SIMULATION OF TRUCK REAR UNDERRUN BARRIER IMPACT

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ABSTRACT

Rear underrun crashes involving heavy vehicles with rear overhangs represent the most extreme examples of incompatibility between heavy vehicles and passenger cars. This type of crash often causes severe or fatal injuries to car occupants.

This paper describes the development of a three-dimensional MADYMO model simulating a car crashing first at 48km/h and then at 75 km/h into the rear of a truck with an energy-absorbing rear underrun barrier attached. The underrun barrier was designed to absorb part of the impact energy of the car and hence reduce the injuries of the car occupants. The collision was simulated in order to aid the design and analysis of energy-absorbing truck underrun barrier systems.

A Hybrid III 50th percentile male dummy was used to model the driver and to calculate the Head Injury Criterion (HIC), head resultant deceleration and the chest resultant deceleration. The vehicle deceleration pulse during impact, resultant forces in the barrier and in the tube-in-tube struts as well as the injury outcomes from the dummy, were first validated using laboratory crash tests carried out at a speed of 48 km/h [Rechnitzer et al 1996]. This model was then used to predict the vehicle deceleration, strut forces and injury outcomes for the 75-km/h crash. The simulation results show fairly good agreement with the crash test indicating that such models can be used at a relatively low cost to design crashworthy structures and investigate such injury prevention counter measures.

INTRODUCTION

Rear underrun crashes involving heavy vehicles often cause severe or fatal injuries to car occupants due to the mismatch in above all geometry and stiffness and then mass ratio [Grzebieta et al 2000]. Rear underrun crashes in Australia account for some 15 or so fatalities every year, and many hundreds are injured.

To overcome the aggressiveness of a heavy truck in a rear underrun crash and hence reduce the severity of injuries, both rigid and energy-absorbing rear underrun barrier systems such as those shown in Figures 1 & 2 have been studied since 1991 at Monash University (Rechnitzer et al 1991, 1996) for VicRoads and the former Federal Office of Road Safety (FORS and now known as the Australian Transport Safety Bureau (ATSB)). A series of crash tests were later carried out for FORS on a prototype energy absorbing rear underrun barrier fixed to a concrete wall as shown in Figure 3, and on a full scale heavy truck with an energy absorbing rear underrun barrier attached to it. However, crash tests are often costly and involve lengthy preparation. To reduce the cost and speed up the design process, a three-dimensional mathematical model simulating a vehicle crashing into an energy absorbing rear underrun barrier was developed using the MADYMO 3D multibody mathematical dynamic program (Zou et al 1997). The critical part of this MADYMO model necessitated obtaining a true contact characteristic of the front end of the vehicle. Due to lack of test data at the time the model was being constructed, the contact characteristic between the car and the barrier was determined based on a deceleration pulse of the vehicle crashing into a concrete wall. The stiffness in that case was over estimated. It is apparent that the contact characteristic should be determined based on the crash pulse of the vehicle crashing into the actual energy absorbing barrier so that a more accurate or realistic simulation of the crash test could be obtained. Thus the aim of this MADYMO simulation was to see if the contact characteristic determined from Figure 7 could be used to predict more accurately a subsequent crash test at 75km/h. This paper describes that study.

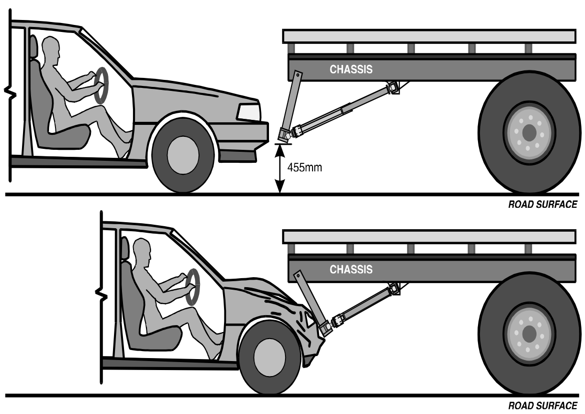


Figure 1. Illustration of the energy absorbing underrun barrier on the rear of a truck, before and after impact. [Rechnitzer et al 1996]

