TEST AND SIMULATION TOOLS IN A ROLLOVER PROTECTION DEVELOPMENT PROCESS

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ABSTRACT

In 2003, rollover accidents caused more than 10.000 fatalities and 229.000 injuries in the US alone. In view of this statistic and in order to provide a better occupant protection, the interest in the behavior of the vehicle structure and passive restraint systems under rollover loads is continuously growing.

In order to ensure a realistic reconstruction of the vehicle behavior in development tests, four new different test setups have been elaborated according to accident analysis results. For the restraint system development, knowledge about the borderline between roll and no roll is essential. To save expensive prototypes, this borderline is determined before performing first tests by using numerical simulations. The test and simulation tools support a comprehensive development process, which allow the adaptation and optimization of protection systems for rollover.

One key component of the restraint system is the algorithm, which has the task of rollover accident detection and determination of the optimal system activation time. For the latter task, knowledge about real occupant movement is essential. The low acceleration and rotation rates over a long period, which occur during some rollover constellations, lead to considerable movement deviations between the test dummy and the human. The firing time therefore, based on the dummy movements can only be determined approximately. Great optimization potential exists for activation algorithms which are adapted to humans. This adaptation is possible with a new developed simulation tool, which takes the possible muscle work of the human against occurring rollover loads into account. It determines the occupant movement during a rollover and has been validated to the human behavior by sled tests.

INTRODUCTION

The American traffic accident statistics, which is publicized by the National Highway Traffic Safety Administration (NHTSA) included for the year 2003 more than 6.3 million police reported motor vehicle crashes that occurred in the United States. More then 42,000 people lost their lives and nearly 2.9 million people were injured in motor vehicle crashes.

In these so called traffic safety facts the rollover accident is a separate category. For the year 2003 nearly 3 % of all passenger vehicles in crashes were rollover events (see Figure 1). This represents a minority in regard to the overall accident details.

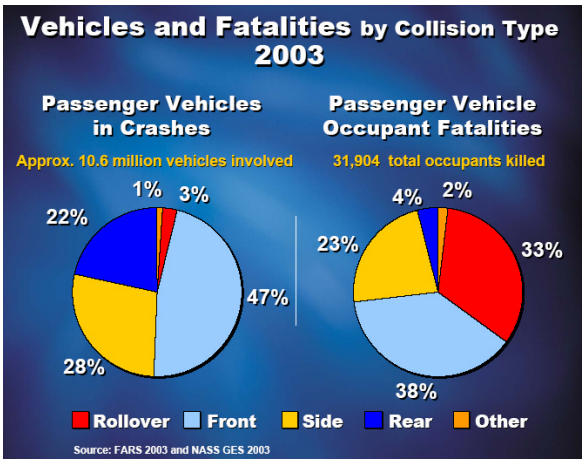

Figure 1. Vehicles and fatalities by collision type 2003

An other impression comes up by looking at the fatalities that occurred in crash events. Here the rollover is on the 2nd grade with nearly 33 % (see Figure 1) and the violence of rollover events is discernable.

In order to protect the occupants in rollover crashes in a better manner, passive safety elements like belt pretensioner and curtain airbags have to be activated in occurrence of such an event. The use of pretensioners help to retain the belted passengers in their seats and the activation of curtain airbags cushions the impacts of the head with interior parts, external environmental objects and prevent partial or full occupant ejection.

For the integration of passive safety elements in occupant protection the algorithm is one key point.

Here full scale rollover crash tests provide information about the sensor signals and the requested trigger time for the activation of these pyrotechnical protection devices under rollover loads. The test results are also useful to analyze the compartment intrusion and damage to the structure, which might occur.

Supplemental to the full scale tests, numerical simulation is a perfect development tool to consider the enormous number of possible rollover constellations and to figure out the borderline between roll and no roll events. This helps to save expensive prototypes during the development. In a further step numerical simulation can help to consider the real human movement behavior in some critical rollover constellations to prevent misuse cases and to optimize the firing time for the occupants.

TESTS DUMMIES

The rollover presents a new area in passive safety development. This explains why an anthropometric test dummy does not yet exist for rollover load cases. Pertaining to this, modifications to existing dummies or the development of new dummies in the near future have not been planned. This applies to Europe as well as to the US. For performing hardware tests an existing test dummy had to be chosen which has been developed for frontal, rear or lateral impact loading cases.

The crash tests, which are presented in this paper, are carried out with the EuroSID. An exception is the FMVSS 208 rollover test. Here the Hybrid III 50% dummy is specified by the corresponding directive. The EuroSID is a lateral impact dummy which is specified in the 96/27/EG directive for the protection of motor vehicle occupants.

The lateral impact dummy was chosen because 97 % of rollover accidents that happen in the field are rolling over the vehicle's x axis. Only 3% of rollover accidents are so-called pitch-over cases which are also described as end over end cases. These involve rolling over the vehicle's Y axis. Due to this distinct split it becomes clear that the area of application for the anthropometric test dummy is rather lateral than frontal.

