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Final Report

Roadside Barrier Design and Vehicle Occupant Safety
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Abstract

This project utilised three-dimensional computer simulation software (MADYMO, TNO, Netherlands) to investigate the effect of roadside crash barrier design on vehicle dynamics and risk of occupant injury. Rigid body models consisting of a vehicle (Ford Taurus) and a longitudinal roadside barrier (concrete barrier) were developed and used to simulate collisions at a range of impact angles. Acceleration data for the impact model was then used in a simulated sled test scenario. A 50%, male Hybrid III dummy was used to evaluate injury parameters. A comparison was made between traditional occupant injury criteria (HIC, $a_p$max, chest acceleration, etc) and criteria derived to assess occupant injury in the evaluation of roadside barriers (THIV, PHD, ridedown acceleration, ASI, etc). Limitations in the finite element analysis capabilities of MADYMO meant that a workable representation of the interaction between the test vehicle and a barrier could not be realised, and hence only rigid body models could be analysed. MADYMO proved to be very useful for the evaluation of occupant motion and enabled the majority of the injury criteria to be calculated directly. Future work on this topic should focus on the use of alternate modelling programs (e.g. LS-DYNA) for evaluating new designs of hardware. An important element of such work is the ability to undertake full-scale testing to confirm any results from the computer simulations.

Keywords

ROADSIDE BARRIERS, OCCUPANT RISK, COMPUTER SIMULATION, VEHICLE DYNAMICS

ACKNOWLEDGEMENTS

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1 EXECUTIVE SUMMARY

This project was funded by the Australian Transport Safety Bureau Road Safety Research Grant T2000/0736. The project investigated the use of three-dimensional computer simulation techniques in assessing the design of roadside safety barriers and the potential effect on vehicle occupant injury.

The original objectives of the project were:

- Develop in-depth knowledge and application of MADYMO for modelling and analysis of automotive vehicle design;

- Apply MADYMO to the modelling of roadside barriers;

- Establish specific relationships between roadside crash barrier design and vehicle occupant injury criteria;

- Establish a test standard for exploring new designs and predicting their performance prior to physical testing;

- Extend the capabilities for road safety research in Australia, and specifically the role of computer software simulation and analysis.

The starting point for this project involved a review of existing literature. This involved examining literature describing:

- the standards for the construction, testing and assessment of roadside barriers;

- definitions of criteria for the assessment of vehicle occupant risk;

- techniques for computer modelling of vehicles interacting with barriers and the resulting motion of occupants in the vehicle.

MADYMO 5.4 software (TNO, The Netherlands) was selected for the computation of the simulations undertaken. This choice was based on a number of factors, including: our previous experience in performing biomechanical modelling of human activity with MADYMO; the capability of calculating both rigid body motion and finite element analysis (FEA) of components; and the comprehensive anthropomorphic dummy database included with MADYMO. EASi-CRASH 2.417 (Easi Engineering, USA) was used for pre- and post-processing of simulations.

Rigid body computer simulations of a public-domain test vehicle (Ford Taurus) into a rigid longitudinal barrier (concrete) were performed at a number of impact angles. Acceleration data for the vehicle during the collision were extracted. These data were used in a simulated sled test, which consisted of a seated, Hybrid III 50th-percentile male dummy. Simulations were performed with an unrestrained (flail space) dummy, and a secured (sash-type seat belt) dummy. A range of direct vehicle injury criteria for the dummy was derived from the results of the sled test. The criteria calculated were:

- HIC 15 ms and 36 ms

- GSI head

- Chest acceleration

- a_p max

- 3 ms contiguous torso

- 3 ms contiguous chest

The results of the flail space model of the vehicle occupant from the sled tests were used to derive indirect injury risk criteria, typically described in standards relating to the assessment of roadside hardware. The following parameters were derived from a mix of results from both the sled test and the vehicle+barrier simulations:

- THIV

- PHD

- ASI

- Ridedown acceleration

These injury risk criteria were tabulated and compared in relation to typical maximum limits.

The use of MADYMO and EASi-CRASH to perform these simulations was also evaluated. In summary, difficulties were encountered with the compatibility of files produced by the pre-processor and MADYMO. No such difficulties were encountered with the post-processing capabilities of EASi-CRASH. Rigid body simulations of the test vehicle colliding with the barrier could be performed. However, the finite element capabilities of MADYMO for such applications have some limitations compared to other FEA packages. The speed of computation is certainly a major consideration when developing new models, due to the long delays associated with creating a model, executing it, identifying the source of errors, attempting to correct those errors, and re-submitting the model to the computation software. No specific functions were available to calculate occupant injury criteria from the barrier simulations. Acceleration data were exported using EASi-CRASH and specific routines were written using the MATLAB programming environment to calculate the required parameters.

In contrast, simulations of the sled tests were able to be initialised using EASi-CRASH, calculated by MADYMO, and the results viewed and extracted using EASi-CRASH. Simulations could be calculated very rapidly, which assisted with the process of learning the characteristics of the software and set-up of the model. Injury criteria of interest could be identified and calculated directly by MADYMO.

In conclusion, this project has demonstrated the capabilities and limitations of MADYMO for the evaluation of occupant injury in roadside barrier design. Rigid body simulations could be successfully computed, and occupant injury criteria could be calculated by the software for the Hybrid III anthropomorphic dummy. Finite element representations of a standard test vehicle (Ford Taurus) and a concrete barrier could not be fully realised due to the limitations in the finite element module of MADYMO. Future work in this area should focus on alternative software programs, such as LS-DYNA, for the investigation and preliminary evaluation of roadside hardware.

2 LITERATURE REVIEW

This section outlines the key literature relating to the conduct and evaluation of vehicle collisions with roadside barriers and the injury risk associated with occupants of the vehicle.

2.1 Evaluation of Roadside Barrier Hardware

The most comprehensive description of procedures relating to the evaluation of roadside barriers is NCHRP Report 350 (National Research Council, 1993). Included in this document are the test parameters for various test vehicles, types of barriers, speeds and impact angles to be evaluated, and methods for the reporting of test results. This report has been endorsed by Australian Standard AS/NZS 3845:1999, in terms of the methods used to evaluate the performance of barrier designs and configurations. These two publications guided the choice of the scenarios simulated and the manner in which the results have been reported.

2.2 Assessment of Occupant Injury Criteria

NCHRP Report 350 (National Research Council,1993) also includes descriptions of the evaluation criteria for occupant risk as related to the vehicle collisions with roadside barriers. The detailed methodology for determining THIV, PHD, ASI and ridedown acceleration is also included. Preferred and maximum limits for some of these criteria are detailed.

It should be highlighted that all of these criteria are indirect risk assessment criteria as they are derived from the motion of the vehicle—the so-called flail space model. Whilst the potential use of an anthropomorphic test dummy is included in this report, no specific guidance is given as to how the data measured by the dummy should be incorporated into the evaluation procedure.

Some research has been undertaken into the use of test dummies for the case of side-impacts into roadside hardware (Ray and Carney, 1992). This report is included as Appendix G in NCHRP Report 350 (National Research Council, 1993). The rationale for using anthropomorphic dummies in side-impact tests is that the severity of crash loading is much more extreme compared to the loading experienced with tests of longitudinal barriers. Ray and Carney recommend that all side-impact evaluations of roadside hardware should include the use of an instrumented side impact dummy.

The choice of anthropomorphic dummy is another area of contention. NCHRP Report 350 concedes "that the Hybrid III dummy is valid for *frontal or head-on impacts* only" [original emphasis]. It is further added that "[T]there is no dummy capable of accurately simulating the kinetics and kinematics of an occupant for oblique movements". However, the use of a Hybrid III dummy is indicated as an option in the evaluation of occupant risk (Table 5.1).

Designers of motor vehicles are required to use a much more comprehensive suite of injury parameters and criteria for the quantification of occupant risk. These typically include parameters for the assessment of head (HIC, GSI), neck (Nij), chest and torso (acceleration, deflection, TTI) and lower limb (femur force, tibia force) injury.

In conclusion, there is still a divide between the roadside barrier design community and vehicle manufacturers, at least in terms of the methods used for the assessment of occupant injury. The difficulties associated with using instrumented anthropomorphic dummies in the routine physical testing of roadside barriers and other hardware is acknowledged. However, some harmonisation of methods for the reporting of occupant risk, beyond those outlined in NCHRP Report 350

(National Research Council, 1993), appears to be a desirable objective for future research and revision of the relevant standards relating to roadside hardware.

2.3   Computer Simulation

The automotive manufacturing industry has come a long way in recent times, aided by numerous technological advancements that have highlighted the potential for computer simulation in a range of transport-related areas. Computer tools have been actively used in the preliminary component design, feasibility analyses, geometric optimisation and manufacture of automotive components. To this end, vehicle crashworthiness evaluation with respect to roadside hardware design has also been widely dealt with in the last decade using different finite element and dynamic simulation packages such as LS-DYNA 3D and MADYMO (Ray, 1997; Grzebieta R, Koay K & Zou R, 1999).

Vehicular models are becoming more sophisticated over the years in terms of their accuracy, robustness, fidelity, and size, with the need for developing multi-purpose models that can be used to address safety issues for a wide class of impact scenarios becomes more apparent.

Advances in crashworthiness research and particularly in dynamic finite element analysis of impacts have opened up new possibilities for the evaluation of the crash performance of roadside appurtenances. In recent years, non-linear explicit finite element codes have significantly advanced the computer modelling and simulation of automobile crashes. This capability additionally allows the application of the software to model and analyse the performance of roadside objects in crashes. The simulations can assist the redesign and optimisation of these devices for the purpose of reducing injuries in highway accidents. The unavailability of functional, computationally efficient and validated, impacting vehicle models is a major impediment to these roadside hardware crash simulation efforts.

