Annex I – Final Public Report

Content

1. Task 1.1: Statistical collection and literature review (GDV)

Scientific and technical description of the results

A detailed literature review with inclusion of the latest US publications on rollover accidents was performed. Data analysis shows, that for restrained occupants head, neck, and spine injuries caused by impacts with the upper vehicle interior account for 35% of the injury harm. Mitigating these injuries constitutes the largest opportunity for reducing rollover casualties among restrained occupants.

In most European countries the official accident statistics contain no information on rolling cars, only Great Britain can deliver official statistical data. Regarding other sources, only a few accident databases on rollover accidents exist. Focus in task 1.1 was especially on the GIDAS database for Germany, and CCIS database for Great Britain. More global information was provided by investigating databases from Spain. The estimations for the frequency of rollover accidents in Europe were 4-5% of all accident cases, and 15% of all fatal crashes. Half of the rollover accidents took place after an initial impact.

The statistics also address the differences between European and US rollover data. First of all, the vehicle fleets in Europe and in the US differ from each other. For instance, the US has significantly more SUVs, MPVs, Pick-ups and other vehicles with a high centre of gravity. Further differences can be found when considering the road environment, e.g. availability and type of barriers, road side objects, congestion levels, road surfaces, proximity of buildings. Moreover, the belt wearing rate in the US, particularly in those vehicles prone to rollover, is lower than in European countries. Finally, there are differences in legislation which affect vehicle design and/or driver behaviour.

Despite the difficulties in comparing US and European rollover data, following common observations could be made:

- Occupant ejection is an important factor, especially when serious injuries are considered
- The risk of injury increases substantially when occupants are unrestrained
- Most rollovers occur about the longitudinal axis of the vehicle
- Most vehicle rollovers involve one complete roll or less
- Ejection takes place most frequently through the side windows.

List of deliverable(s)

The work performed by GDV for Task 1.1 was finalised with deliverable D1.1, consisting of following reports:

- “Literature Review on Rollover Accidents”
- “Report on Statistical Importance of Different Types of Rollover Accidents”

2. Task 1.2: Selection of cases for in depth studies (Ford)

Scientific and technical description of the results

Approximately 500 to 3,000 variables per accident were obtained in total. Any personal data included is processed according to data protection regulations. Medical confidentiality and the rights of the individuals are guaranteed. All information was stored anonymously in an Access database and is available for evaluation.

Statistics

Based on the statistical collection form T 1.1 for selection of cases for in-depth studies the following criteria have to be considered:

- General: Up to one turn, direction longitudinal, belted occupant(s)
- 40 started with roll followed by impact
- 40 started with side impact followed by roll
- 40 started with front impact followed by roll
- No convertible; they will be included only in the report on statistics in T1.1 due to the small percentage of accidents with convertibles
- In each category 1-2 cases with SUVs

Involved partners and their possibilities

Partners in this task have different data available. The following table shows the resources which can be used for gathering well documented cases for in depth studies:

Partner	*Resources for cases*	*Number of rollover cases*	*Selected for integration*
TUG	Curt cases	20	20
IDIADA	Cases from local authorities	22	12
GDV	Internal database	75	75
FORD	GIDAS database	24	24
BOLTON	VSRC – CCIS database	36	5
RENAULT	-	0	0
DELPHI	Internal cases	9	9
Sum		**186**	**145**

Selected cases

The selected cases did not always meet the criteria for the selection. The cases were also selected by the quality of documentation.

Information on case selection

Ford delivered 25 detailed rollover cases from the GIDAS sample and reviewed the CCIS cases supplied by VSRC via Bolton Institute.

The cases include such information as:

- Environmental conditions
- Road design
- Traffic control
- Accident details and cause of the accident
- Crash information e.g. driving and collision speed, delta-v and EES,
- Degree of deformation
- Vehicle deformation
- Impact contact points for driver and passengers
- Technical vehicle data
- Information relating to the people involved, such as weight, height
- etc.

The information collected "on the scene" is complemented by more detailed measurement of the vehicles (usually on the following day), further medical information on injuries and treatment and an extensive accident reconstruction generated from evidence collected at the accident scene.

By applying established physical principles, the impact events are reconstructed (e.g. collision speed) using proven software such as PC-Crash.

The output can be displayed graphically to allow a full understanding of the crash events.