A further point making the case for the EuroSID is it's availability due to it being laid down in the 96/27/EG directive. New developments in the dummy sector such as THOR or the World-SID are rare and currently not available in the testing labs. This is also the case for the Bio-SID. It is admittedly older but is mostly just used for development purposes.

A further argument supporting the choice of the EuroSID is his reproducibility. This goes hand in hand with the calibration of a dummy. All test dummies for frontal impact, for example the Hybrid III dummy, are exclusively calibrated for this loading case only. This explains why it's reproducibility laterally can not be determined, due to the lack of a calibration method in this direction.

Due to the high frequency of head injuries from rollover accidents, reproducibility should be particularly paid attention to in this body area (see Figure 2).

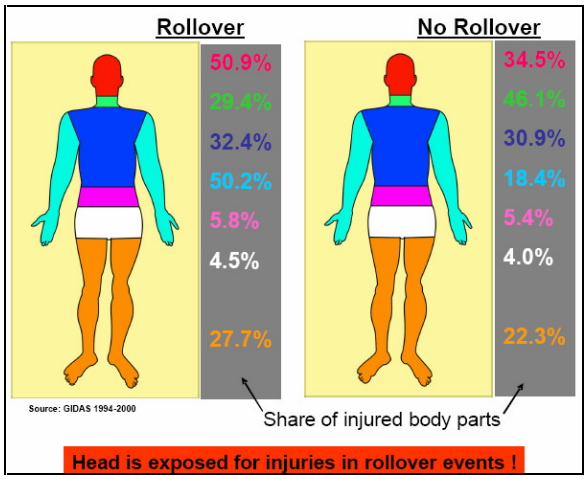

Figure 2. Injuries in roll/ no roll events [3]

This is the reason why the US-SID was not selected as a rollover dummy for hardware tests. The head and neck of the US-SID are not calibrated. Reproducibility of the head accelerations therefore and also of the neck-head kinematics is not possible.

The biofidelity, which describes the behavior similar to humans, is restricted with all anthropometric test dummies and has already been examined in many studies, for example by Professor Kallieris [1] from University of Heidelberg, to analyze the differences between anthropometric test dummies and humans.

Biofidelity of new developments on the dummy sector has certainly improved in comparison to older test dummies. However, these dummies have not been thoroughly investigated and the availability already discussed, is not adequately given.

Generally speaking, the test dummies developed for frontal impact react very stiff, particularly the neck-

head areas under lateral loads. The US-SID and the Bio-SID were developed for lateral loads. However they use components in the neck-head area from dummies which have been configured for frontal loading cases. This explains, why the neck-head area is very stiff, even with both lateral impact dummy representatives. In this case the EuroSID is an exception. The neck-head area consists of a construction which is more flexible. Due to this the EuroSID does not show the stiffness of the other anthropometric test dummies described.

TESTS TOOLS

The following description of the different test set ups, represents an overview of the tests that have been developed by Siemens Restraint Systems together with other suppliers and OEMs.

The field relevance for the laboratory tests was assessed in a study from C. Parenteau [2] for the US by using field data from the National Accident Sampling System-Crashworthiness Data System (NASS-CDS) from 1992-1996.

The NASS-CDS consists of police reported tow-away traffic crashes in the US and defines different initiation types for rollover. The definition includes trip-over, fall-over, flip-over, turn-over, end-over-end, climb-over and bounce-over (see Figure 3).

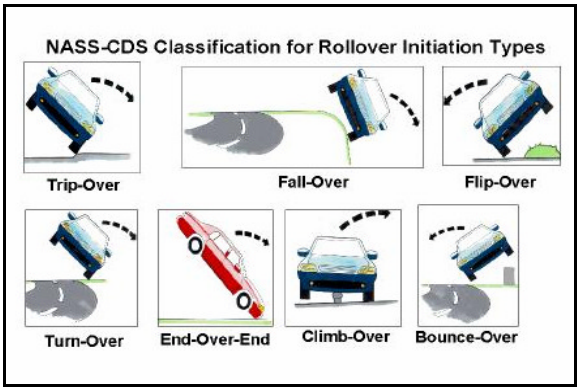

Figure 3. NASS classification for rollover initiation types

The **soil-trip** rollover is a lateral movement of the car into a sand bed. The car is placed on a flying floor and slides laterally into the sand after a sharp deceleration of the sled with deformation tubes (see Figure 4).

This test induces a fast occupant movement, which requested an early firing time. The lateral acceleration is in a middle range over a long period. The roll conditions of the test car varied with the adjusted velocity and the used soil.