Brasch & Brasch (1983) reported a review on impact collision of vehicles. This was one of the first efforts to define existing computational codes and their efficiency in simulating vehicular collisions with roadside hardware vis-à-vis with other vehicles. Their work paved the way for a structured approach to future modelling and post-processing.

Since the early 1990s, a large quantum of research has been reported in the area of vehicular crashworthiness. This research can be broadly categorised into two areas:

1. Vehicular collisions into roadside hardware, and
2. Inter-vehicular collisions

Two basic approaches have been adopted in the investigation of roadside hardware. Multi-body simulations in which individual components are modelled as a series of connected (linked) rigid body segments is typical of many of the simpler two-dimensional (2-D) and the more recently developed three-dimensional (3-D) simulation software programs. NCHRP Report 350 (National Research Council, 1993) provides an historical perspective and critique of a number of the earlier software programs, including HVOSM and SMAC. More recently, MADYMO has extended the capabilities of performing simulations of highly complex multi-body configurations and has incorporated finite element analysis calculations.

Parallel developments have occurred with finite element analysis (FEA) software. Programs such as Barrier VII employed 2-D models to simulate the performance of roadside barriers. The

development and subsequent release of DYNA3D and LS-DYNA3D made highly capable software widely available (Ray, 1997).

Matsumoto et al (1990) conducted a parametric evaluation of vehicle crash performance. They described the behaviour of a driver side occupant restrained by an airbag system in a passenger vehicle involved in a frontal barrier crash. The authors examined the influence of two parameters on occupant injury indices using a MADYMO 2D computer simulation program. They report that it is important to model the axial collapse and rotation of the steering system in the vertical plane caused by dashboard deformation, in order to achieve good correlations between experiment and simulation. They demonstrated that the parametric study clarifies the influence of the vehicle deformation characteristics, which is represented by a combination of two simplified trapezoids, as well as of the movement of the steering system, on effective occupant protection for an example vehicle.

More recently, MADYMO has been extensively used to study passenger behaviour in such crashes, using standard test dummies. Lupker, de Coo et al (1991) and Langdon (1991) report the use of MADYMO to study the behaviour of dummies in the case side impact. These papers review the findings that characterise the human factors, biomechanics, and occupant position envelope of the typical side impact crash victim, along with the economic benefit and cost relationships which appear to put side impact crash protection about an order of magnitude less favourable than frontal protection. The findings regarding the effect of accident reconstruction errors on side impact benefit appraisal are employed to analyse the safety community's inability to measure the effect of countermeasures in practice. The proposal for a simplified crash test procedure is reviewed, as it pertains to the generation of side impact crush energy data, and its contribution to understanding and designer judgement regarding the efficacy of various countermeasures and overall economic savings.

Kerkhoff et al. (1993), enlarged the database for the 1981-1985 Ford Escort crash test data. Barrier crash test speeds in that paper were conducted at 6.66, 8.88, 17.77 and 22.22 m/s. The purpose of this paper was to examine the issue of low speed impacts and the corresponding damage or shock isolator movement to the vehicle.

Neptune, Flynn et al (1995, 1998) conducted an impact analysis using the CRASH 3 damage algorithm. They discuss the accuracy of accident reconstruction and a methodology to obtain the crash stiffness coefficients in the simulation of frontal and near side impacts.

Navin et al (1998) and Wood (1999) examined the influence of the elastic compressive properties in the frontal impact of cars. These papers examine on a fundamental basis the elastic deformation of car structures during frontal impact and propose models for the elastic stiffness of cars. The papers show that the rebound energy and rebound velocity is a function of the impact force at the instant of maximum dynamic crush and of the elastic stiffness. Theoretical predictions of the rebound velocity and its manner of variation with approach velocity for full width barrier impact are similar to the pattern of rebound velocity variation found from staged tests. The implications of the model for rebound velocity in offset collisions are reviewed and an explanation is provided for both tangential and normal restitution coefficients at angled impact surfaces.

Campbell (1974) reported a study on the energy involved in collision severity. This paper presents an objective technique for estimating the severity of automobile collisions. The vehicle damage and the dynamic force-deflection characteristics of the vehicle structure are used to estimate the energy absorbed in plastic deformation of the vehicle. This energy can then be

expressed as an "equivalent barrier speed" (EBS). The development is limited to frontal damage, although the technique is general and could be extended to side and rear damage. Data are presented relating residual crush and impact speed for full frontal barrier tests to provide the basis for a simple model of the force-deflection characteristics of the vehicle front structure. EBS is then estimated by integrating this force-deflection characteristic over the deformation of the field vehicle. The results of this model were compared with test data to indicate the types of damage patterns for which the model appears valid. Calculations are made for damage patterns resembling angle and offset barrier impacts, and the computed EBS is compared with the actual impact speed. For both types of test, the errors seem within normal test variability.

Tominaga et al (1996) conducted a numerical analysis of side impact phenomena using a MADYMO-3D DOT-SID dummy. They incorporated both lumped parameter (LP) modelling and finite element (FE) modelling. Experimental tests and analytical modelling using LP and FE techniques were performed on an experimental vehicle in order to evaluate the compatibility and interrelationship of the two numerical methods for crashworthiness simulation. The objective of the numerical analysis was to simulate the vehicle crashworthiness in a 0 degree, 48.6 km/hr frontal impact.

Sledge and Marshek (1997) evaluated the influence of the coefficient of friction on the critical speeds of cars. This paper provides an exposition of the basic and some refined inertial critical speed estimation formulas. They incorporated a literature review of existing inertial formulas for estimating critical cornering speed for developing a useful, compact, and more accurate speed estimation formula. Background information is presented covering the general definitions and utility of critical speed formulas. They showed that the basic formulas are founded on the fundamental principles of physics and engineering mechanics; namely, Newton's Second Law and centrifugal force. Refined formulas are presented that account for the effects of many important kinematic and dynamic factors ignored in the basic formulas such as: road grade, vehicle weight distribution, vehicle sides-slip angle, axle and tire slip angles, superelevation, lateral and longitudinal drag factors, wheelbase, front steering angle, cornering stiffs, lateral load shift, friction dependency on load, aerodynamic forces, and antilock brake effectiveness.

Wismans et al (1988) and Bedewi & Bedewi (1998) reported work on the use of MADYMO in biomechanics. They address the application of finite element methods to the simulation of humans in an impact environment. The literature survey reported reveals several rigid body dynamics models of the human and sub-components, however, relatively little work has been performed using finite elements. Difficulties remain in characterising the material properties of the associated biological materials because of non-linear, inhomogeneous, anisotropic, and rate dependent behaviour. Physical testing using cadavers remains the primary means for determining human impact response and for validating the models created. A method for creating human finite element models is presented that requires the model to be developed in a ground-up approach and in a component-wise manner. Each component has five levels of detail with level one being a collection of rigid segments connected by simple joints and level five consisting of a highly detailed model with proper material properties and injury mechanisms included.

These methods have been employed to create a level two human lower extremity model. The model consists of accurate geometric segments of the individual bones in the leg. Each segment was connected using joint definitions in LS-DYNA3D that contains the non-linear stiffness characteristics of the hip, knee, and ankle. The model was used to simulate the loading conditions of a 50% overlap frontal collision of two mid-sized cars with a closing speed of 112

km/hr (70 mph). A parametric study to determine the effects of muscle tensioning was performed for twenty-seven different joint loading cases. Results indicated that muscle tensioning greatly affected the kinematics of the leg during high-speed impact events.

In summary, there is an opportunity to utilise computer simulations to fill the need of obtaining more detailed knowledge of the behaviour and potential risk to vehicle occupants.

3   METHODOLOGY

3.1   Computer Hardware and Software

The software simulations conducted as part of this project were performed using MADYMO 5.4 (TNO Automotive, The Netherlands). Pre- and post-processing of models utilised EASi-CRASH 2.417 (Easi Engineering, USA). Computations were performed using a Silicon Graphics (SGI) Octane workstation. The hardware configuration consisted of a single RISC10000 processor, 512MB RAM running the IRIX 6.4 operating system.

3.2   Model Geometries

It was not the intention of this project to independently develop fully detailed models of test vehicles. Hence existing databases of objects for use in vehicle crash simulations were identified. Of particular relevance to this project is the repository created by the U.S. National Highway and Transport Safety Authority (FHWA/NHTSA National Crash Analysis Center, 2000). For the purposes of this project, the modified 1991 Ford Taurus vehicle (LS-DYNA input deck), consisting of 28,400 elements was selected as a starting point (Figure 1). This vehicle was assigned a mass of 1,800 kg.