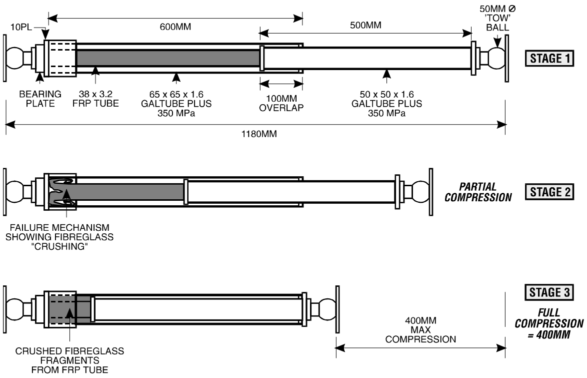


Figure 2. Schematic diagram of an energy absorbing tube-in-tube struts. [Rechnitzer et al 1996]

Figure 3. Photograph of a vehicle in a 48kph impact with an energy absorbing barrier. [Rechnitzer et al 1996]

MODEL DESCRIPTION

The MADYMO model was developed using the following findings from both the static load tests and the underrun crash tests.

- Bending of the barrier head (cross beam) is significant.
- No bending occurs in any energy absorbing unit, i.e. it is subject to a pure compression load only.
- Car and truck chassis come into contact, but their interactions are insignificant.
- Twisting of the underrun barrier is insignificant.

It is clear that the model which simulates a full scale truck underrun crash has to include all the following parts: an underrun barrier attached to a moveable truck, a vehicle model representing the passenger car and a Hybrid III dummy sitting in the car to calculate injury parameters. The model set-up is briefly discussed in the following sections.

Underrun Barrier Model

Because the bending of the barrier head was significant, it's bending stiffness had to be taken into account. Thus, the barrier head is modelled using three flexible beams as shown in Figure 4. An ellipsoid was attached to the middle beam, which is used to define the contact interaction between the barrier head and the car. Since the elongation and the torsion of the beam were not important in this model, they were eliminated by setting the area of the beam (AREA) and the torsional stiffness (I_{xx}) to zero. Beam dimensions and properties were calculated from the actual steel square hollow section being a 100x100x3.0 SHS. The specific beam properties used were, the density DENS=7800 kg/m^3, the area of cross-section MAREA=1.2E-3 m^2, Young's modulus E=2.1E11 Pa, Poisson's ratio NU=0.3, the bending moment of inertia of the cross-section around the y-axis and the z-axis $I_{yy}=I_{zz}$=1.77E-6 m^4.

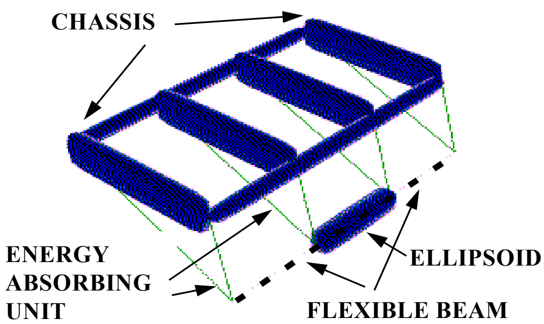


Figure 4. Energy absorbing underrun barrier model

The energy absorbing tube-in-tube units [Rechnitzer et al, 1996], which connect the barrier head and truck chassis, were modelled using Maxwell elements since they were subjected to pure compression only. The force-deformation curve was determined experimentally from the test data shown in Figure 5. To simplify the model, the idealised force-deformation curve for the energy absorbing module was adopted as shown in Figure 6. In the full scale crash model, the energy absorbing barrier was attached to the truck frame, which in turn was attached to a concrete wall.