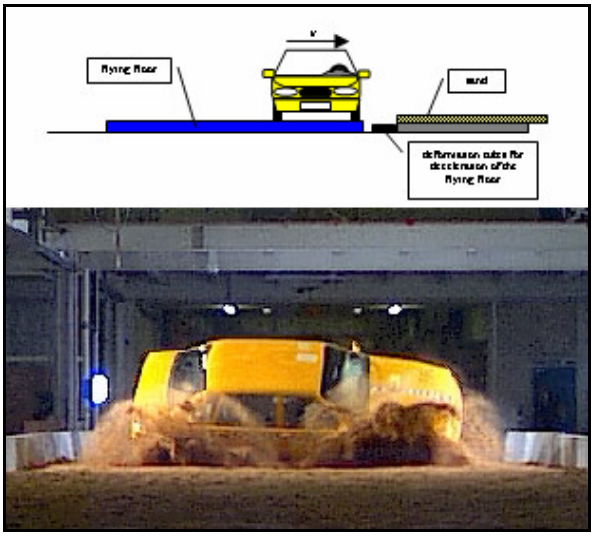

Figure 4. Soil-trip rollover test set up

In the US, the soil-trip represents 91 % of the trip-overs in the field for passenger cars and 93 % for LTVs (light truck vehicle). With this the soil-trip test covers nearly 52 % of the rollover crashes for passenger cars in the field and nearly 48 % for LTVs.

A study from Siemens Restraint Systems and the medical university of Hannover concerning rollover accidents in Germany between 1994 and 2000 shows the same result [3]. In this study 6713 passenger vehicle crashes were analyzed from the German In-Depth Data Accident Study (GIDAS).

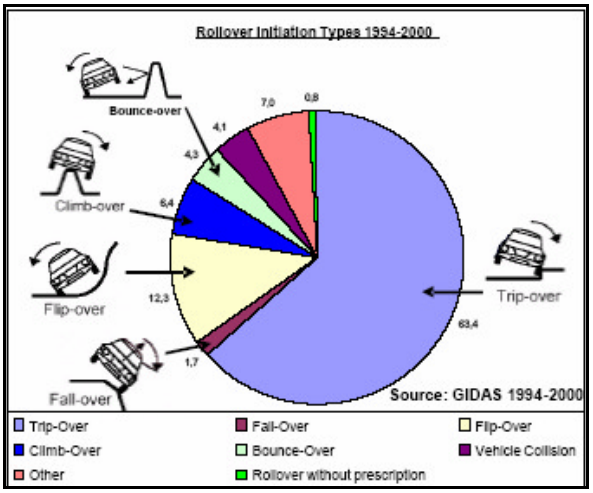

Figure 5. GIDAS Rollover initiation Types 1994-2000

4.2 % of the involved passenger vehicles rolled over. The distribution of the rollover initiation types in this study states the trip-over as the most frequent reason for rollover in Germany (see Figure 5).

In the **embankment** rollover test the vehicle is leaving the crash track and drives on a slightly declined slope of a ditch (see Figure 6). The surface of the slope is sand to enable a lateral sliding of the car. Different approach angles and slope angles can be adjusted in this test set up. Also steering can be considered, which is necessary in some cases to ensure rolling over.

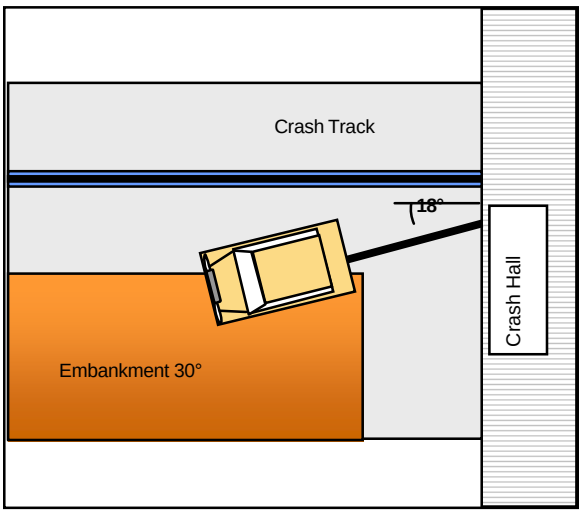

Figure 6. Embankment rollover test set up

This test induces a slow occupant movement, which requested a relatively late deployment time. The lateral acceleration is in a lower range. The roll conditions of the test car vary with the adjusted velocity, approach angle, slope angle and steering actuation.

The field relevance for this laboratory test was assessed for the US with 100 % of the fall-overs in the field for passenger cars and LTVs. With this the embankment test covers nearly 13 % of the rollover crashes for passenger cars in the field and nearly 15 % for LTVs.

For Germany the embankment test plays not such a significant role, because fall-overs are less frequent in the field, with 1.7 % of all rollover events in the years 1994 - 2000.

The **ramp** rollover test is performed on the crash track. During the test, the vehicle drives with one side of the car over a ramp (see Figure 7). Different ramp types are used to realize roll and no roll events (see Figure 8).