The archive contained finite element models developed in LSDYNA-3D. It was found that there is an incompatibility in the material properties that could be described in the different programs. While, LSDYNA-3D could define over 140 different materials, MADYMO can handle only 17 material types. For example, while the former used linear elasto-plastic material properties, all of these had to be converted into isolinear for use by MADYMO.
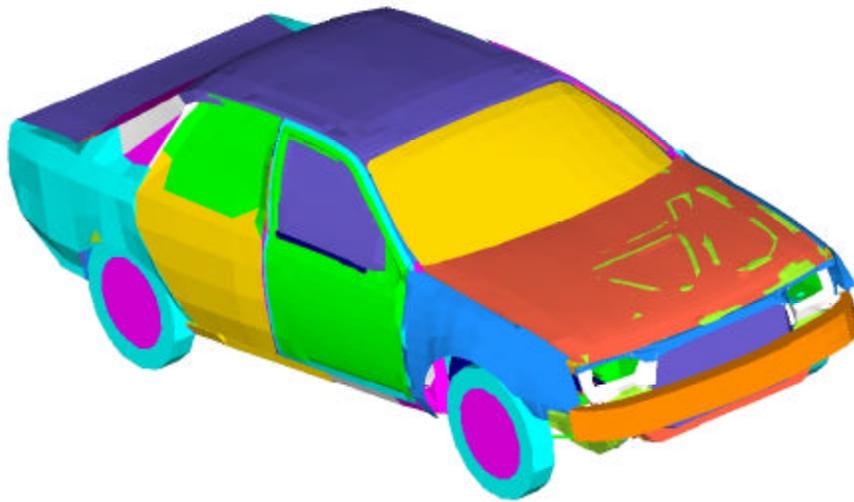
Figure 1: Model of 1991 Ford Taurus vehicle selected for crash simulations. Image of model created by EASi-CRASH v2.417.

It was decided to first conduct simple rigid body collisions. For this, all the material properties of the car were specified as rigid. A facet surface was created from the original finite element nodes and vertices, resulting in a reduction by a factor of four (28,400 to 7,864) in the total number of elements used in the model. All components were assigned a Young's modulus of 200 GPa, Poisson's ratio of 0.3. Densities ranged from 2500-7800 kg/m^3. All components had a nominal thickness of 1 mm.

Due to computational limitations associated with the use of finite element models, simple rigid planes modelled the road surface.

No anthropomorphic dummy was located within the vehicle during these simulations.

The geometries of the various roadside crash barriers were created by a number of different methods. The vertical wall and concrete longitudinal barrier (Profile Type 1, Figure 3.12(1), AS/NZS 3845:1999) were represented by single or multiple planes and were constructed within EASI-CRASH. A capability to define more complex geometries was also tried whereby solid modelling software (e.g. Pro/ENGINEER or Solid Works) was used to create object definitions. Data files could be imported into EASI-CRASH using the IGES Import facility. The intention was to use these geometries to define finite element models. However, the results of the initial simulations performed highlighted severe limitations in the use of MADYMO for undertaking such computations.

Hence, both technical difficulties and long computation times required the barrier geometry to be modelled by planar surfaces, rather than finite element models.

The loading and unloading functions required for the planar barrier and road surfaces were defined using the hysteresis models for rigid elements.

A finite element mesh for the test vehicle was constructed for use with MADYMO. The model consists of 7,864 isolinear elements and incorporates MADYMO tyre (SOLID8) elements,

described by the Moony-Rivlin model for vulcanised rubber (Poisson's ration = 0.48) (TNO Automotive, 1999). Uniform material properties were assigned for all other elements (density = 7850 kg/m^3, Poisson's ratio = 0.3).

The approach used was to incorporate a finite element mesh using SHELL4 elements for only the front left quadrant of the vehicle (i.e. for only the portion of the vehicle to come into contact with the barrier). A material of thickness of 1 mm was used. The remainder of the vehicle was modelled as rigid body elements with a Young's modulus of zero. The net effect was to decrease the computation time without affecting the overall contact behaviour with the barrier.

3.3   Contact Interactions

Contact interactions had to be defined between the facet surface elements of the test vehicle and planar surfaces of the barrier and road. Initially, nominal values of contact friction coefficient were assigned for these contacts. The unrealistic behaviour of the vehicle in the initial simulations conducted identified the sensitivity of the simulations to the magnitude of the parameter. The need to identify more realistic values led to the identification of existing data in the literature.

The final values for the coefficient of friction between the various components were estimated using the formula, $m = ae^{bV}$, where a=0.874, b=0.00393 and V is the car velocity in km/h (Sledge and Marshek, 1998). This resulted in a range of 0.2-0.4 and 0.6-0.7 for the coefficient of friction for the car-barrier and car-road, respectively.

The loading functions for the road and barrier, and the corresponding stiffnesses, were estimated using the data reported by Sledge & Marshek (1998).

3.4   Initial Conditions

Initial speeds, vehicle trajectories, relative positions of model geometries (car, barrier, road) were all set using either EASi-CRASH, or by direct text editing of the MADYMO data file prior to conducting the simulations using MADYMO. Text editing was found to be necessary due to errors experienced when importing some MADYMO data files into EASi-CRASH, and similar errors created by EASi-CRASH when MADYMO data files were exported.

A constant gravitational acceleration field (9.81 m/s^2) was used for all vehicle simulations.

3.5   Crash Simulations

Simulations of the vehicle crashing into roadside barriers were computed using MADYMO. All simulations conducted used a time increment of 0.1 ms and were conducted for a period of 0.4 s.

The vehicle approach speed was set to 70 km/h. Three different impact angles—15°, 20° and 25°— were evaluated.

Output parameters selected from the vehicle simulations were the linear accelerations (resultant, x-, y- and z-directions) for the centre of mass (CoM) of the vehicle and the estimated position of the driver's seat.

Full animations of the vehicle+barrier simulations were created by MADYMO and viewed using EASi-CRASH as the post-processor. Acceleration data was plotted using EASi-CRASH and exported as text files.

3.6   Sled Test Simulations

Acceleration data (in the x- and y-directions only) calculated from the vehicle simulations was incorporated into the MADYMO data files describing the configuration of the sled test simulations (Figure 2). A Hybrid III dummy representing a 50th-percentile male was selected from the MADYMO dummy database and positioned within the seat geometry. Two different configurations for the dummy were developed: one in which the dummy was unrestrained; and one in which the dummy was restrained by a lap and shoulder seat belt. MADYMO was used to perform the sled test simulations. Once again, a time increment of 0.1 ms was used.
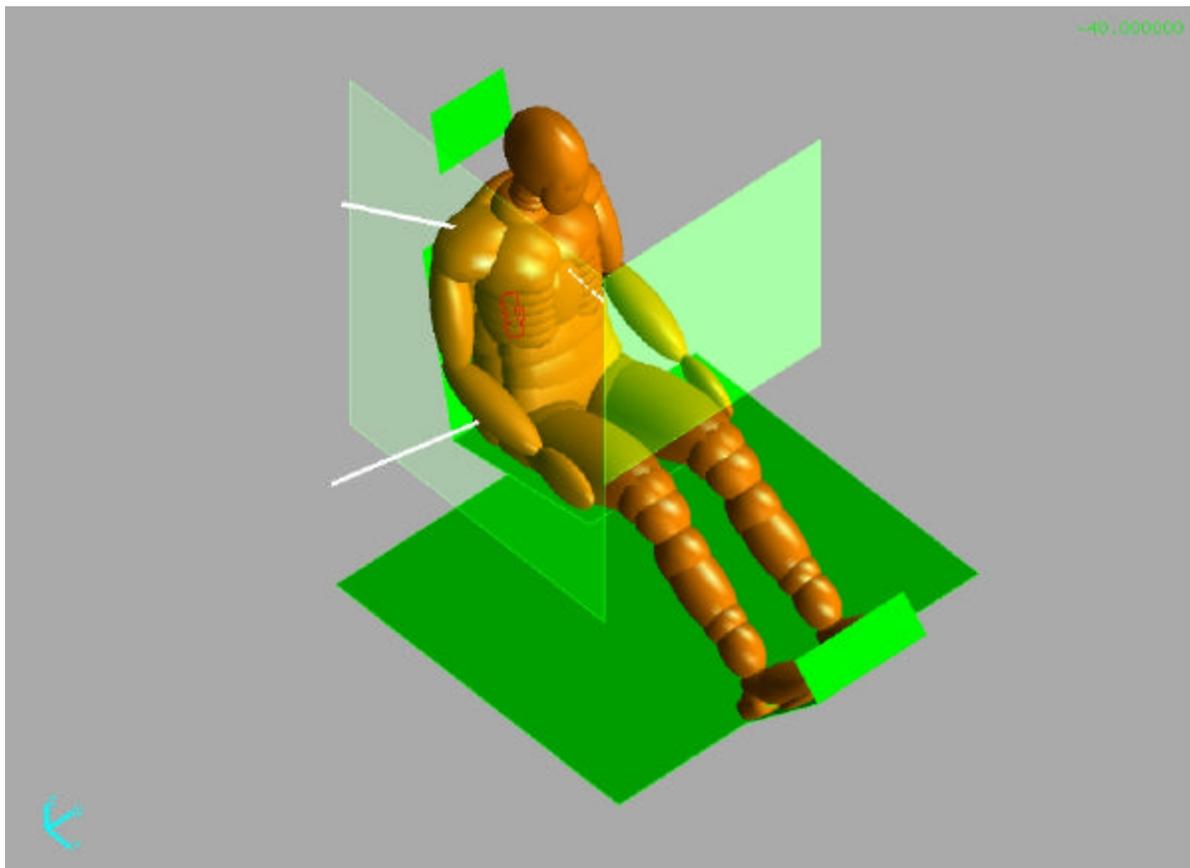
Figure 2: Configuration of Hybrid III dummy in seated position used to simulate sled tests. Dummy is secured by a sash-type seatbelt.

The distance measurements required for analysis of the flail space model (0.3 m to the side of the head, 0.6 m in front of head) were represented by planes to aid visualisation. Other injury criteria such as HIC, GSI, etc. for the dummy were calculated directly by MADYMO.