List of deliverable(s)

D1.2 Report on case selection

3. Task 1.3: Database integration (TUG)

Scientific and technical description of the results

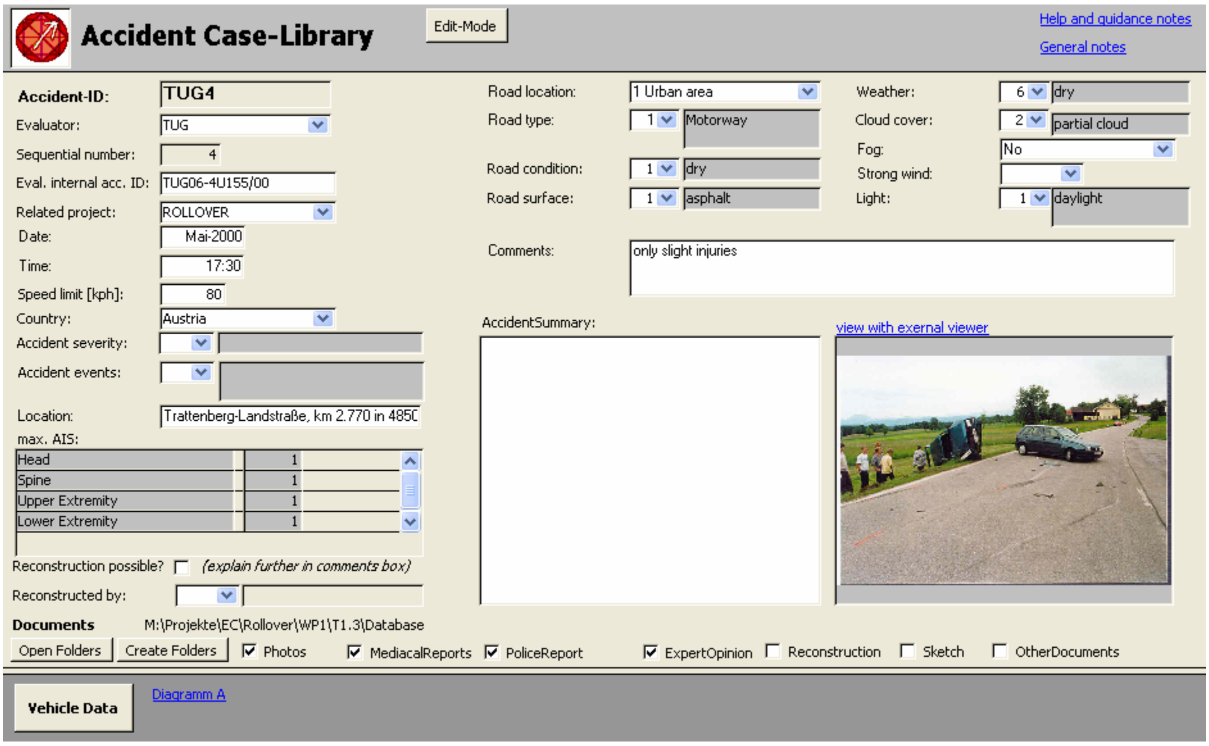
In the task 1.1 “Statistical collection and literature review” the following sources were analysed:

- GIDAS database
- VSRC internal data collection
- GDV internal data collection
- IDIADA internal data collection
- TUG internal data collection

Based on the results of these analyses about 150 rollover cases could be separated. To get a uniform collection of the data, the stairs protocol [1] was chosen for data structure. This data structure is accident based:

- GENERAL DATA MODULE
- VEHICLE DATA MODULE
- PRE-CRASH AND SEATING DATA MODULE - CAR
- POST-CRASH DATA MODULE - CAR
- RESTRAINT DATA MODULE
- CHILD RESTRAINT DATA MODULE
- INTRUSION DATA MODULE
- CASUALTY DATA (CAR) MODULE
- PRE AND POST-CRASH DATA (TWO-WHEELER) [not used]
- MODULE CASUALTY DATA (TWO-WHEELER) MODULE PEDESTRIAN [not used]
- DATA MODULE
- CASUALTY DATA MODULE
- INJURY DATA MODULE

Figure 1 **Main screen**



Accident-ID: TUG4
Evaluator: TUG
Sequential number: 4
Eval. internal acc. ID: TUG06-4U155/00
Related project: ROLLOVER
Date: Mai-2000
Time: 17:30
Speed limit [kph]: 80
Country: Austria
Accident severity:
Accident events:
Location: Trattenberg-Landstraße, km 2.770 in 485C
max. AIS:

Head	1
Spine	1
Upper Extremity	1
Lower Extremity	1

Reconstruction possible? ☐ *(explain further in comments box)*
Reconstructed by:

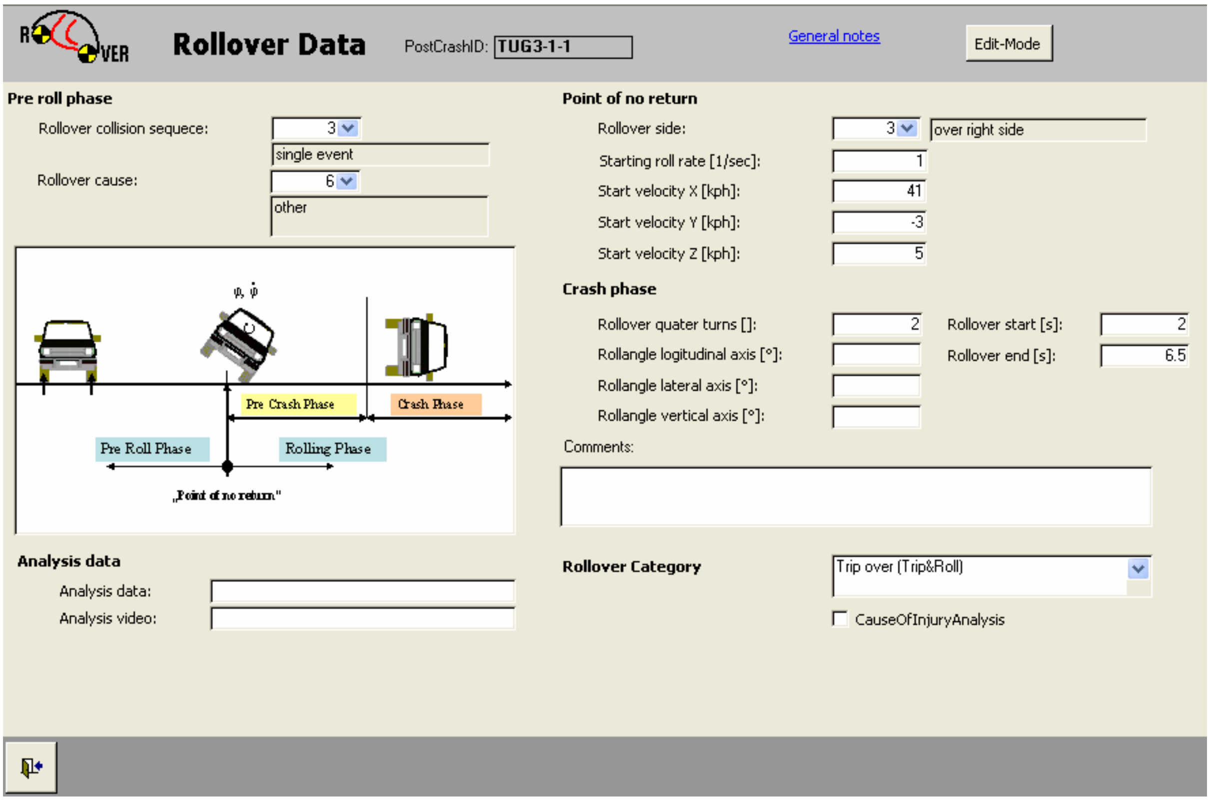
Road location: 1 Urban area
Road type: 1 Motorway
Road condition: 1 dry
Road surface: 1 asphalt
Weather: 6 dry
Cloud cover: 2 partial cloud
Fog: No
Strong wind:
Light: 1 daylight
Comments: only slight injuries
AccidentSummary:

Documents M:\Projekte\EC\Rollover\WP1\T1.3\Database
☑ Photos ☑ MediacalReports ☑ PoliceReport ☑ ExpertOpinion ☐ Reconstruction ☐ Sketch ☐ OtherDocuments

This data structure was adopted to include as many of the information provided by the different data sources and individual accidents as possible.

Finally the case library was extended by a specific “ROLLOVER Module” to include the data of in-depth analyses.

Figure 2 **Rollover module**



PostCrashID: TUG3-1-1

Pre roll phase

Rollover collision sequece: 3 single event

Rollover cause: 6 other

Point of no return

Rollover side: 3 over right side

Starting roll rate [1/sec]: 1

Start velocity X [kph]: 41

Start velocity Y [kph]: -3

Start velocity Z [kph]: 5

Crash phase

Rollover quater turns []: 2

Rollover start [s]: 2

Rollangle logitudinal axis [°]:

Rollover end [s]: 6.5

Rollangle lateral axis [°]:

Rollangle vertical axis [°]:

Comments:

Analysis data

Analysis data:

Analysis video:

Rollover Category Trip over (Trip&Roll)

☐ CauseOfInjuryAnalysis

Beside the modules a specific data structure is implemented to store the different documents and analyses:

- Reconstruction
- Expert Opinion
- Medical Reports
- Photos
- Police Report

The whole case library is available in electronic format on DVD.