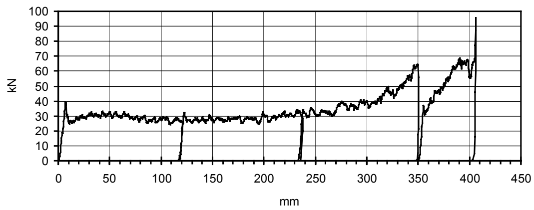


Figure 5. Force deformation curve for the static compression test of the energy absorbing unit

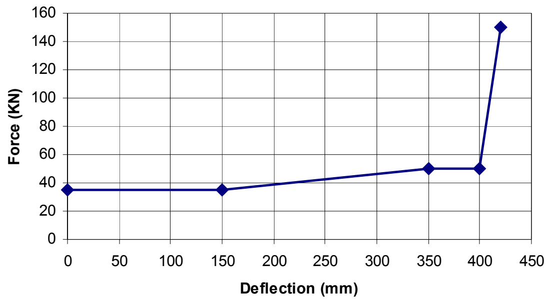


Figure 6. Idealised force deformation curve of the energy absorbing unit used for the MADYMO model

Vehicle Model

The vehicle model was built based on the frontal impact model of a MADYMO application known as a TNO sedan [TNO Automotive 1999]. An engine compartment and wheels were added to the model and some joints were modified to allow the vehicle to move. However, the stiffness and contact characteristic for the vehicle interior members such as the steering column, steering wheel, seat and knee bolster are virtually the same as used in the TNO sedan front impact model. Basically, the vehicle model was comprised of some key interior surfaces, a collapsible steering column system, a seat, and a three-point belt system. Interior surfaces were used for visualization and contact. The steering column and steering wheel were set up for occupant contacts. The column is collapsible and the stiffness given to the column allowed it to deform when loaded by the occupant. The seat was represented by planes, which attached to the vehicle. The belt model consisted of two parts, the conventional spring belt model and a finite element model. The part of the belt interacting with the dummy was made up of truss elements. As the ellipsoid-node contact model uses a proper implementation of contact friction, belt slip-off could occur. The part of the belt interacting with the vehicle was modelled with the standard belt model. This allowed the use of all the additional features such as slack or pretension.

In this application, the vehicle came into contact with the barrier head (cross-beam) during the underrun crash. Before the contact interaction between the two can be defined, the elastic contact characteristic of the vehicle's front end had to be determined. This characteristic becomes a physical property in the case of the underrun barrier crashes. Normally the contact characteristic is determined from a laboratory static compression test, but no such test data was available. Hence, a crash pulse, of an 1830kg sedan impacting an energy absorbing underrun barrier system at 48kph, was used instead to determine the contact characteristic. The crash pulse is shown in Figure 7.

The force-time curve as shown in Figure 8 was then derived from the crash pulse by using the formula $F = ma$, where m is the mass of the vehicle and a the deceleration pulse. By combining the force-time and the deformation-time data, the load-deformation curve of the car's front end was determined and is plotted in Figure 9.

It should be pointed out that to determine the deformation of the car's front end relative to the barrier head, the displacement of the barrier head was subtracted from the displacement of the car.

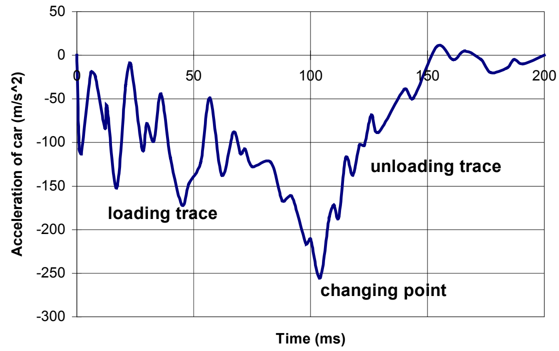


Figure 7. Crash pulse of an 1830kg sedan impacting an energy absorbing underrun barrier system at 48km/h

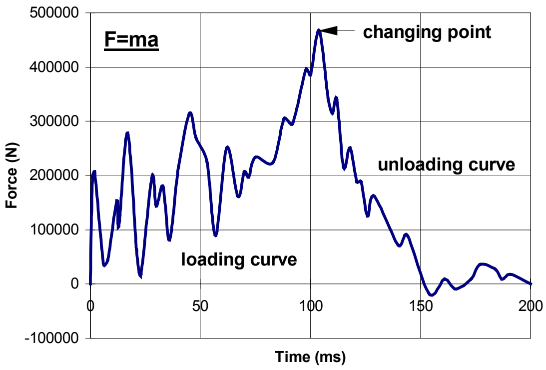


Figure 8. Force-time curve of the car's front end derived from the crash pulse shown in Figure 7.