4   RESULTS

4.1   Vehicle Colliding with Longitudinal Barrier

Figure 3 illustrates the components of linear acceleration produced by the rigid body simulation of the test vehicle colliding with the concrete longitudinal barrier. The X-direction is in the direction of travel. The Y-direction is to the left of the vehicle. The Z-direction is vertical. Figure 4 illustrates the relative position of the vehicle at different times of the simulation. Time = 0 ms corresponds to the start of the simulation. Time = 40 ms is the time at which the vehicle and the barrier first make contact. Times = 140 and 240 ms are at periods of 100 and 200 ms respectively after the first contact time.
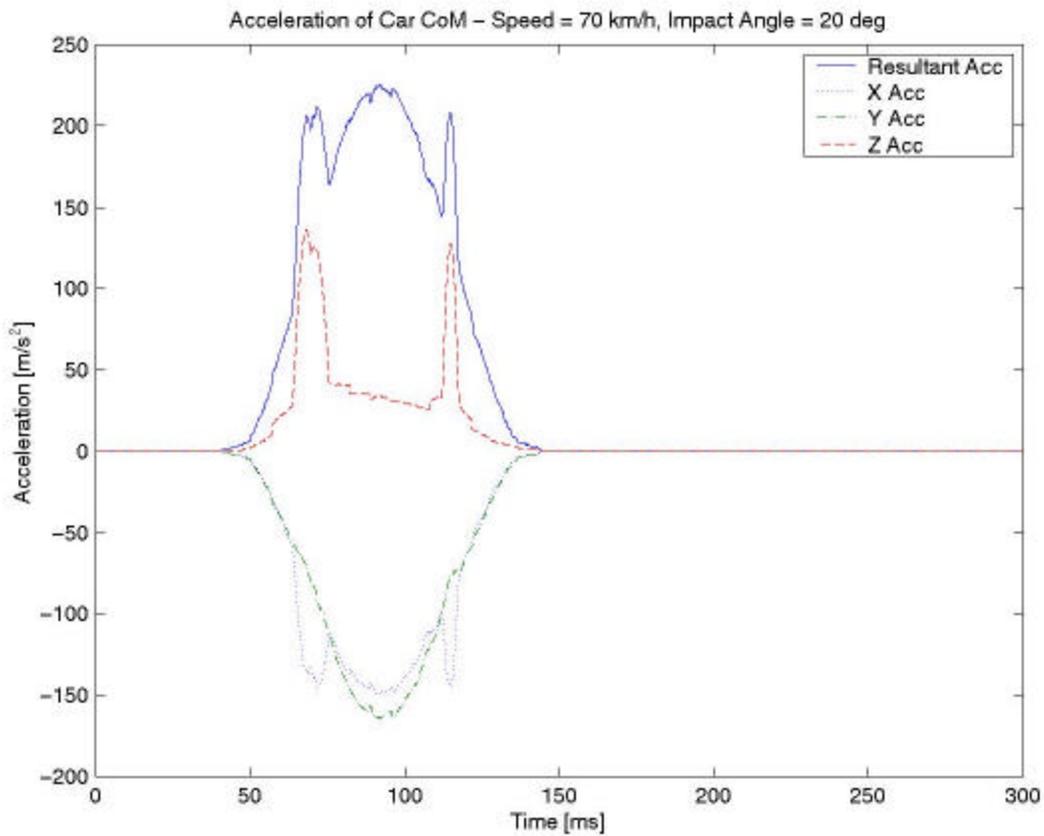
Figure 3: Plot of acceleration of CoM versus time for test vehicle colliding with concrete longitudinal barrier. Speed = 70 km/h, Impact Angle = 20°.

Figure 4: Plan and frontal views of vehicle colliding with longitudinal barrier. Speed = 70 km/h, Impact Angle = 20°.
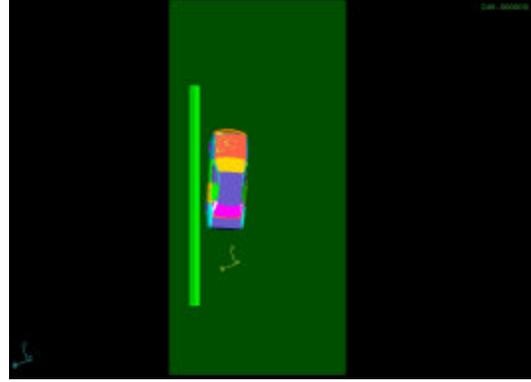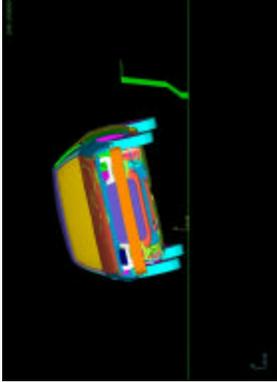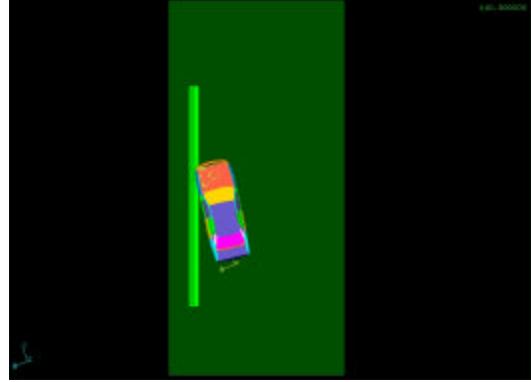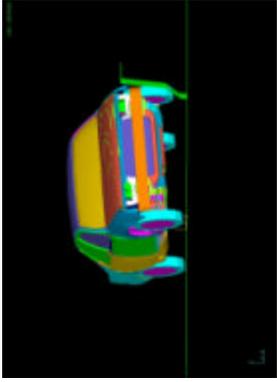
d. 240 ms

c. 140 ms

b. 40 ms
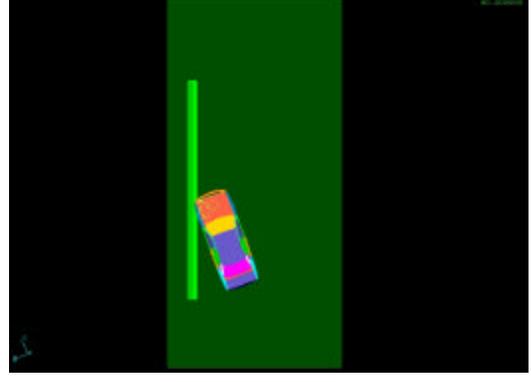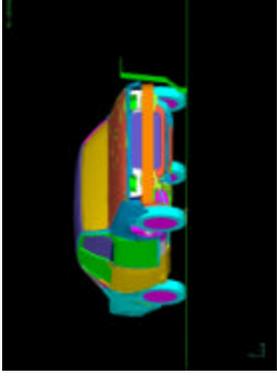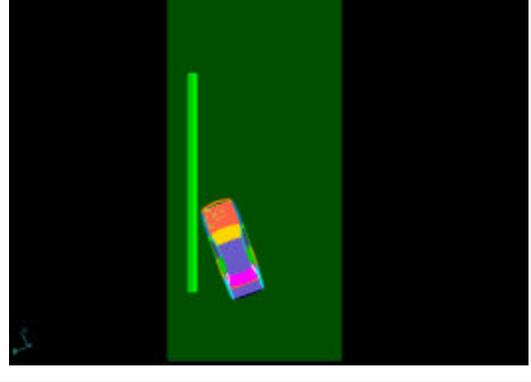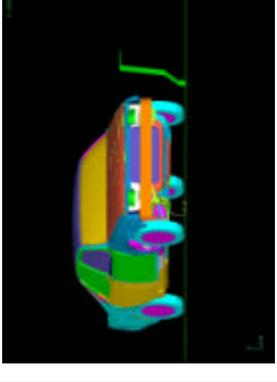
a. 0 ms