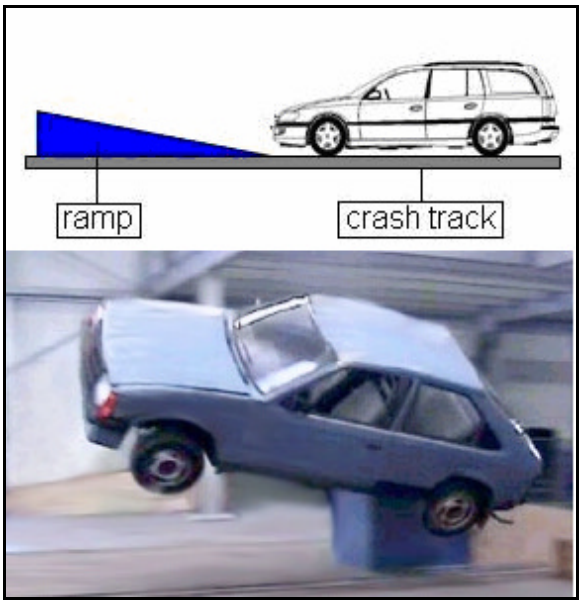

Figure 7. Ramp rollover test set up

This test induces a fast occupant movement, which requests an early deployment time. The lateral acceleration is in a middle range. The roll conditions of the test car vary with the adjusted velocity and used ramp type.

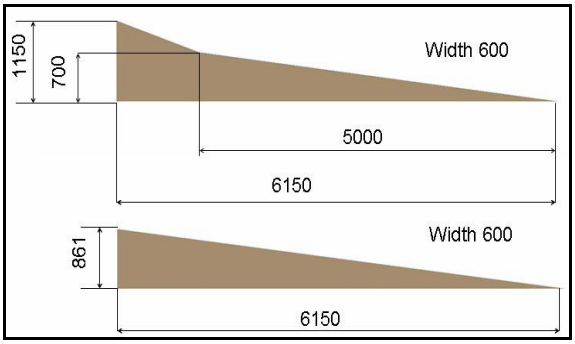

Figure 8. Different ramp types

The field relevance for this laboratory test was assessed for the US with 83 % of the flip-overs in the field for passenger cars and 74 % for LTVs. With this, the embankment test covers nearly 10 % of the rollover crashes for passenger cars in the field and nearly 5 % for LTVs.

For Germany the ramp test plays a more significant role, because flip-overs are more frequent in the rollover accident field, with 12.3 % of all rollover events in the years 1994 - 2000.

The **curb-trip** rollover test has only a lateral movement. The test car is placed on a flying floor and hits laterally against a curb with the wheel rims. The height of the curb depends on the wheel size. After the impact between the wheel rims and the curb, the sled is decelerated by deformation tubes without influence on the car movement (see Figure 9).

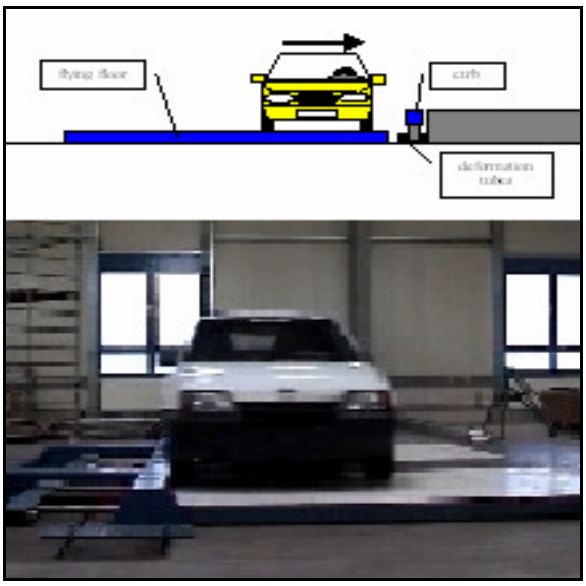

Figure 9. Curb-trip rollover test set up

This test induces a rapid occupant movement, which requests an early deployment time. The lateral acceleration is in a higher range. The roll conditions of the test car vary with the adjusted velocity and used curb high.

The field relevance for this laboratory test was assessed for the US with 51 % of the bounce-overs in the field for passenger cars and 47 % for LTVs. Additional the curb-trip test was assessed for the U.S. with 8 % of the trip-overs in the field for passenger cars and 6 % for LTVs. With this the curb-trip test covers nearly 9 % of the rollover crashes for passenger cars in the field and nearly 7 % for LTVs.

For Germany the curb-trip test plays also a significant role. Although bounce-overs are less prevalent in Germany, with 4.3 % of all rollover events in the years 1994 - 2000, trip-overs are more frequent in the rollover accident field in Germany, with 63.4 % of all rollover events in the years 1994 - 2000.

