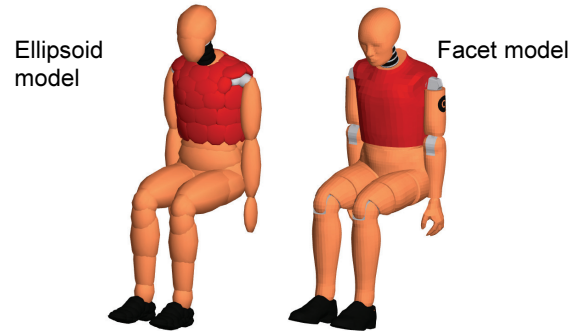

Fig. 2.2.1   Example of the Crash Dummy CAE Models in the Database

A crash dummy consists of mechanical elements, which limits the possibility of accurately analyzing human body behavior and injury in a collision. On the other hand, it is possible on computers to recreate with fewer constraints the dynamic properties, structures and functions of the actual human body, which makes it possible to study things, not possible with crash dummies, such as human response characteristics and injury mechanism.

MADYMO is also supported by a various database of multi-body human body CAE models (of occupants and pedestrians). As they are multi-body models, it is relatively easy to change dimensions, posture and dynamic properties (**Fig. 2.2.2**).

These models are verified in simulation performance by the impact test with examinees and the reproduction simulation of the sled testing.
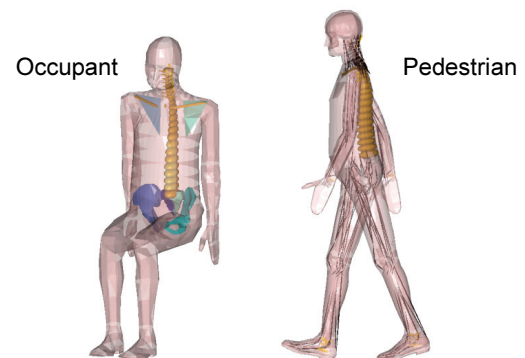

Fig. 2.2.2   Example of the Human Body CAE Models in the Database

2.3 Pre- and post-processors

MADYMO is equipped with two dedicated processors: the pre-processor XMADgic and the post-processor MADPost. XMADgic has a belt fitting tool to facilitate settings for occupant safety simulation. This tool can be used to create a seat belt model by entering the width, both endpoints, contact area, route and other data of the webbing and to easily

position the belt relative to the position and posture of the crash dummy and other elements.
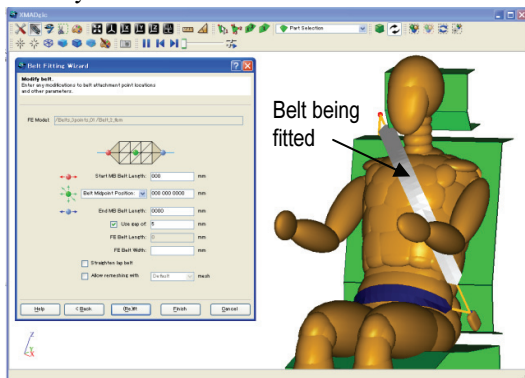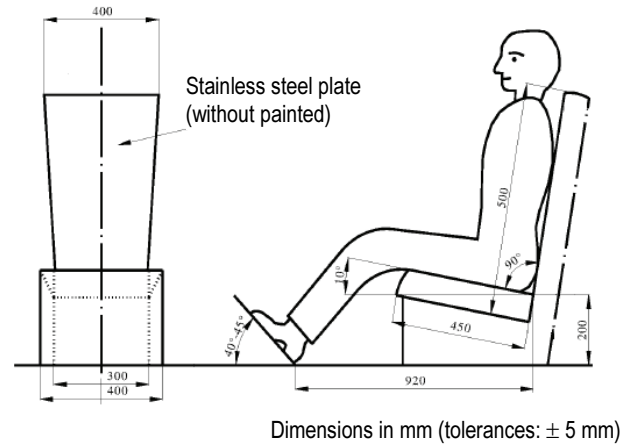