This database also contains the results of the accident reconstruction from task 2.1.

List of deliverable(s)

Electronic Database containing approx. 150 selected accidents

References

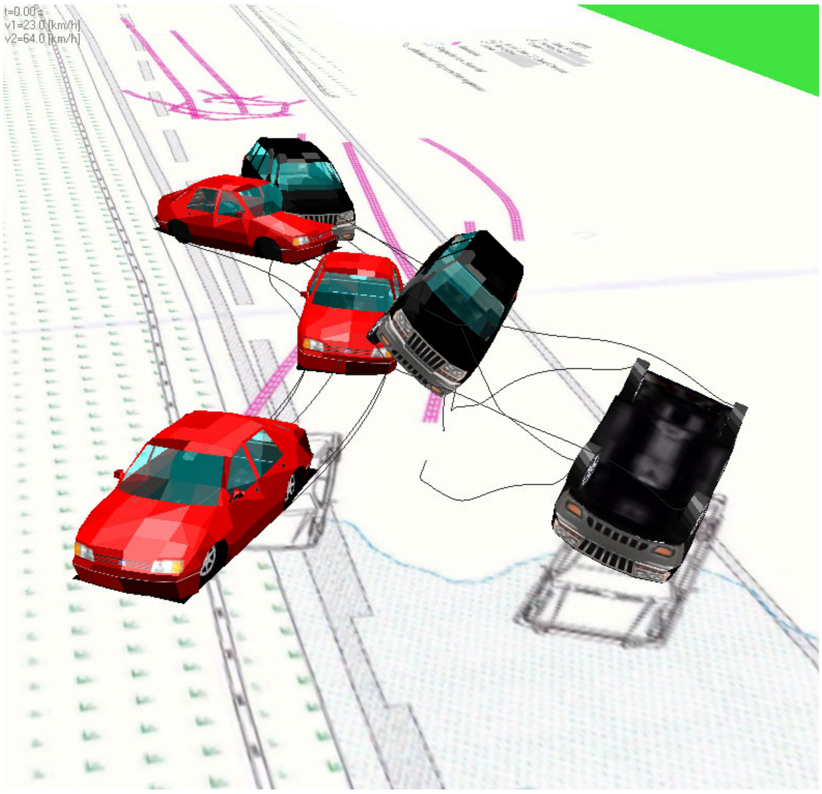
[1] STAIRS Standardisation of Accident and Injury Registration, Final Report, Contract N° RO-96-SC.204, Project funded by the European Commission under the transport RTD programme of the 4th framework programme

4. Task 2.1: Accident reconstruction using simulation methods (vehicle) including pre roll phase (TUG)

Scientific and technical description of the results

In task 1.2 “Selection of cases for in-depth studies” specific cases for reconstruction and accident analysis were selected. These cases were reconstructed with PC-Crash [1].

Figure 3 **Example of a virtual reconstruction**



Therefore it can be observed that for well documented cases an estimation of the rollover event is possible. Because rollover is a long time event compared to other crash scenarios e.g. front crash it is important to use a small time step of about 1ms for virtual reconstruction. The output of the reconstruction can then be used later as prescribed motion for numerical methods on occupant movement or sensor system simulation.

Rollover accidents can only be usefully reconstructed for in-depth studies if the documentation is of good quality. That means that sketches and photographs of the scene and of the damages are necessary.

The reconstructions were integrated into the database (simulation data, overview and movie).

List of deliverable(s)

75 reconstructed rollover cases integrated into Electronic Database

Acknowledgements (if appropriated)

References

[1] PC Crash – Accident reconstruction software tool, DSD, Linz, Austria

5. Task 2.2: Full scale reconstruction of vehicle & occupant movement during pre-roll phase (UVMV)

What were the objectives?