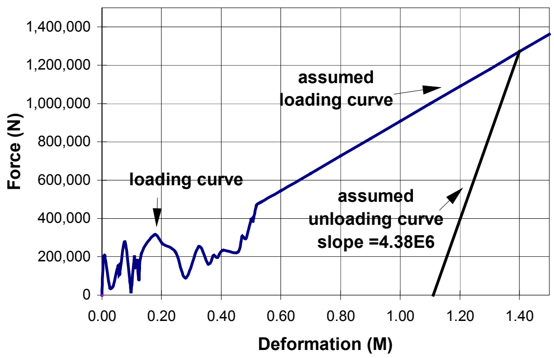


Figure 9. Load-deformation curve of the car's front end determined from the crash test data shown in Figures 7 & 8.

Dummy Model

A dummy model from the MADYMO database was used to calculate the injury parameters of the occupant. The dummy was a 50th percentile Hybrid III male seated in the vehicle restrained by a three-point belt system. Contacts were defined between the head and the steering wheel, the upper/lower torso and the seat/belt, the knee and the bolster and interactions were also modelled between the dummy parts. It should also be noted that the dummy used in this MADYMO model was not calibrated against dummy calibration test data measured for the crash test. Thus the injury outcomes resulting from this simulation were treated cautiously. The whole model set up which includes the Hybrid III driver, the vehicle, the underrun barrier and the truck is shown in Figure 10.

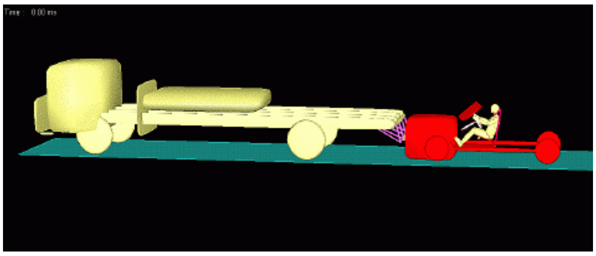


Figure 10. Model set-up

SIMULATION RESULTS – WITHOUT AIRBAG

The MADYMO model simulating a vehicle crashing into an energy absorbing underrun barrier was firstly validated using data from yet another second crash test (Rechnitzer et al, 1996 & 2001). The second test involved a 1700kg mass vehicle impacting an energy absorbing barrier system fixed to a concrete wall also at a velocity of 48kph. Finally the MADYMO model developed on the basis of the crash pulse of Figure 7 was again used to predict the crash behaviour of a third subsequent test, a 1350kg sedan impacting at 75 km/h into the energy absorbing rear underrun barrier system fitted to a 9100kg truck (Figure 10).

Figure 11 shows the kinematics of the vehicle and the Hybrid III dummy during the impact. From 0 to 90 ms, the vehicle's front end crushes into the underrun barrier and forces the barrier to compress. At approximately 60 ms after impact, the four energy absorbing units of the underrun barrier are fully compressed. The Hybrid III dummy slides forward and the head/neck bends forward immediately after impact. At approximately 80 ms after impact, seat belts start pulling the upper torso back and the hands start to lift up. At approximately 90 ms, the vehicle stops and starts to rebound. The vehicle continues to rebound after 90 ms and separates from the barrier at approximately 200 ms after impact and the dummy's upper torso continues to be pulled back and the hands continue to lift up.