Fig. 2.2.3 Belt Fitting Screen

Dimensions in mm (tolerances: ± 5 mm)

Fig. 3.2.1 Seat Dimensions

3. Application 1: Simulation of Dynamic Testing on Seatbelt

3.1 Purpose

The Japanese safety regulations for road transport vehicles stipulate that a seatbelt assembly going through dynamic testing shall be a belt assembly that has not been subjected to any load and that each component shall have passed relevant testing such as corrosion testing for the belt, dust resistance testing for the retractor and 500 opening-closing cycles for the buckle. If a seatbelt assembly fails dynamic testing, the applicant must start again by going back to the component tests.

The authors performed a simulation to predict the forward displacement of a dummy (one of the dynamic test items). This simulation could minimize the possibility of retest.

3.2 Outline of the dynamic test

The dynamic test is outlined in this item.

A belt assembly that has been successfully pretested is mounted on a trolley equipped with a seat, shown in **Fig. 3.2.1**, at the same location as that on the actual vehicle. Then, the dummy is seated and the belt is attached to the dummy.

The trolley is propelled that at the moment of impact its free running speed is 50 ± 1 km/h. The stopping distance of the trolley is 40 ± 5 cm. Deceleration at that time must be within the range shown in **Fig. 3.2.2**.

The trolley speed immediately before the collision, the trolley deceleration and the forward displacement of the dummy are measured.

To meet the standard for the belt assembly, which in this particular test is a lap belt, the forward displacement of the dummy must be between 80 and 200 mm at the pelvic level.
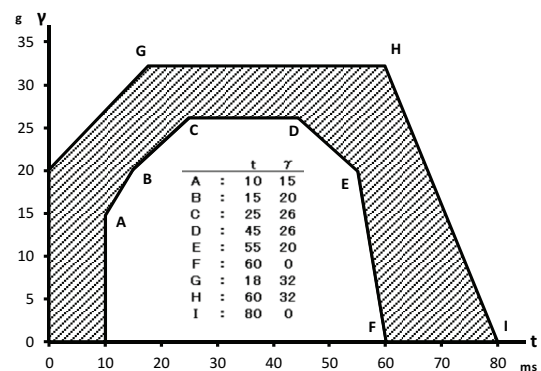

Fig. 3.2.2 Deceleration Range

3.3 Dummy CAE model

UNECE Regulation No. 16 stipulates the use of a dummy called "TNO-10" as a dynamic seatbelt loading device. This dummy represents a male adult (175 cm in height and 76 kg in weight), consisting of the head, the neck, the torso (which includes the arms), the tights and one lower leg. The head and neck, the torso and upper legs, and the thighs and lower leg are connected by spherical and revolute joints. For reasons of simplicity, the dummy has only one lower leg and the arms are skipped (included in the torso).

The MADYMO crash dummy database includes the CAE model (d_tno10fc_inc.xml) of this dummy. This model, which has been verified in simulation, is used in the test. **Fig. 3.3.1** shows the CAE model of TNO-10.
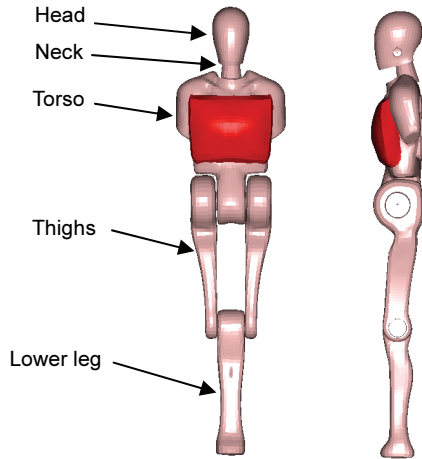
Fig. 3.3.1 CAE Model of TNO-10