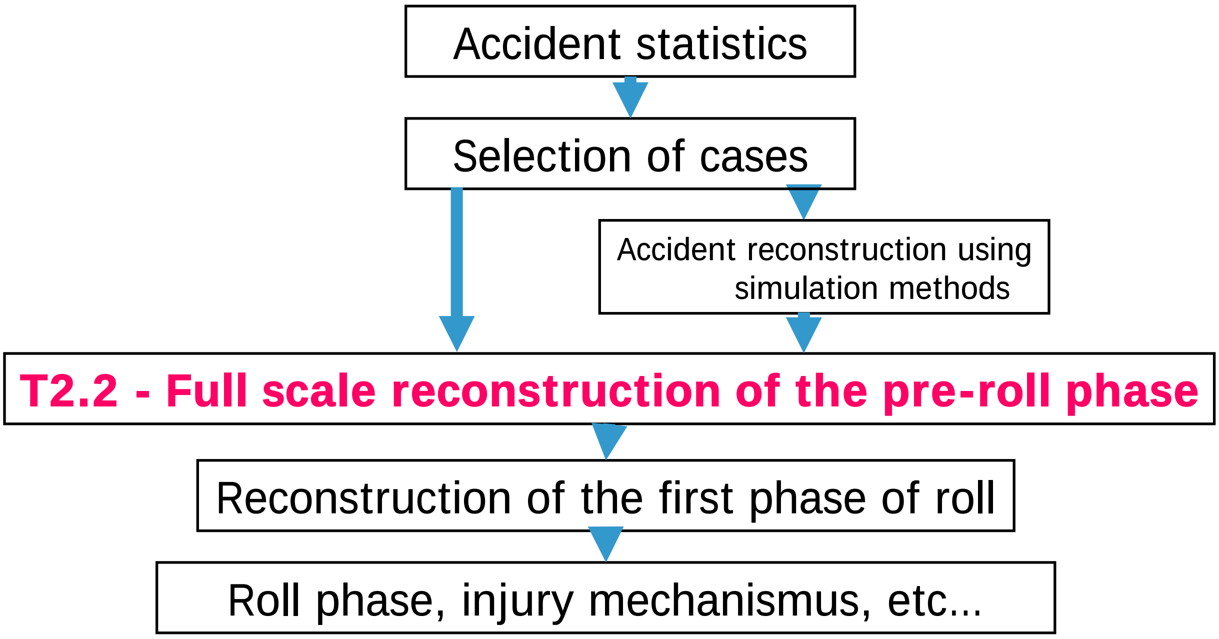
- description of the passenger and vehicle movement during the pre-roll phase
- determining of the initial state (esp. passenger position) for the first phase of roll

Way how to reach it?

The simplest way is to perform a series of full scale experiments with volunteers.

- **Volunteer Tests -** special attention was given to pre roll phase where typical occupant movements prior to roll will be determined through volunteer tests
- **Occupants out of position initial conditions study -** data will be used to learn about out of position initial conditions of the occupants

Figure: Task T2.2 philosophy



Description of work

- input from T2.1 accident reconstruction

- to determine typical occupant actions prior to roll
- to determine possible out of position scenarios
- a “driving simulator” in form of a vehicle will be used where volunteers are undertaken typical pre roll scenarios
- the movement will be monitored using video cameras
- vehicle accelerations, orientations and angular velocities will be monitored

All these measurements as output were used for rollover triggering.

Scientific and technical description of the results

Measuring quantities

The vehicle measurement is based on following measured features:

- accelerations in 3 axis
- orientations in 3 axis
- angular velocities up to 3 axis if required
- vehicle speed in longitudinal and lateral axis
- steering wheel angle
- other quantities after requirements of our partners are possible up to or up to 16 (32) channels in total of the Dell notebook with A/D card or alternatively even 128 channels (DAS of KaiserThrede, maximum sampling rate 10kHz, record length 60s with 1kHz)

with following instrumentation:

- Strap-down platform FES 33/1
- Velocity and angle sensor Corrsys SCE
- Optical height sensor IDL 2010-50
- Measuring steering wheel Elfe LWA with evaluation unit Corrsys
- Accelerometers Brüel & Kjaer type 4367 with amplifiers Analog Devices
- Accelerometers Endevco Isotron with amplifier Nexus
- High speed cameras Kodak ExtaPro HG 2000
- Light barrier W124-B2331 Corrsys
- Digital anemometer Windmaster 2
- Electrical thermometer ETHG913R
- Multimeter Voltcraft VC608 (etalon)

- Digital pressure gauge for tire pressure checking

In the left figure is seen full instrumentation in the vehicle: supply and evaluation units in a rear left seat compartment, batteries as a power source for cameras (at the back), computers for saving of measured data and interface for communication with the cameras (down) and equipment for EMG measurement provided by LMU (upstairs) in the luggage compartment