4.2   Sled Test Simulation

Figures 5 and 6 illustrate the motion of the restrained and unrestrained Hybrid III test dummy. Included in these figures are the boundaries of the flail space model, described in NCHRP Report 350 (National Research Council, 1993). This was used as a visualisation aid and a check of the time calculated and used for the derivation of the THIV, ASI, PHD and ridedown accelerations. Of note in these diagrams, and in Figure 3, are the magnitudes of the acceleration components resulting from the collision between the test vehicle and longitudinal barrier. The motion of the unrestrained dummy is clearly oblique, with the dummy first exceeding the lateral boundary of the flail space. This point is relevant to the issues raised earlier regarding the choice of anthropomorphic dummy for such simulations, as well as for physical crash testing.
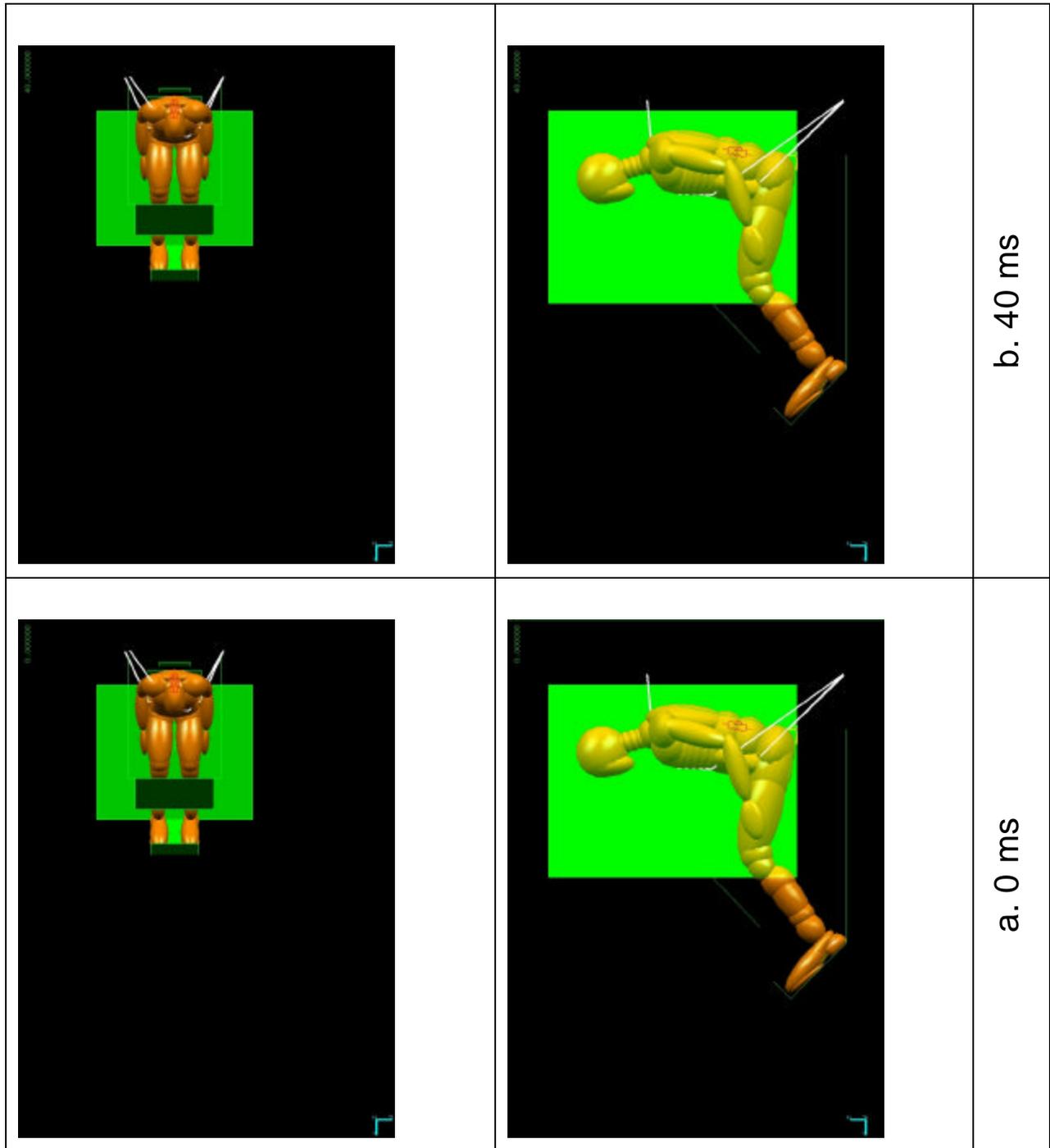
Figure 5: Plan (above) and side (below) views of sled test simulation. Restrained Hybrid III dummy. Speed = 70 km/h, Impact Angle = 20°.
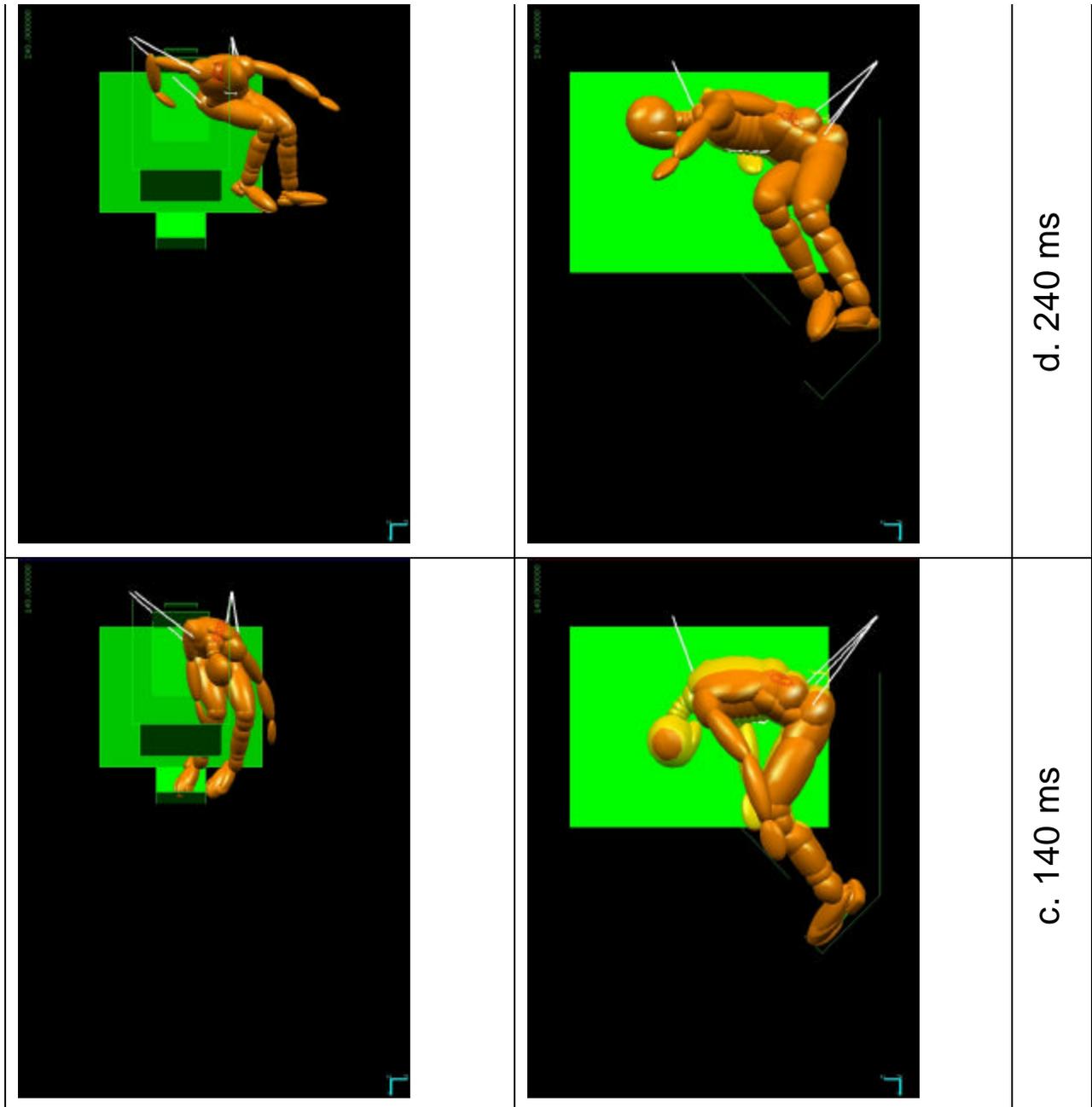
Figure 5 (cont'd): Plan (above) and side (below) views of sled test simulation. Restrained Hybrid III dummy. Speed = 70 km/h, Impact Angle = 20°.
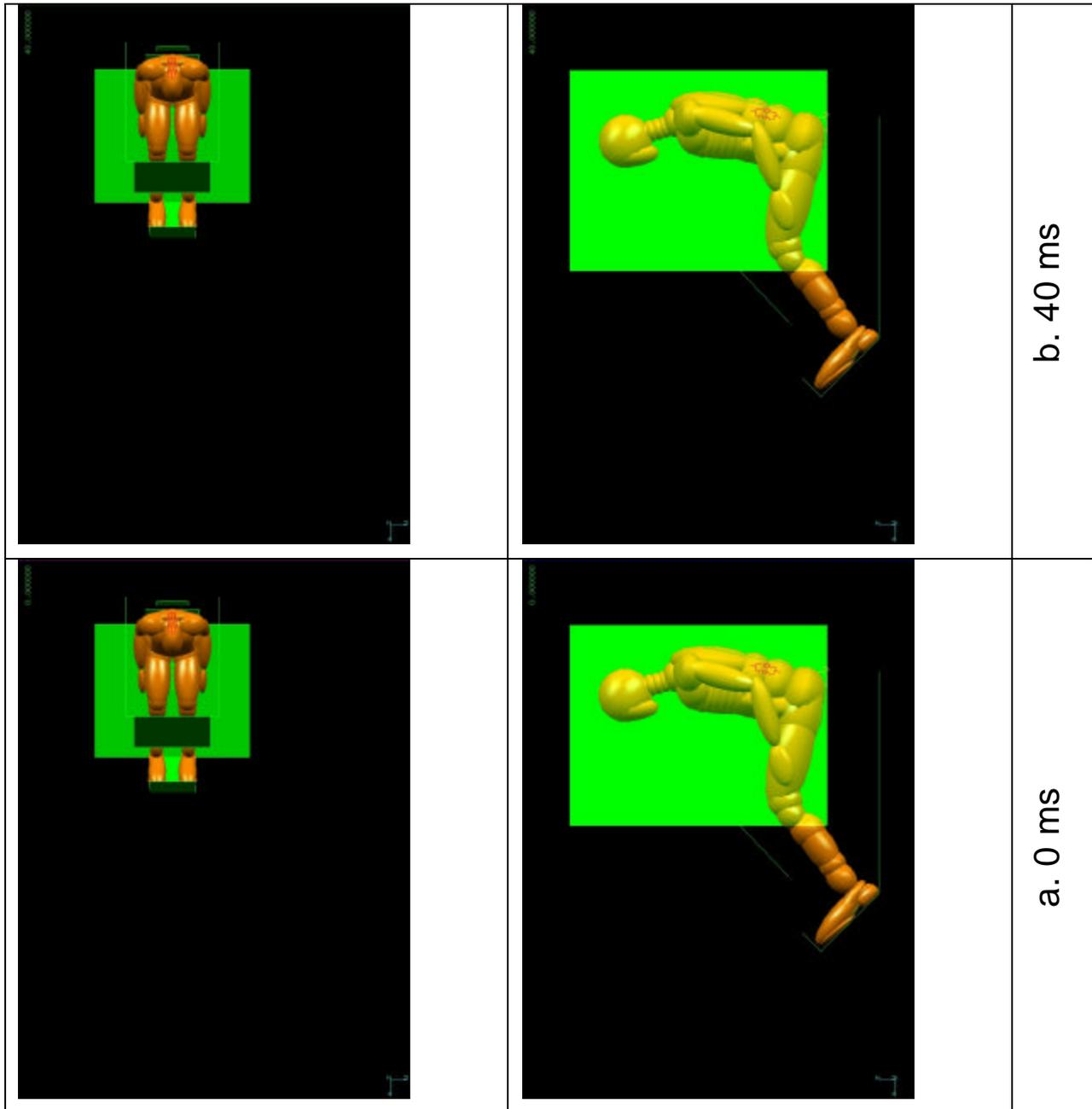
Figure 6: Plan (above) and side (below) views of sled test simulation. Unrestrained Hybrid III dummy. Speed = 70 km/h, Impact Angle = 20°.