3.4 Simulation model

In the simulation model, instead of subjecting the trolley to propulsion, rapid deceleration and stop, acceleration and deceleration fields were applied to the dummy, belt assembly and other elements while the seat and anchorage were fixed for the sake of simplicity. Therefore, the simulation model only covered the seat, floor, belt assembly, anchorage and dummy. The seat, shown in **Fig. 3.2.1**, was a rigid, finite element model. **Fig. 3.4.1** shows the simulation model. For those parts that might contact each other, the following items were prepared: contact detection procedure, contact load calculation procedure, loading characteristics and the coefficient of friction. In this particular test, contact detection procedures were established between the seat and dummy, the floor and dummy, and the belt assembly and dummy.
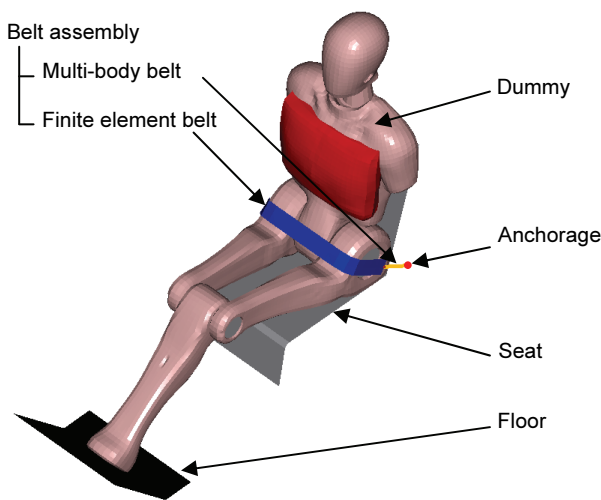

Fig. 3.4.1 Simulation Model

This particular belt assembly was a lap belt equipped with an emergency locking retractor. The buckle that connected the left and right belt halves was skipped for simplification. The belt webbing was modeled as a finite element in the area that came in contact with the dummy and as a multi-body at both endpoints for simplification.

In MADYMO, this type of belt is called a "hybrid belt." The relationship between the load and elongation measured on the webbing alone was entered as table data for each finite element belt and multi-body belt (**Fig. 3.4.2**).

An emergency locking retractor is installed on the right end of the belt while the left end of the belt is equipped with mounting bracket. The emergency locking retractor locks when belt feed acceleration exceeds a predetermined level. Retracting characteristics (load-elongation relationship) beyond this threshold have been entered as table data, as with the belt webbing.
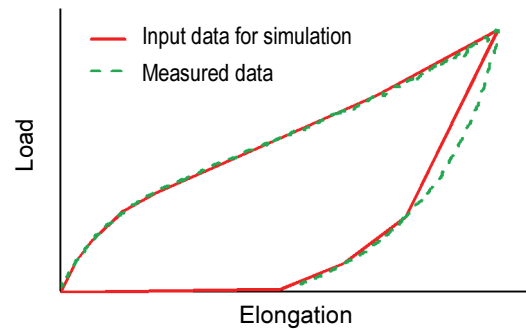