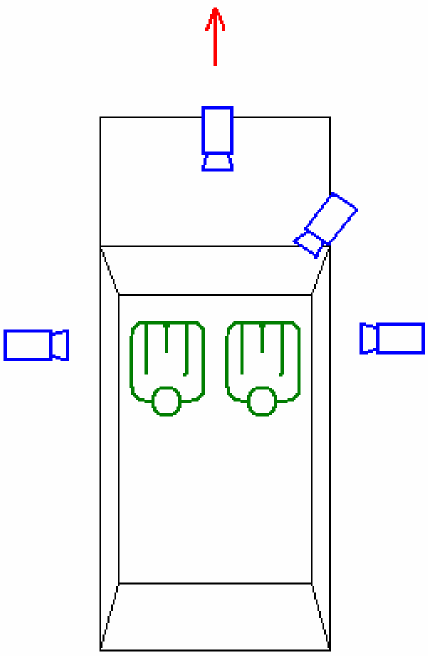
Right hand side figure presents mode 1 of high speed cameras Kodak.

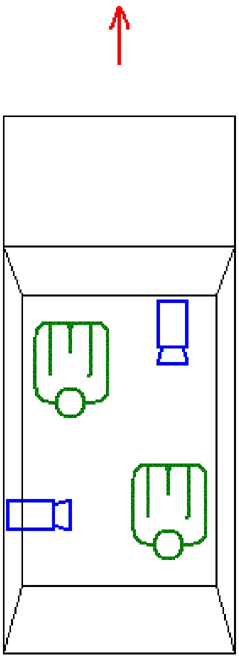
The tests were performed in 2 modes:

Mode 1

- Windscreen removed
- 4 cameras for filming the driver and the front-seat passenger
- Occupants wear protective helmets with embedded accelerometers

At the first mode, the driver's and front-seat passenger's behaviour was investigated. Both were filmed from the front and side. On order to enable this, the windscreen was removed from the test car. Both passengers wore protective helmets with accelerometers installed on the top. Camera positions are apparent from the left figure bellow. Distances of the targets on the vehicle and passengers necessary for motion analysis from the video sequences are in deliverable report.





<u>Mode 2</u>

- Windscreen not removed
- 2 cameras for filming the rear-right seat passenger
- The advantage of this mode is a more realistic head motion, because the occupants do not need the helmets

The second mode was compiled to enable filming of the passenger without helmet. At this mode, the front-right seat is dismounted from the vehicle. Only the rear-right seat passenger is filmed from the front and side. Both cameras were placed inside the vehicle and no glass was removed from the vehicle. Camera positions are apparent from the left figure; relevant measured distances are in deliverable report.

Two volunteers took part in the test. One (hereafter called as "experienced") was the professional test driver, the second (called as "non-experienced") was common driver with no experience in vehicle road testing. The volunteers took turns so that when one of them was driving, the second was the passenger. The "non-experienced" driver has not learnt the manoeuvre before testing – the first test trial with this driver was also his first trial ever.

Results of the tests presented in technical reports UVMV No. 40325-03 and 40345-03 represent full and comprehensive output of the Task 2.2 of the Rollover project. It can be claimed that the objectives of this part of the project were successfully realized. This document resumes briefly the most important results of the tests.

1. The test manoeuvres, test methods, measured quantities etc. were selected after discussions with partners in the Rollover project as a

compromise solution, which made possible to reach the test objectives in the given time and at acceptable costs.

2. At all test manoeuvres the ultimate state was reached. Maximum roll angle ranged in 8 ÷ 10 degrees at VDA-test and 6 ÷ 8 degrees at fishhook manoeuvre, maximum lateral acceleration was about 8 $m.s^{-2}$ at all variants.
3. In all phases of the ultimate state respond both passengers (especially the co-driver) with violent motions in lateral direction. The co-driver moves his head subconsciously against the direction of the centrifugal force. (It appears that he tries to avoid an impact with the sidewall of the vehicle.) Unlike this, the motion of the dummy follows always the direction of the centrifugal force; the dummy behaves similar as a solid body. Lateral motions of the passenger are damped by muscular activity, while the dummy moves with larger velocities and amplitudes.

Comparison of the direction of motion of the passenger’s and dummy’s head can be made from those pictures. The passenger moves his head against the centrifugal force, while the dummy’s head follows the direction of the centrifugal force.