For the **FMVSS 208 rollover** test the car is placed on a sled inclined under 23°, which is moved laterally (see Figure 10). The test velocity is 30 mph. After a sharp deceleration of the dolly with deformation tubes, the car is thrown off the sled under high roll conditions around the longitudinal axis of the car.

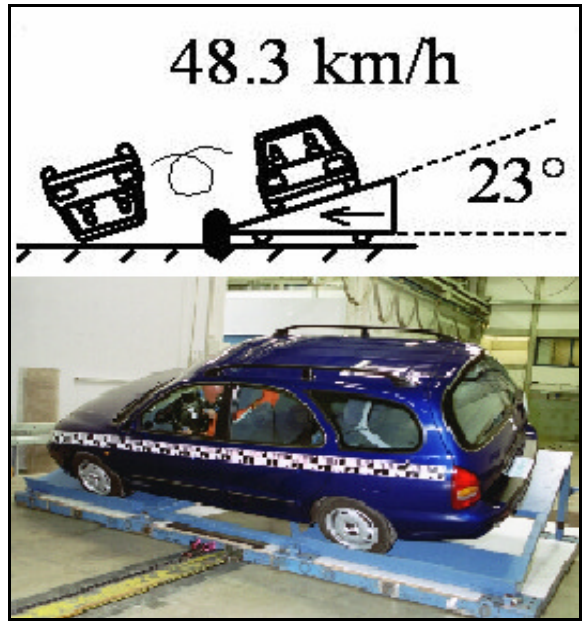

Figure 10. FMVSS 208 rollover test set up

This test is used to analyze the behavior of the vehicle structure under rollover loads and here especially the remaining survival space for the occupants.

The field relevance for this laboratory test is very low. This statement is valid for passenger cars and LTVs in USA and Germany.

As well, different **misuses** rollover tests are performed on a proving ground or in the laboratory.

Figure 11. Proving ground for rollover misuse tests

The tests are implemented to avoid inadvertent activation of the pyrotechnical protection devices and to increase the robustness of the rollover algorithm (see Figure 11).

Tests for rollover misuse typically include up and down hill driving, hill jumping, slalom, elk test, U-turn, figure eight and sliding. Results of misuse programs from lateral and frontal applications like curb impact or washboard track will be considered for the rollover algorithm, too.

SIMULATION TOOLS

For the protection of the occupants in rollover events roll bars, belt pretensioners and the curtain airbags have to be activated in order to retain the belted passengers in their seats, to cushion the impacts of the head and to prevent partial or full ejection. The key component for activating these pyrotechnical protection devices is the algorithm. The algorithm has to determine the system activation time in cases of rollover event detection. The system activation time is defined as the Requested Time To Fire (RTTF). The RTTF is determined through the time, when the head of the occupants penetrates the space, which is necessary for the curtain airbag deployment. This information is provided by rollover crash tests and will be supported by numerical simulation with ADAMS and MADYMO.

The rollover protection development process contains the crash and misuse tests and the simulation. (see Figure 12).

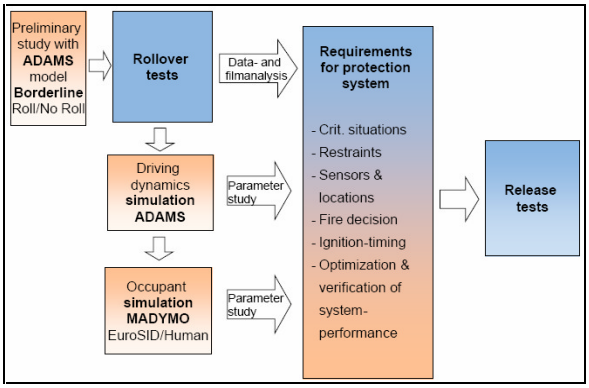

Figure 12. Rollover protection development process

Here ADAMS is used for the simulation of the vehicle dynamics, while MADYMO is used for the prediction of the RTTF.

ADAMS is an adequate software tool to simulate vehicle dynamics. The different test set ups for rollover like ramp, soil-trip, embankment and curb-trip were generated in ADAMS as road models for simulation (see Figure 13).