Fig. 3.4.2 Load - Elongation Relationship of Belt Webbing

3.5 Simulation results

Simulation was conducted with input of acceleration waveforms measured during a separate test on the real machine. The results of the simulation are shown in **Fig. 3.5.1** together with the results of the real machine test. **Fig. 3.5.2** shows the moment at which the maximum forward displacement was measured in animation. Good reproducibility was confirmed in both forward displacement of the dummy and belt tension. To simulate the duration of 80 msec, it took about two minutes to calculate using a general-purpose personal computer, which is considered fairly practical in terms of application.
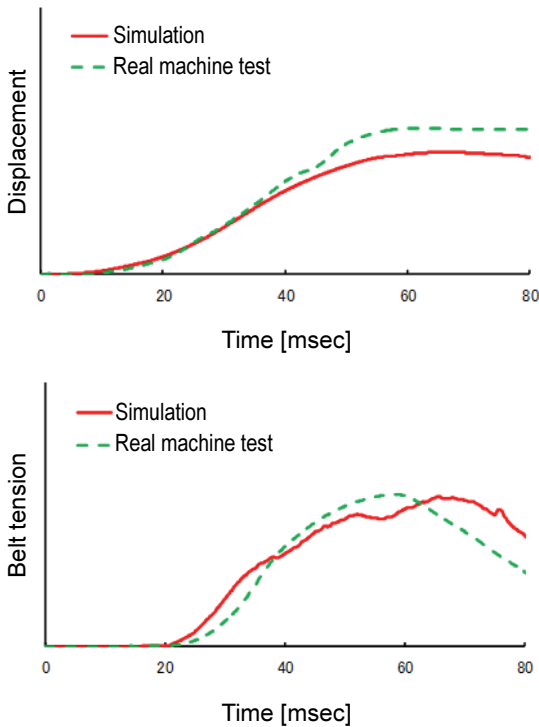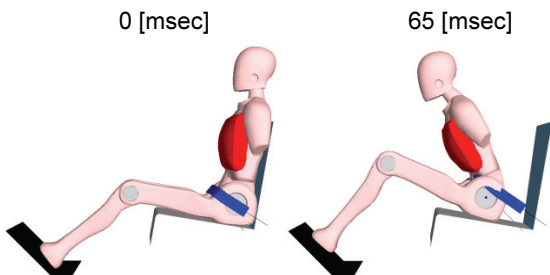
Fig. 3.5.1 Simulation Results

0 [msec]　　　　65 [msec]

Fig. 3.5.2 Animation

4. Application 2: Simulation of Occupant Behavior in Rollover

4.1 Purpose

Occupant behavior in vehicle rollover was simulated to study the occupant injury mitigation devices such as seatbelts. The test methods and occupant injury criteria used in the simulation were established with reference to the rollover tests using vehicles (FMVSS 208) of the National Highway Traffic Safety Administration (NHTSA) of the US.

4.2 Outline of the real test

In this test, a Hybrid III 50th male crash dummy is restrained with a seatbelt on a seat of a test vehicle and the vehicle is then placed on a trolley sloping at 23 degrees in a direction 90 degrees from the direction of travel. This trolley

is then moved laterally at 30 mph (48 km/h) and suddenly stopped (min. 20 g, within min. 0.04 sec). This should cause the vehicle to be thrown onto the ground and roll over about the roll axis. **Fig. 4.2.1** shows the schematic of the test.
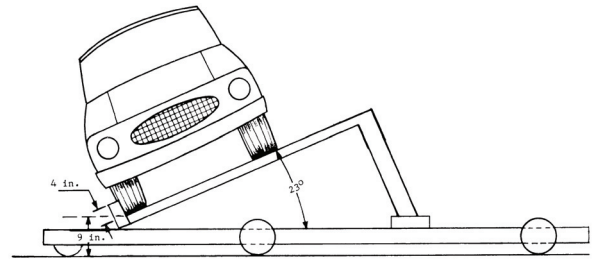

Fig. 4.2.1 Test Schematic

4.3 Simulation procedure

A vehicle CAE model was produced for a finite element program to calculate vehicle behavior in rollover. Then, creating the occupant and seatbelt CAE models by MADYMO, occupant behavior and injury were calculated.

MADYMO offers two techniques for this type of simulation: coupling method and Prescribed Structural Motion (hereafter "PSM") method. In coupling method, the finite element program and MADYMO both calculate at the same time: at set intervals MADYMO receives input from the finite element program of the locations of possible contact, calculates the contact reaction force of the occupant model and the contact area, and sends the calculations back to the finite element program. This method, in which vehicle motion and deformation analysis is made with input of an occupant model, is more accurate method, although the calculation often takes a significant amount of time.

In PSM method, the finite element program is executed without an occupant in the seat to calculate the locations of finite elements in time series. The time-series data is then entered into MADYMO, which then calculates the occupant model. This method, while less accurate than coupling, offers quicker calculation, having the merit of being able to perform a large number of simulation including a various parameters.

In our simulation, PSM method was used as the impact of occupant on vehicle motion and deformation simulation was considered insignificant. For the vehicle motion and deformation simulation, the non-linear dynamic structural calculation program LS-DYNA was used.