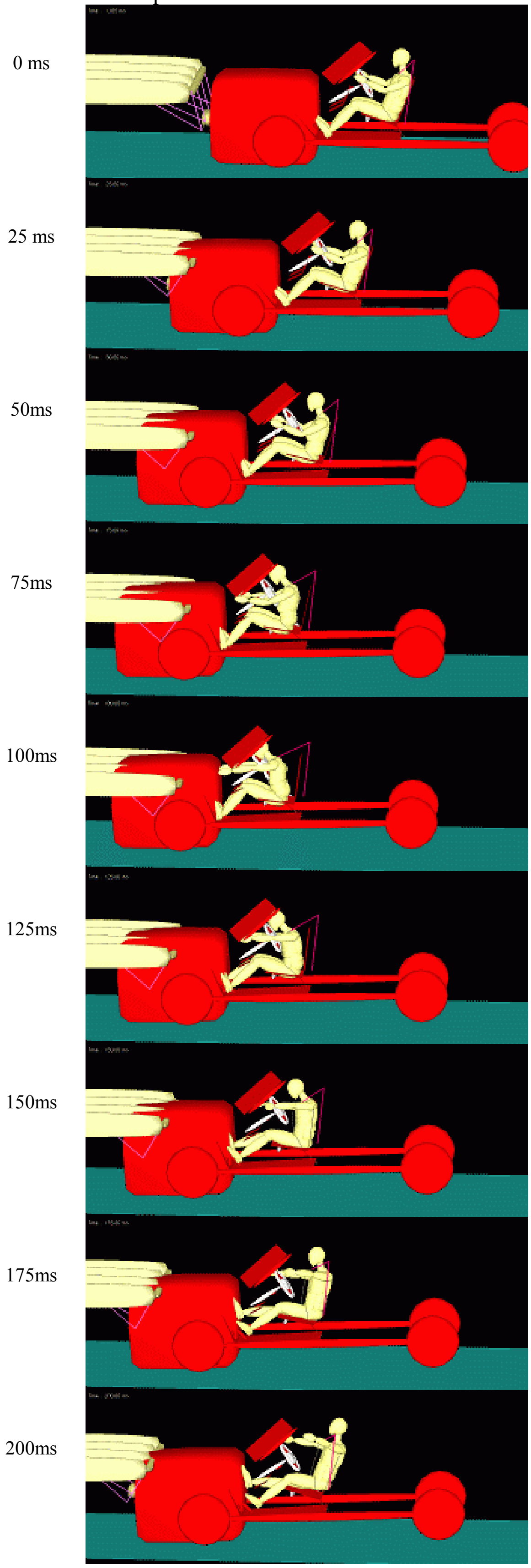


Figure 11. Kinematics of the 1350kg sedan impacting an energy absorbing underrun barrier system fitted to a 9.1 tonne truck at 75km/h.

By reviewing the high speed video of the full scale crash test, it was found that the kinematics of the simulation results agreed well with the test.

The car crash pulse from the MADYMO simulation is shown in Figure 12 and is compared with the crash test carried out at the Autoliv Test Centre in Melbourne Australia. Apart from the timing difference, where in the simulation the peak acceleration was reached at 75ms whereas in the test the peak was reached at 50ms, there is in general good agreement with the test. The peak deceleration in the simulation is 41g compared with 40g in the test. The pulse duration for the simulation is 120ms compared with 130ms for the test.

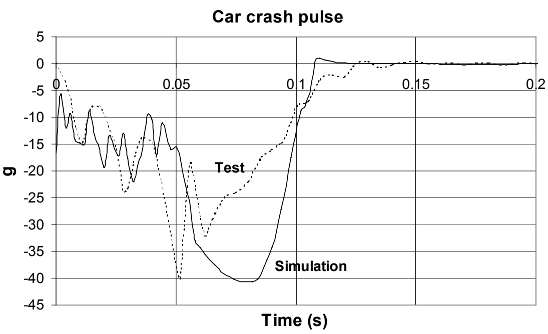


Figure 12. Car crash pulse for the 1350kg sedan impacting at 75km/h into the energy absorbing rear underrun barrier system fitted to a 9.1 tonne truck.