Those two pictures demonstrate the same response of the passenger in the next phase of the manoeuvre (with an opposite direction of yawing).

These pictures document the driving condition of the vehicle in the phase, in which the last set of pictures on the previous page were recorded. In this phase the vehicle yaws to the right between the middle (offset) and last section of the VDA-manoeuvre. The ultimate driving state is noticeable from the large roll angle connected with inner-rear wheel lift-up. (These pictures were recorded during the pre-test; hence the vehicle is not equipped by cameras.)

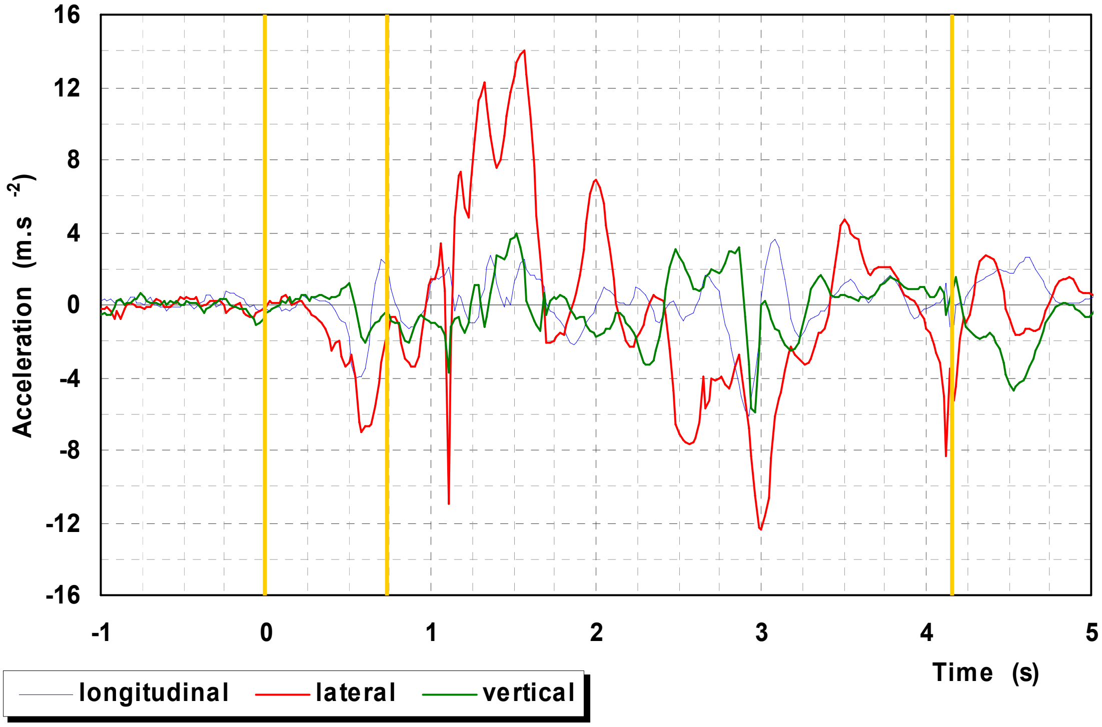
As the side-view records show, the passenger and the dummy perform no significant motions in longitudinal direction.

1. It can be claimed that occupant reactions are similar at front and rear seats. (Compare following pictures with the pictures on page 1.)