4.4 Vehicle motion simulation model and results

The vehicle motion simulation model covered the trolley on which the vehicle was placed, the ground and the vehicle. The locations of vehicle components were entered, including the body panels and tires that would come into contact with the

ground and trolley, the seat, steering wheel, interior panels etc. that would come into contact with the occupant. The trolley, shown in **Fig. 4.2.1**, was modeled using rigid finite elements and its travel and sudden stop were entered as time-series motion data. At the start of simulation, the vehicle was given the same initial velocity as that given to the trolley. As the trolley was suddenly stopped, the vehicle was thrown onto the ground and rolled over about its roll axis. The following items, therefore, were prepared between the ground and the body panels and tires, and between the tires and the trolley for contact detection procedure, contact load calculation procedure, and loading characteristics. **Fig. 4.4.1** shows the vehicle motion simulation model. **Fig. 4.4.2** shows the simulated animation.
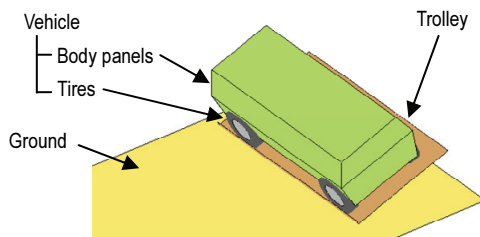

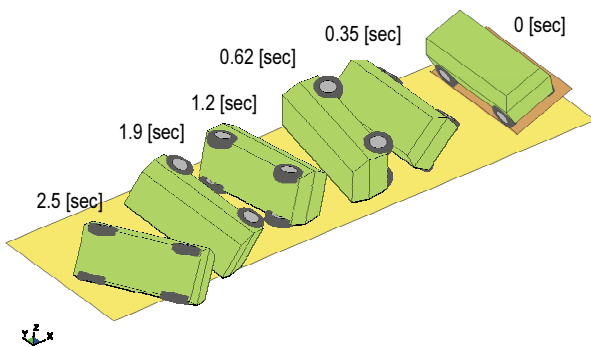**Fig. 4.4.1**   Vehicle Motion Simulation Model

Fig. 4.4.2   Simulated Animation

4.5   Occupant behavior simulation model and results

The occupant behavior simulation model covered the driver and the assistant driver, both Hybrid III 50th male crash dummies, the seatbelts, the seats, the steering wheel, the interior panels and other interior components and the body panels. Time-series displacement data of the vehicle exterior and interior components was created by importing d3plot output from LS-DYNA using MADYMO-dedicated post processor MADPost.

The Hybrid III 50th male crash dummies, both an ellipsoid model (d_hyb350el_Q_inc.xml), were seated properly. Contact detection procedure, contact loading characteristics, etc. were prepared between the dummies and the vehicle exterior and interior components.

The seatbelts were modeled as hybrid belts as in 3. Application 1. In our simulation, two types of belt, (a) lap belt and (b) 3-point belt, were used for comparison in occupant behavior and the severity of injury. **Fig. 4.5.1** shows the differences between the two belt types in the severity of injury to the driver. **Fig. 4.5.2** shows simulated animation in the occupant behavior simulation model.
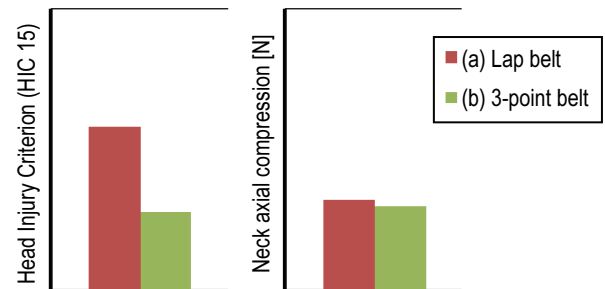

Fig. 4.5.1   Comparison in Severity of Injury to the Driver

4.6   Consideration

The lap belt (a) had a higher severity of injury than the 3-point belt (b). This was considered to be due to the lap belt, lacking the shoulder belt which the 3-point belt has, could not suppress the movement of the upper body of the crash dummy. As a result, the head can hit the side of the vehicle at a faster velocity, causing severer injury.