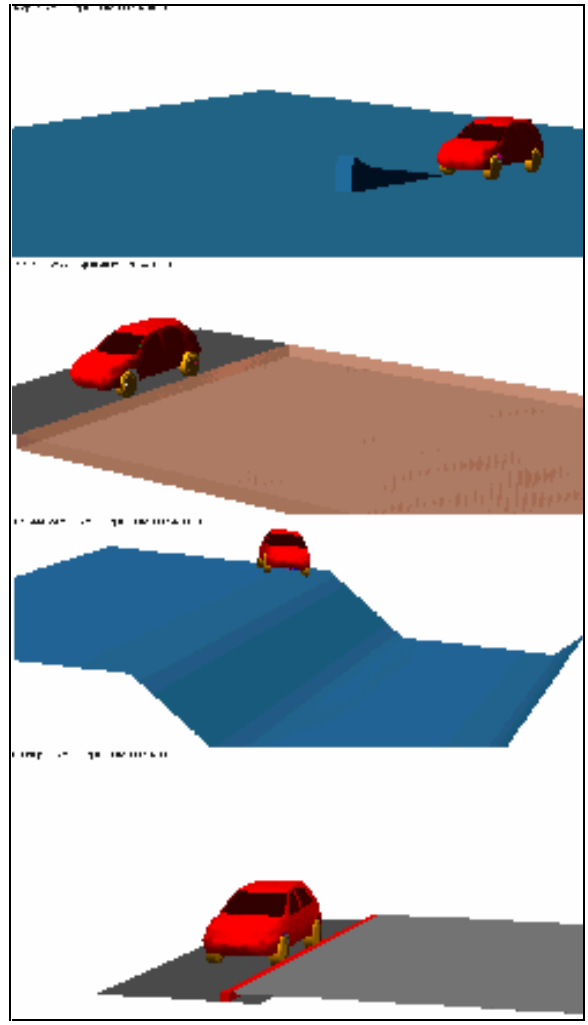

Figure 13. ADAMS road models; above: embankment, middle: ramp, down: curb-trip

Also some misuse rollover tests are simulated with ADAMS like lane change and slalom.

In the beginning, ADAMS simulation is used to restrict the borderline between roll and no roll for the baseline crash tests in a preliminary study. For this first step, a car model is used, which is validated against all available test data in this development stage e.g. driving tests.

The data of the performed rollover crash tests will then be used to validate the ADAMS models for rollover (see Figure 14).

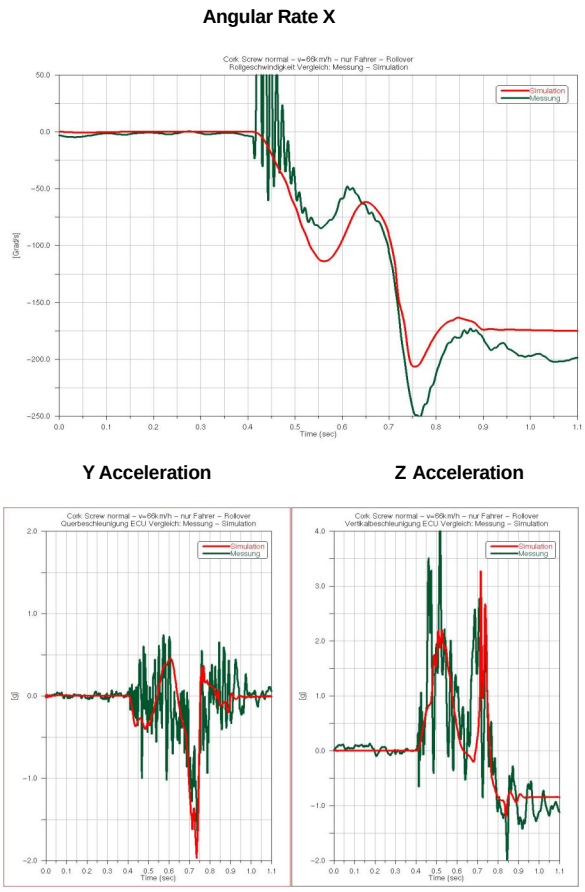

Figure 14. Validation of ADAMS against rollover crash test

After validating these models a parameter study will be performed in ADAMS. Here e.g. different car loads, different ramp geometries, different velocities, different approach and slope angles are considered.

The outputs of every ADAMS simulation run are e.g. accelerations, displacements and angles in X, Y and Z direction for a specific point in the car. The result of the parameter study with ADAMS represents the basis for the MADYMO simulation.

For the **MADYMO simulation** a model of the specific passenger compartment has to be generated. Usually this is done with CAD data, which is provided by the car manufacturer. In the compartment model different contact characteristics for door trim, B-pillar trim and seats are considered, to represent the different stiffness of the interior.

The movements of the occupants are represented in the MADYMO simulation by using EuroSID dummy models. Typically the MADYMO model contains a driver and a passenger occupant (see Figure 15). The rear passengers on the second or third row can also be considered if necessary.

The movements of the simulation EuroSID dummy models are validated against the dummy movements in the performed rollover crash tests.

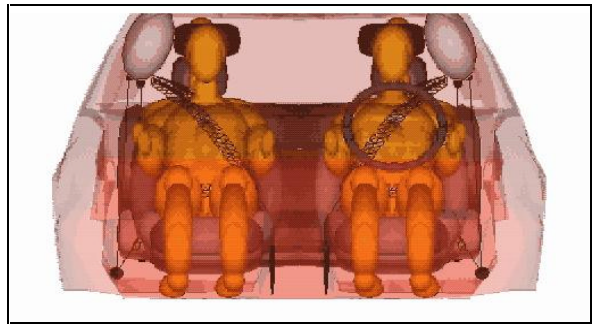

Figure 15. MADYMO model for driver and passenger

For the validation, the movement of head, neck and shoulder is considered to get the information for the RTTF. The MADYMO simulation enables to consider the occupant movements in far more possible rollover constellations, than in crash tests.