b. 40 ms

a. 0 ms
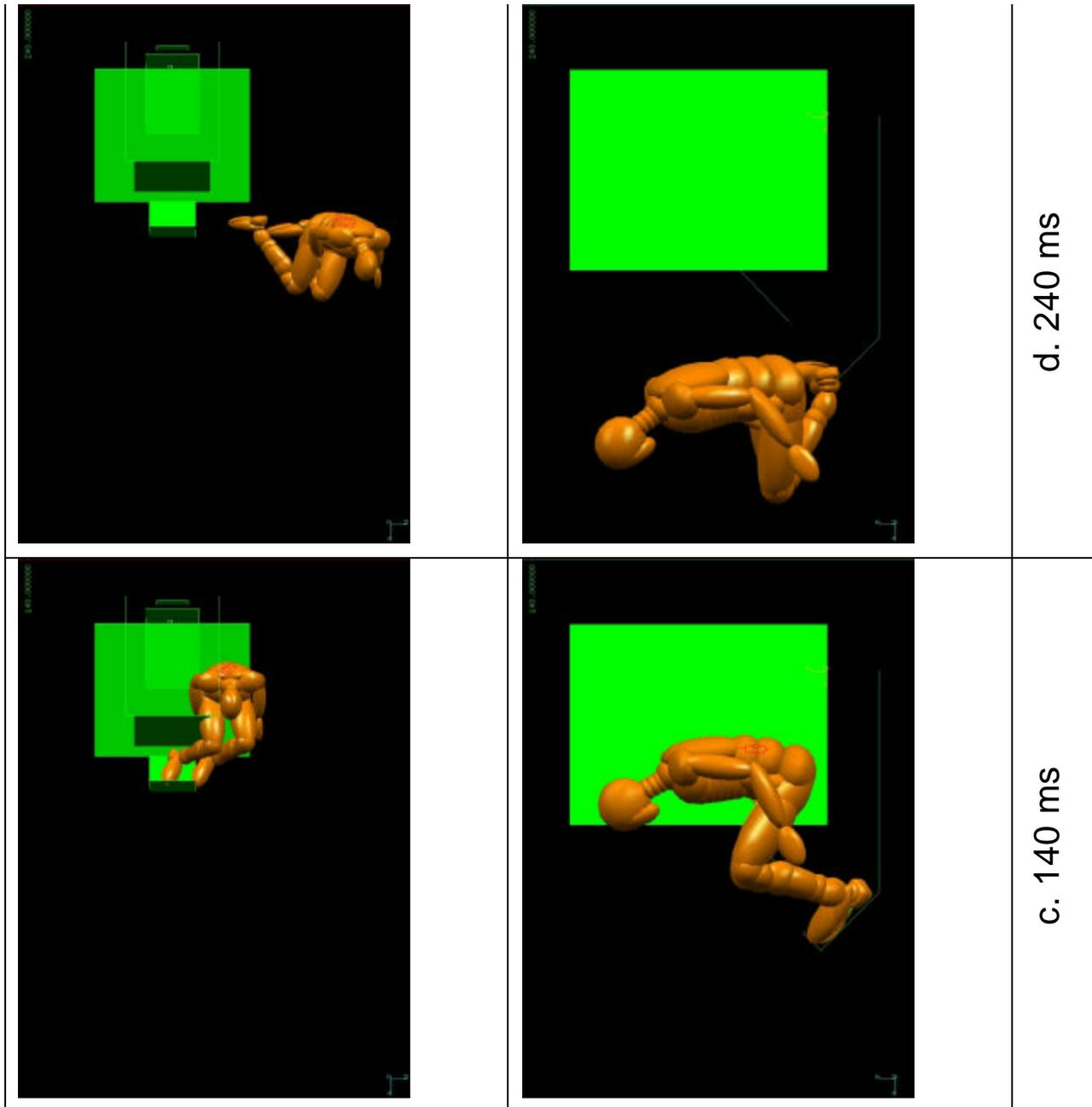
Figure 6 (cont'd): Plan (above) and side (below) views of sled test simulation. Unrestrained Hybrid III dummy. Speed = 70 km/h, Impact Angle = 20°.

4.3   Occupant Injury Risk Criteria

Table 1 summarises the injury assessment criteria calculated for the unrestrained and restrained sled test simulations. The effect of the seatbelt has resulted in an increase for many of these criteria. It should be highlighted that no other limits nor contact surfaces were included in these simulations, other than the presence of the seat, backrest and headrest. The presence of structures such as steering wheels, airbags, knee bolster, etc., would obviously affect the potential risk to the vehicle occupants.

Table 1: Comparison of occupant injury risk criteria for unrestrained and restrained Hybrid III dummy. Speed = 70 km/h.

Injury Criterion	Unrestrained dummy			Restrained dummy		
	15°	20°	25°	15°	20°	25°
THIV[1,2]						
- longitudinal [m/s]	6.1	8.1	9.3	N/A	N/A	N/A
- lateral [m/s]	6.3	8.9	11.4	N/A	N/A	N/A
ASI[1] [g]	1.3	1.9	2.4	1.3	1.9	2.4
Ridedown acceleration[2]						
- longitudinal [g]	14.9	16.8	28.4	N/A	N/A	N/A
- lateral [g]	13.2	18.4	22.0	N/A	N/A	N/A
PHD[1] [g]	7.9	17.2	24.5	N/A	N/A	N/A
HIC[3]						
- 15 ms	7.5	17.6	26.9	18.2	55.4	113.4
- 36 ms	14.3	33.0	51.4	36.7	108.2	213.8
GSI[3]	19.3	44	427.6	79.2	214.1	450.8
Maximum chest acceleration[3]						
- longitudinal [g]	13.2	13.8	22.9	10.2	13.6	22.2
Maximum pelvis acceleration[3]						
- resultant [g]	13.7	20.0	40.3	23.3	44.3	49.3
3 ms-criterion torso contiguous[3] [m/s^2]	116.5	162.9	230.8	172.4	254.1	339.0
3 ms-criterion chest contiguous[3] [m/s^2]	138.2	204.5	331.4	188.8	260.4	368.2

N/A = Parameters not applicable to restrained models as time of theoretical contact between head of dummy cannot be determined.
[1] Calculated using the method of NCHRP Report 350 Appendix F.
[2] Calculated using the method of NCHRP Report 350 Appendix A5.3.
[3] Calculated by MADYMO 5.4.

4.4   Finite Element Model

The results of the finite element model were less than satisfactory, for a number of reasons. Despite numerous attempts, there remained a high degree of visible deformation (flexing) of the front hood as the vehicle approached the vertical barrier, despite the fact that there were no contact forces being applied to this part of the car. Attempts to increase the thickness and stiffness of the material within realistic limits did not adequately reduce this effect. The net result of the vehicle, in terms of the acceleration of the centre of mass, exhibited a large amount of noise, thus limiting the use of such data in sled test simulations, as was performed from the rigid body simulations.

The simulation was completed without errors, and was able to demonstrate the contact of the front wing of the vehicle with the barrier. Deformation of the relevant parts of the car were observed, and appeared to be within expected limits.

The computation time for an analysis of 0.4s duration with a time increment of 0.1 ms was approximately 5 hours. This was largely a result of the approach used, in which only a portion of the vehicle was modelled as a finite element mesh. Limited attempts to use a finite element mesh of the entire vehicle had to be abandoned due to the excessive computation time.

In summary, the use of the finite element capabilities of MADYMO was of limited practical application. This was due to the limited material types included within MADYMO, excessive computation times, and a lack of physical testing data with which to compare the output of the simulations.

5   DISCUSSION

The original objectives of the project were:

- Develop in-depth knowledge and application of MADYMO for modelling and analysis of automotive vehicle design;

- Apply MADYMO to the modelling of roadside barriers;

- Establish specific relationships between roadside crash barrier design and vehicle occupant injury criteria;

- Establish a test standard for exploring new designs and predicting their performance prior to physical testing;

- Extend the capabilities for road safety research in Australia, and specifically the role of computer software simulation and analysis.

Each of these objectives will be addressed in turn.