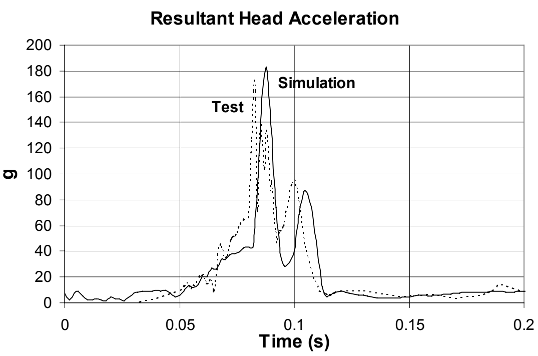
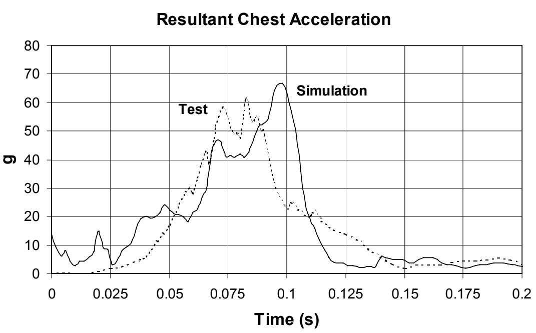


Figure 13: Simulation compared with test results for resultant head and chest acceleration for the



Hybrid III dummy (Driver).

Similarly, the head resultant acceleration and chest resultant acceleration from the MADYMO simulation shown in Figure 13, compared well with those of the test. In particular, the simulation predicted a peak head resultant acceleration of 182g and a chest acceleration of 67g, compared with the test result of 173g and 61g, respectively.

Table 1 shows a summary of the major simulation results for the barrier forces and the vehicle resultant deceleration. They agree fairly well with the crash test. The resultant force on the car/barrier of 542 kN obtained from the MADYMO simulation compared very closely to 529 kN obtained from the crash test. The total force on the energy absorbing struts (modelled using Maxwell elements) of 474kN from the simulation compared reasonably to the total of 500kN measured from the crash test.

Table 2 shows the injury parameters. As mentioned earlier, these values should be read with caution because the MADYMO simulation dummy was not calibrated against pre-test calibration data from Sydney's Crashlab. The results, however, are in reasonable agreement between the simulation and the test although the values for the simulation are generally higher than those for the test. The high left femur load in the test could have been due to contact that was not modelled in the MADYMO simulation. Both the test and simulation resulted in a high HIC value, well above the critical value of 1000, which indicates the driver is unlikely to survive such an accident.

Table 1.
Summary of key results for MADYMO simulation and comparison with the crash test of a 1350g mass vehicle impacting at 75km/h.

	Madymo Simulation	Crash Test
Car (CG) Result Deceleration	41 G	40 G
Resultant car-barrier force	542kN	529kN
Total peak strut force (4 struts)	474kN	500kN

Table 2.
Injury outcomes from the MADYMO simulation compared with the crash test – without airbag

	Madymo Simulation	Crash Test
Head Injury (HIC 36) - Critical value 1000	1913	1842
Chest Injury (3ms clip) - Critical value 60g	62g	56g
Max. Femur compressive load (kN)	Left 1.2 Right 2.1	14 4.1

SIMULATION RESULTS – WITH AIRBAG

In order to determine if the 75km/h impact into the rear of the 9.1 tonne truck equipped with energy absorbing underrun barrier is survivable when the passenger car is equipped with an airbag, an airbag model was added to the vehicle and the crash simulation was carried out again. Injuries for the Hybrid III driver were again calculated and presented in Table 3. The HIC value reduced to 869 in comparison with the non-airbag vehicle where HIC was 1913. The 3ms chest deceleration also reduced to 52g. Hence a driver may survive such a crash if the vehicle were equipped with an airbag.

Table 3.
Injury outcomes from the MADYMO simulation for an airbag equipped 1350kg sedan impacting an energy absorbing underrun barrier system fitted to a 9.1 tonne truck at 75km/h.