Critical rollover cases in regard to the dummy movements and the upcoming loads can be simulated with an **adapted dummy model** [4]. This dummy takes the possible muscle tension of human beings against the occurring rollover loads into account.

A critical situation is defined, when the dummy during a test permanently penetrates the necessary space for the curtain airbag deployment before the measured loads indicates a rollover. If, in the ongoing test, then a roll event is introduced by counter steer or tripping, the head of the occupant is Out of Position (OoP). Activating a state of the art curtain airbag, which deploys from the roof downwards, will keep the occupants head out of the car in this situation. This is the opposite of the intended effect of the curtain airbag and will lead to severe or fatal injuries for the involved occupants. This critical situation can occur in rollover cases with low acceleration and rotation loads, e.g. in embankment rollover tests.

The standard simulation dummy model maps only translational load directions. The rotational movement as it happens during a rollover is not considered. A dummy simulation model, which takes such a behavior into account, is not available at the moment. Therefore it is necessary to analyze the

difference between dummy and human movement behavior and to modify the standard simulation EuroSID dummy model in MADYMO for a better forecast of the human behavior during rollover situations.

In order to provide a basis for the simulation model a series of sled tests were performed with a bungee driven sled for translational and/or rotational movements with low accelerations. For the validation 5 different test constellations for dummy and volunteer were performed.

The performed tests contain pure translation or pure rotation or a combination of both (see Table 1). The pulses are a cutout from the acceleration curves of performed rollover crash and misuse tests.

Table 1.
Test constellations

Test No.	Specification
1	Pure translation
2	Pure rotation
3	Translation with following superposed rotation
4	Pure low translation (0,3 x test no. 1)
5	Rotation with following superposed translation

Because of the in section "test dummies" mentioned reasons an EuroSID dummy was used. For the comparability, a volunteer was chosen with a mass of 74.5 kg and a height of 1.78 m, which is very close to the dimensions of the EuroSID, which has a mass of 76 kg and a height of 1.75 m (see Figure 16).

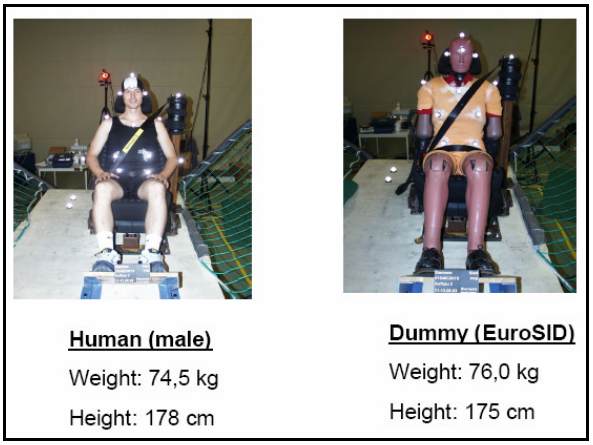

Figure 16. Test set up of the sled with dummy and volunteer

On the sled a seat, footrest and B-pillar with retractor and belt deflection point was mounted (see Figure 16). The belt pretensioner was not in use to avoid injuries on the volunteer.

The dummy and the volunteer have been marked on several points with targets for film analysis to compare the different movement behaviors (see Figure 17).

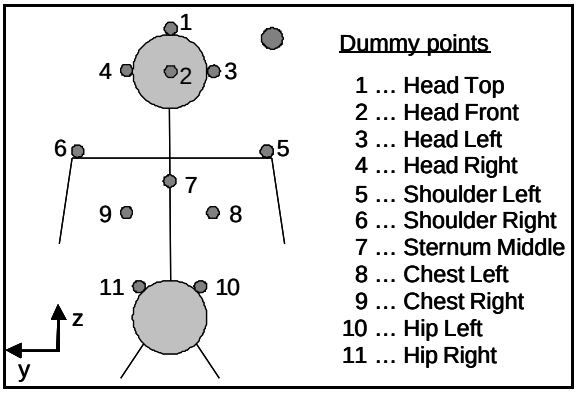

Figure 17. Position dummy target points for film analysis

In the comparison between dummy and volunteer, the differences in head movement behavior can be seen (see Figure 18).

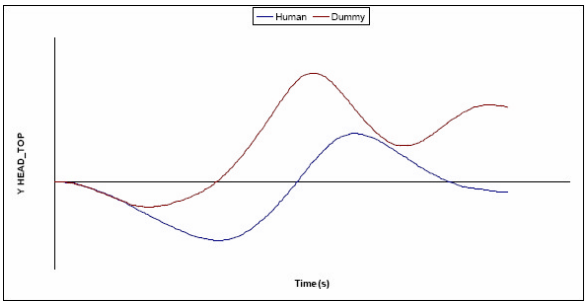

Figure 18. Head top displacement for dummy and volunteer during test number 5

The results of the volunteer tests show different behavior within a certain range of lateral loads. While the human being acts actively against his body displacement with muscle tension, this is impossible for the dummy.