5.1   Knowledge and Application of MADYMO

Our experience in using MADYMO has been greatly enhanced by this project. The in-depth knowledge which was necessitated by the problem-solving required to achieve the project outcomes has placed us in a much better position for continued work in this and associated areas.

The specific combination of software used, viz. MADYMO and EASi-CRASH, presented some unexpected difficulties. As outlined in the Methodology, circumstances arose where the interpretation of files created by using EASi-CRASH as a pre-processor were not considered "valid" by MADYMO. This resulted in run-time errors when MADYMO was executed. Examples of the errors produced included definitions of joint degrees-of-freedom, and the graphical positioning of planes. Other difficulties were experienced due to the limited material types available in MADYMO compared to those able to be defined in LS-DYNA3D. This is of significance if considering the use of public-domain FE models of test vehicles and, more recently, roadside hardware, such as those produced by the FHWA/NHTSA National Crash Analysis Center at George Washington University (2000).

As a result of these limitations, manual editing of text files was the only feasible method of creating valid MADYMO input data files. The additional time that resulted from this was not insignificant.

An additional problem was encountered by the units used for defining material densities in MADYMO. Despite the general adoption of SI units within MADYMO, densities that were assumed to be in the units of kg/m^3 resulted in rigid body objects that were incorrect, far exceeding the expected total mass. Once this error was noticed, numerous attempts were made to identify the cause, before it was realised, by trial-and-error, that the units were t/m^3. Correction of this error greatly improved the simulations of the test vehicle interacting with the longitudinal barrier.

The capacity for large finite element models to be simulated by MADYMO is quite limited. Initial trials of FE models containing relatively large (~200,000) numbers of elements indicated that excessively long computation times would result. This severely limits the utility of MADYMO where an iterative, trial-and-error learning process is being undertaken. This was the case for this project where we had had limited previous experience of MADYMO FE analysis.

As a result of the experience gained during the early stages of this project, complex geometric modelling prior to the creation of detailed finite element models of roadside barriers was not carried through to completion. The capacity to create such models certainly exists within MADYMO, but our experience has shown that the feasibility of such an approach with this software is not without considerable disadvantages and limitations. Recent work on this topic (Ray et al, 2001) has confirmed the suitability of LS-DYNA as an analysis tool for evaluating roadside hardware design. They have also demonstrated the need for full-scale testing to be undertaken on both individual components of the barriers and the interaction between the test vehicle and the barrier hardware.

The rigid-body simulations appeared to produce realistic trajectories of the test vehicle after impact. However, it must be acknowledged that there are a number of parameters that affect such results. It may be possible to produce what might be considered good results through a process of varying parameters by trial-and-error. However, accurate values of some of these parameters can only be derived by empirical testing of specific components, and this highlights another of the limitations of computer simulations. As has been noted by other researchers, the conduct of computer simulations without an associated physical testing program is prone to quantitative errors (Ray, 1992; Grzebieta et al, 1999; Duncan et al, 2000). Any simulation is exactly that—a simulation, rather than reality. The value of a model is the ability to compare different configurations, rather than to produce highly accurate numerical results. Hence models of this nature should be used as a qualitative, rather than quantitative, assessment tool.

In contrast to these problems, the creation of the test sled and the selection of appropriate injury criteria was able to be readily performed using EASi-CRASH, without having to resort to manual editing of MADYMO input data files.

This confirmed our previous experience with MADYMO, and the general consensus of other researchers in the area of human biomechanical modelling. MADYMO is certainly well suited to the simulation of multi-body systems, and it is well recognised that it is a leader in the field of test dummy simulations. However, the limited capacity for performing finite element calculations is less acknowledged publicly. In contrast, many researchers still promote the suitability of MADYMO for performing such computations in an efficient manner (e.g. Duncan, Corben, Truedsson & Tingvall, 2000).

Planned improvements in the most recent version of MADYMO (6.0) have yet to be formally assessed.

In conclusion, it is recommended that future work in the area of finite element modelling for the assessment of roadside barriers should be undertaken using software other than MADYMO. LS-DYNA (Livermore Software Technology Corporation, 2001) may be a more appropriate software tool for such analyses. MADYMO is extremely well suited to the assessment of human injury risk criteria. Recent developments in the creation of software which combines the capabilities of MADYMO and LS-DYNA may very well fulfil the needs identified by this, and other work, in the area of roadside hardware assessment (Formicola, 2001).

5.2   Relationship between Injury Criteria

The injury criteria results obtained by using the acceleration impulses from vehicle and barrier collision simulations as input into sled test simulations are summarised in Table 1. The only injury limits exceeded in these tests were those for ASI, which should be less than 1 (Appendix F3, NCHRP 350, National Research Council, 1993). It should be noted that the criteria stated in NCHRP 350 have been selected from European safety guidelines for occupants wearing seat belts, and therefore these particular criteria are probably not applicable for the flail space model. All remaining criteria exhibited sub-maximal values, when compared to current safety limits.

This study has demonstrated the capabilities of the software to calculate numeric values for these injury criteria. The absolute value of the individual criterion is limited by the comprehensiveness of the model that was examined. For example, the detail of seatbelt configuration will obviously affect the response of the dummy to a particular acceleration impulse. Hence it is extremely difficult to determine the precise relationship between specific injury criteria from the results of this study. What can be observed is the general trend of the injury parameters to increase as the angle of incidence of the vehicle into the barrier was increased from 15° to 25°.

Further limitations of the current standards, as they have been interpreted for use in these simulations, is the use of the Hybrid III dummy. As previously noted, the specification of this dummy for the test scenarios examined here is not optimal. Observation of the results for THIV and PHD indicate that the longitudinal and lateral accelerations and velocities are almost equal in magnitude. This would support the notion that the use of an anthropomorphic dummy designed for frontal collisions needs revision.

5.3 Establishment of Test Standard

The results of this study are insufficient for a specific test standard for crash barrier evaluation to be outlined. However, Section 5.4 outlines the potential role for computer simulation in evaluating proposed designs of new barriers.

5.4 Future Role of Computer Simulation in Road Safety and Human Injury Research

There is no doubt that computer simulation can be a powerful tool for the analysis of new situations for which physical testing is either impossible, or extremely difficult to conduct. The existing literature on this topic is further testament to this assertion. There are, however, a number of issues that must be understood before embarking on simulation studies.

Firstly, the exact reason for undertaking the simulation should be clearly outlined. For example, is the purpose of the study to examine the sensitivity of the test scenario to changes in the input parameters (e.g. speed, approach angle, material properties, test masses, etc.)? If so, then computer simulations can be very beneficial in terms of producing data for qualitative comparisons. Undertaking computer simulations with the aim of determining response data of high accuracy is possible, however this usually requires an extremely detailed knowledge of the material properties, boundary conditions, load response behaviour in contact situations, etc. In vehicle crash testing situations, such detailed information is not usually available. Many assumptions are used to simplify the performance of materials and to predict the behaviour of human occupants. Finite element models can be used to examine such events, but the results must be interpreted with knowledge of the underlying simplifications. Of particular relevance to studies such as this, is the requirement for detailed material behaviour and contact mechanics. Computer software such as MADYMO is able to incorporate most material properties, but the availability of such information is not always generally available.

MADYMO has been shown to be a very competent tool for the prediction of human response and the calculation of occupant injury criteria. Unfortunately, the finite element module has been shown to be less capable than other dedicated FEA software.

Future studies should aim to use software such as LS-DYNA to perform simulations of the vehicle and barrier interactions. An alternate approach is to use MADYMO to investigate the behaviour of crash dummies in sled tests. The acceleration impulse could be obtained empirically from full-scale barrier tests, and then used as input to the sled test simulations, using a method similar to that used in this study. Various vehicle interiors, restraint mechanisms and safety features could then be examined and compared without the time and costs associated with physical testing. The material properties of the specific components to be investigated should be obtained by laboratory testing using standard engineering methods.

An example of some current research, which has used such an approach, is that being undertaken by Justin Ludcke at Queensland University of Technology (Ludcke, 2001). Whilst the specific scenario being examined is not directly applicable to the evaluation of roadside barrier hardware, the approach that has been used gives an indication of the potential for computer simulation. This work is examining the behaviour of surf lifesavers as occupants of inflatable rescue boats (IRBs) as they traverse waves. For this application, acceleration profiles of an IRB going over a number of different waves were recorded using a portable data logger system. The acceleration profiles were then used as acceleration impulses as part of a computer simulation of the IRB and front crew-member (see Figure 7). MADYMO was used as the modelling tool, with the boat structure being modelled as a pressurised finite element mesh. A Hybrid III

anthropomorphic dummy was used to represent the human occupant, with joint stiffnesses being modified to more accurately represent the behaviour of a live subject. The beauty of such a model is the ability to examine particular design features, such as the thickness and density of foam covering the floorboards, and the position of the footstraps. The intention of this work is to identify the sensitivity of changes to these parameters on the loading experienced by the lower limbs of the crew. This is an area of high importance due to the increasing incidence of strains, sprains and fractures being sustained by surf lifesavers during active duty and races.
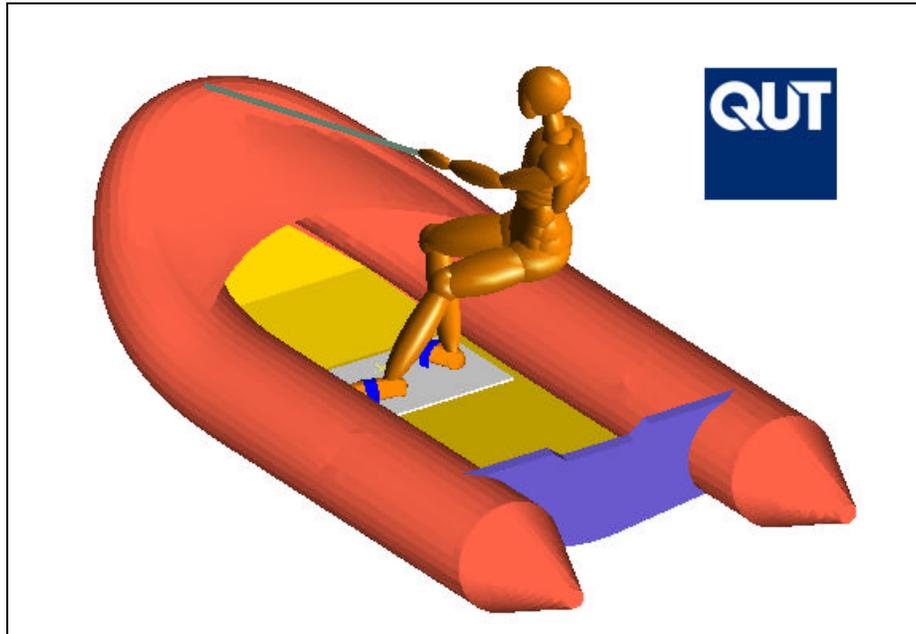
Figure 7: 3-D Mathematical Model of the Hybrid III Dummy Crewing an IRB