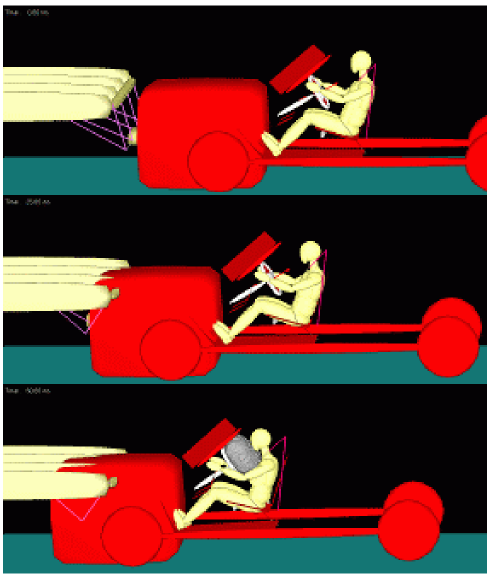
	MADYMO Simulation With airbag
Head Injury (HIC 36) - Critical value 1000	869
Chest Injury (3ms) - Critical value 60g	52g
Max. Femur compressive load (kN)	Left 1.2 Right 2.1

Figure 12 shows the kinematics of the hybrid III driver in an airbag equipped 1350kg sedan during the crash. The kinematic sequence is similar to the non-airbag equipped sedan crash shown in Figure 11. However, in the case of the airbag-equipped vehicle, the airbag prevented the head directly contacting the steering wheel. The airbag also reduced the impact severity to the chest.

0 ms

25 ms

50ms



75ms

100ms

125ms

150ms

175ms

200ms

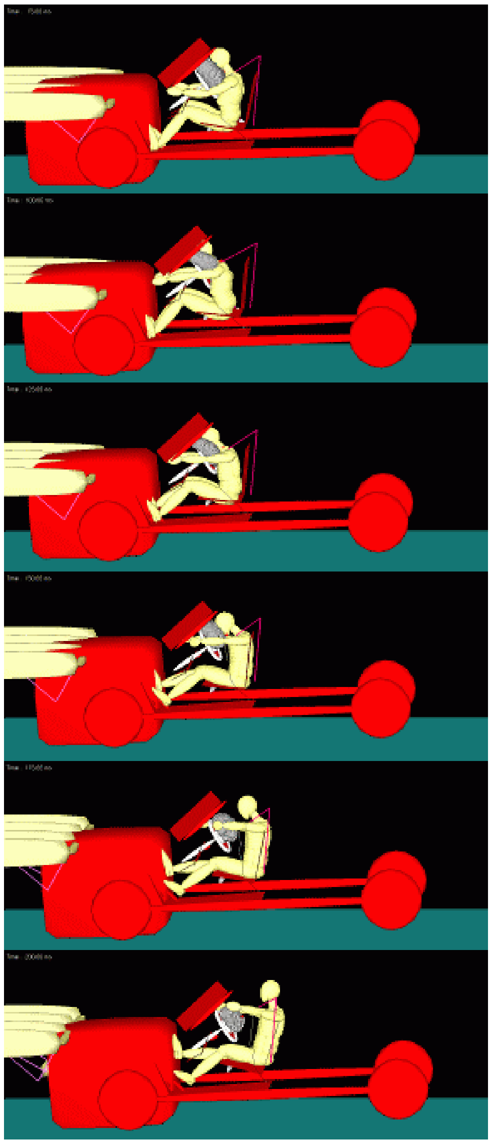


Figure 12. Kinematics of an airbag equipped 1350kg sedan impacting an energy absorbing underrun barrier system fitted to a 9.1 tonne truck at 75km/h.

CONCLUSIONS

A three-dimensional mathematical model for simulating a light vehicle crashing into an energy absorbing truck underrun barrier was developed using a 3D multibody model. The results of the computer simulation show good agreement with crash tests in terms of the crash pulse, the kinematics of the vehicle and the resultant forces in the energy absorbing struts (modelled using Maxwell elements). This means that on the basis of data obtained from an initial crash test, MADYMO can be used to predict subsequent crash tests where minor variations to the underrun barrier system can be investigated.

A deceleration crash pulse is a crucial measurement in judging whether an energy absorbing underrun barrier is effectively designed, i.e. whether the system can offer the best protection for vehicle occupants. Although the MADYMO simulation described in this paper is a simplified mathematical model, it can be used to estimate some of the important parameters such as the resultant barrier force and forces in the energy absorbing units in the design of effective energy absorbing underrun barriers.

ACKNOWLEDGMENTS

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