NOTE: Head Injury Criterion (HIC 15) is a value calculated based on resultant acceleration of the crash dummy head. Neck axial compression is the maximum load applied in the axial direction of the crash dummy neck.
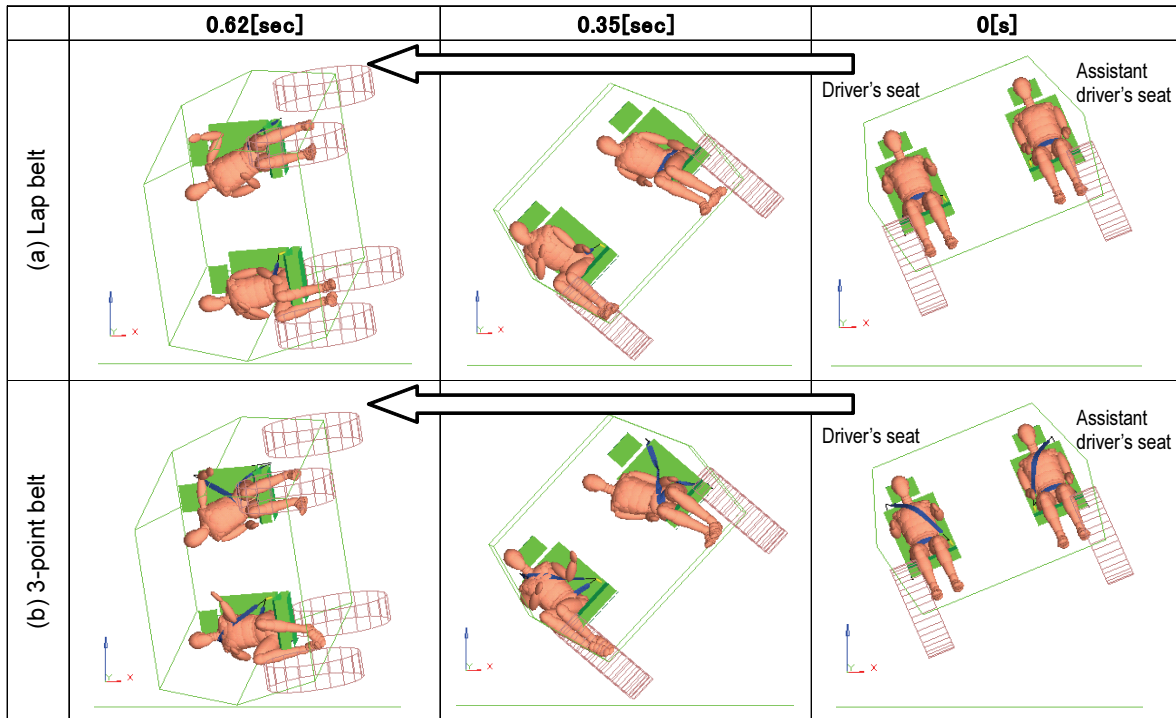
	0.62[sec]	0.35[sec]	0[s]
(a) Lap belt			Driver's seat / Assistant driver's seat
(b) 3-point belt			Driver's seat / Assistant driver's seat

Fig. 4.5.2 Occupant Behavior Simulation Model and Simulated Animation

5. Future Plans

The importance of occupant safety will continue to grow in human-friendly design of machines. We will try to widen the scope of applications while at the same time upgrading the quality of our modeling techniques such as in simulation accuracy and reproducibility.

6. Acknowledgements

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Introduction of the writers

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[A few words from writers]

The simulations based on human body models have been commonly conducted for safety reasons in the automotive industry, but it's new to Komatsu. The overseas dispatching can take the credit for being an effective catalyst for the introduction of the latest simulation techniques to Komatsu in such a short period of time. For Ueda, the life overseas in a different culture proved to be highly productive both in public and private. Hopefully, similar opportunities of research will increase as globalization advances.