Therefore the dummy is only beneficial for lateral loads, because the response regarding rotation of a vehicle is exclusively a result of the dummy inertia.

The volunteer reacts differently on translational and rotational movement. For pure translation the

volunteer is not able to resist against this motion. In case of rotation the volunteer reacts against this movement to keep the upper body and the head upright.

Major differences between human and dummy in lateral head displacement can be stated for low accelerations, low rotation rates and temporal long lasting loads, which occurs e.g. in embankment tests. Minor differences are realized for higher accelerations and rotation rates and temporal short lasting loads, which occurs e.g. in soil trip tests.

For the validation of the MADYMO model, the correlation of the points head top (1) and chest left (8) and right (9) had been used. The head targets are the main points to get information of the RTTF for human occupants, which are needed for activating the curtain airbag (see Figure 19).

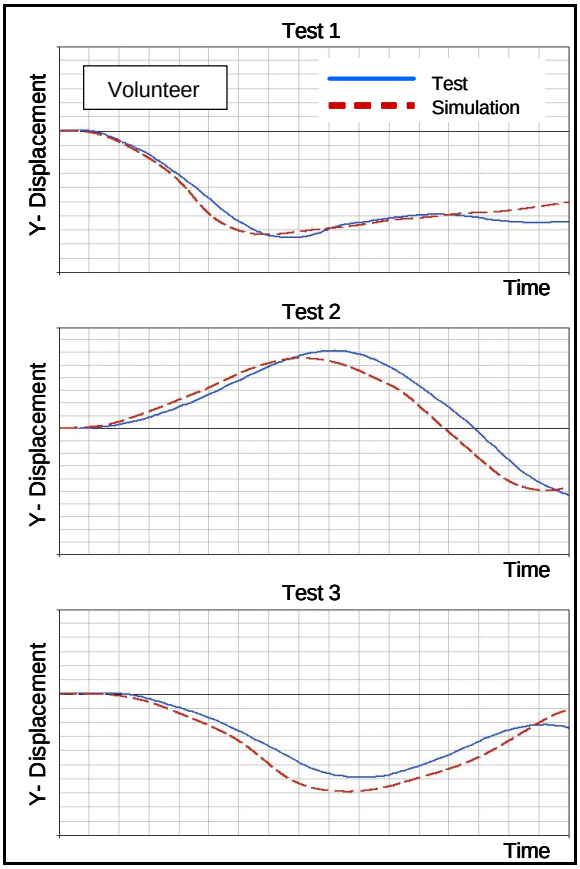

Figure 19. Head Top displacement curves for simulation model in comparison to the sled tests with volunteer

Due to the already mentioned active work against the body displacement, the head of the volunteer penetrates the deployment space for the curtain airbag distinctively later then the dummy. Therefore there is more time available for rollover sensing and curtain airbag deployment for human occupants (see Figure 20).

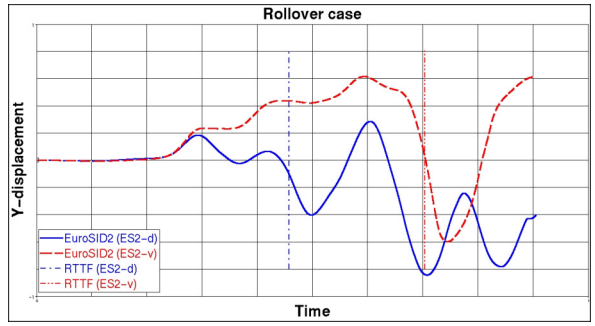

Figure 20. Head displacement and RTTF during rollover case

The positive effect of the active work on the RTTF depends on the input signals for rollover cases and is actually limited to the lateral loads which were reached during the tests. For rollover cases with high accelerations a shifting of the RTTF can not be observed.

For more information about this adapted dummy model see [4]

CONCLUSION

Rollover events often result in severe injuries or fatalities. Most often the heads of the occupants are affected. Therefore rollover detection and protection systems are focusing more and more. For the US some legal regulations are expected in the future. The first step is done by NHTSA with the rollover resistance rating for new cars. For a dynamic rollover crash test the soil-trip seems to be suitable because of the high field relevance of this test set up.

By using the presented test and simulation tools a comprehensive development process for rollover protection is possible. The adaptation and optimization of the protection systems for rollover events are considered in this process. Additionally the differences in movement behavior between human and dummy are considered to analyze critical situations and to provide the best possible rollover protection for the occupants together with high misuse performance simultaneously.

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