5.5   Summary

In conclusion, this project has demonstrated the capabilities and limitations of MADYMO for the evaluation of occupant injury in roadside barrier design. Rigid body simulations could be successfully computed, and occupant injury criteria could be calculated by the software for the Hybrid III anthropomorphic dummy. Finite element representations of a standard test vehicle (Ford Taurus) and a concrete barrier could not be fully realised due to the limitations in the finite element module of MADYMO. Future work in this area should focus on alternative software programs, such as LS-DYNA, for the investigation and preliminary evaluation of roadside hardware.

6   REFERENCES

AS/NZS 3845:1999 'Road safety barrier systems'. Standards Australia.

ADVEA Engineering Pty. Ltd., 7 Calderwood Avenue, Wheelers Hill, VIC 3150, Australia.
Contact: Prof Josef A. Tomas, Managing Director.
Phone: +61 3 9561 4054, Fax: +61 3 9562 5530 http://www.advea.com

Bedewi PG and Bedewi NE 'Modeling of occupant biomechanics with emphasis on the analysis of lower extremity injuries', http://www.ncac.gwu.edu/archives/papers/lower/lower.html

Brach RM and Brach RM (1983) 'A review of impact models for vehicle collision'. SAE Paper 830468.

Campbell KL (1974) 'Energy basis for collision severity', SAE Paper 740565.

Duncan C, Corben B, Truedsson N and Tingvall C (2000) 'Motorcycle and safety barrier crash-testing: Feasibility study'. Report CR 201. Australian Transport Safety Bureau, Department of Transport and Regional Services. Canberra, Australia.

Easi Engineering http://www.easiusa.com/

Eskandarian A, Marzougui D, Gaith A and Bedewi NE (1995) 'Computer simulation of roadside hardware using LS-DYNA3D'. Presented at the International IEMS Conference, Cocoa Beach, FL, 1995.

FHWA/NHTSA National Crash Analysis Center at George Washington University (2000) 'Public Finite Element Model Archive'. http://www.ncac.gwu.edu/archives/model/

Formicola J (2001) 'MADYMO helps optimize integrated car seat'. Hoff & Associates. http://www.hoff.com/study2.html

Grzebieta R, Koay K and Zou R (1999) 'Road-side crash barriers – Can they be modelled?' 1999 MADYMO Users' Meeting, Sydney, Australia.

Huang Y, King AI, Cavanaugh, JM (1994) 'MADYMO model of near-side human occupants in side impacts', J of Biomechanical Engineering, Transactions of the ASME, 116(2):228-35.

Kerkoff JF, Husher SE and Varat MS (1993) 'An investigation into vehicle frontal impact stiffness, BEV and repeated testing for reconstruction', SAE Paper 930899.

Langdon MG (1991) 'Simulation of side impact on cars', Proceedings of the Institution of Mechanical Engineers. Part D: Journal of Automobile Engineering, 205(2):101-8.

Livermore Software Technology Corporation (2001) 'LS-DYNA Applications'
http://www.ls-dyna.com/

Ludcke J (2001) 'Modelling of inflatable rescue boats (IRBs) in surf conditions to reduce injuries'. Current PhD project. Queensland University of Technology.

Lupker HA, de Coo PJA., Nieboer JJ and Wismans J (1991) 'Advances in MADYMO crash simulations, Side Impact Occupant Protection Technologies'. SAE Special Publications, February 1991, Pages 135-146.

Matsumoto H, Sakakida M and Kurimoto K (1990) 'Parametric evaluation of vehicle crash performance'. SAE Special Publications, February 1990, Pages 73-84 900465.

Navin F, MacNabb M and Miyasaki GW (1998) 'Elastic properties of selected vehicles', SAE Paper 880223.

National Research Council (1993) 'NCHRP Report 350 Recommended procedures for the safety performance evaluation of highway features'. National Academy Press, Washington, D.C.
Available at:
http://www4.nationalacademies.org/trb/crp.nsf/NCHRP+projects?OpenView&Start=20.10&Count=30&Expand=20#20

Neptune JA and Flynn JE (1998) 'A method for determining crush stiffness coefficients from offset frontal and side crash tests'. SAE Paper 980024

Neptune JA, Flynn JE, Underwood HW and Chavez PA (1995) 'Impact analysis based upon the CRASH3 damage algorithm'. SAE Paper 950358.

Ray MH and Carney III JF (1992) 'Side impact crash test and evaluation procedures for roadside structures crash tests'. Report No. FHWA-RD-92-062, Federal Highway Administration, McLean, V.A.

Ray MH (1997) 'The use of finite element analysis in roadside hardware design'. Int J Crashworthiness, 2(4).

Ray MH, Engstrand K, Plaxico CA and McGinnis RG (2001) 'Improvements to the Weak-Post W-Beam guardrail'. Transportation Research Record No. (in press), Paper No. 01-2282, Transportation Research Board, Washington, D.C., 2001.

Renfroe DA and Lafferty J (1998) 'Modelling of vehicle rollover and evaluation of occupant injury potential using MADYMO', SAE Paper 980021.

Sledge NH and Marshek KM (1998) 'vehicle critical speed formula-values for the coefficient of friction - A review', SAE Paper 971148.

TNO Automotive, Crash-Safety Centre, P.O. Box 6033, 2600 JA, Delft, The Netherlands.
http://www.automotive.tno.nl

TNO Automotive (1999) 'MADYMO Theory Manual Version 5.4'. TNO Automotive. Delft, The Netherlands.

Tominaga K, Yamaguchi S and Kizuki K (1996) 'Numerical analysis of side impact phenomena using MADYMO-3D DOT-SID dummy'. Proceedings of Stapp Car Crash Conference, November 1996, Pages 51-61

Wismans J, Griffioen JA and Nieboer J (1988) 'Use of MADYMO in general impact biomechanics', American Society of Mechanical Engineers, Bioengineering Division (Publication), BED, Volume 9, Pages 177-184

7   GLOSSARY

a$_p$ max Maximum acceleration of the pelvis.

ASI Acceleration Severity Index. As described in Appendix F, NCHRP Report 350.

Centre of Mass (CoM) Theoretical point within a test vehicle at which its total mass can be assumed to be concentrated.

Chest acceleration Maximum acceleration of the chest.

Exit Angle Angle between normal direction of traffic and path of test vehicle after interaction with the test article (e.g. longitudinal barrier). For roadside barrier evaluations, this is typically expected to be less than 60 percent of the impact angle.

Femur Force Maximum axial compression force transmitted through the upper legs.

Finite Element Model Geometric definition of (typically) a physical structure, which is represented by individual elements, arranged to form a mesh or grid. Each element is assigned material properties. Boundary conditions define the behaviour of elements on the periphery of the model. Loads are applied at the boundaries and the stress and strain at each element is determined. This process may be repeated at successive time intervals for dynamic events and loading patterns.

Flail Space Model Model in which a hypothetical occupant is permitted to move during impact.

GSI Gadd Severity Index. Used to assess the risk of potential injury (concussion) to a vehicle occupant based on the resultant linear acceleration of the centre of mass of the head. Maximum limits of 1000 and 1500 are typically used for contact and non-contact situations, respectively.

HIC Head Injury Criterion. Used to assess the risk of potential injury (concussion) to a vehicle occupant based on the resultant linear acceleration of the centre of mass of the head. Typically used to assess risk in hard contact situations. A time-averaging interval of 36 ms or 15 ms is used in the calculation of HIC.

Hybrid III Dummy An anthropomorphic dummy, representing the 50th percentile male, as per the specification of Part 572, Subpart E, Title 49 of the Code of Federal Regulations, Chapter V-(10-1-88 Edition).

Impact Angle Angle between normal direction of traffic and approach path of test vehicle into test article (e.g. longitudinal barrier).

PHD Post-Impact Head Deceleration. As described in Appendix F, NCHRP Report 350.

Rigid Body Model Representation of an object or structure that does not change shape due to applied loads. Contact forces may define the behaviour resulting from contact between two or more rigid bodies.

Sled Test Experimental test used to evaluate the effect of acceleration pulses on crash test dummies. Used as an alternative to full-scale car crash testing.

THIV Theoretical Head Impact Velocity. As described in Appendix F, NCHRP Report 350.