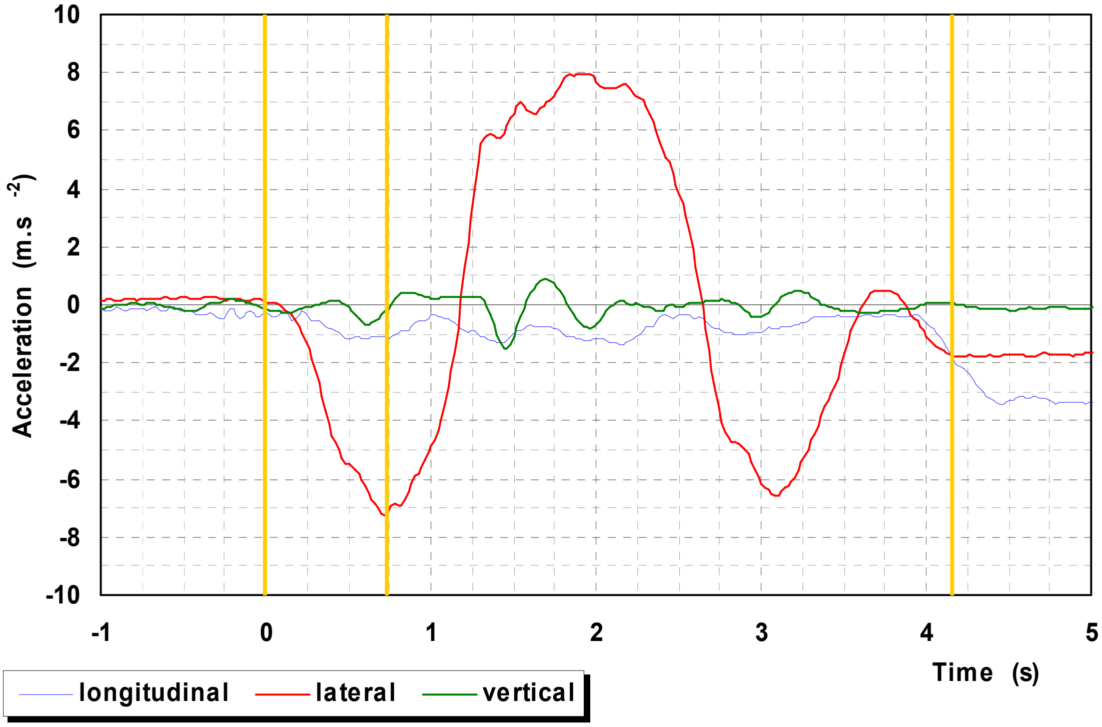
Similarly as at the front seat, the passenger moves his head subconsciously against the centrifugal force, while the dummy’s head follows passively the direction of the centrifugal force.

Also in the second phase of the manoeuvre, where the direction of yawing of the vehicle is rapidly reversed (the vehicle is now turning to the right), the passenger moves his head against the direction of the centrifugal force (it means to the right), while the head of the dummy inclines to the left and follows then the direction of the centrifugal force passively again.

The pictures can be supplemented by following graph, which shows time history of the passenger's head accelerations at VDA-test. It is well apparent that the most important component of the acceleration vector is the lateral acceleration with two large and one moderate peak, whereas the longitudinal and vertical components have no or only some small peaks.



Lateral acceleration curve of the passenger's head can be compared with the lateral acceleration of the vehicle, which is depicted on the following graph:



1. At both types of manoeuvre, no substantial motions of passengers and dummies in longitudinal direction were found out (see pictures on page 2).
2. It can be claimed that the passenger must sleep if his reactions should not be influenced by his muscles. Some experiments made during the preliminary tests showed that the co-driver's reaction is significantly influenced by muscle activities also when he has closed eyes and the driver makes unexpected manoeuvres (although this influence is a little more moderate and delayed).
3. Motions of the driver can apparently not be evaluated as reactions to an unexpected impulse, because he consciously controls a vehicle in the given manoeuvre. His trajectory and activities is thereby largely influenced.
4. The movement of the occupants is well visible from the pictures and video sequences acquired by high-speed cameras, which are included as the Appendix 2 to the test reports. Detailed evaluation of those movements can be rationally carried-out by experts, who will make a further use of the test results for a biomechanical or other research. Those experts can make this evaluation in such a way that is effective for acquisition of the results, which are relevant for their research.
5. Six test variants were selected from possible combinations of two volunteers, two modes of vehicle occupation and camera configuration and two different types of manoeuvre (VDA-test and one fishhook-like manoeuvre). Except of originally supposed filming of the driver and front-seat passenger through a removed windscreen, the second mode was added in which the rear-seat passenger is filmed. This made possible to gain more accurate records of passenger's head movement since in this mode the windscreen has not been removed and the passenger has not needed to wear a helmet.
6. After requirements of some partners of the Rollover project, measurement of driver's and passengers head accelerations was carried-out at some test variants. However, results show that this type of measurement is not very suitable for description of such low frequency and low intensity motions; the head movements can be better evaluated from video sequences.

WP 2.2 – Analysis of muscle activity

Full scale crash tests are performed with hardware dummies positioned in the car. The dummies represent the human occupant in a real crash scenario. Accelerometers, force sensors and digital high-speed video cameras supply data for the analysis of the kinematics of the dummies as well as the loads acting on the dummies. From the recorded data several injury parameters can be derived. These parameters are used for the assessment of vehicle safety.

Important questions arise about the comparability of the pure mechanical dummy with the real human occupant.

What are the main differences in the kinematics between the dummy and the human occupant?

Which muscles are activated during a real accident or during the immediate time before the crash?

How does muscle activity influence the kinematics of the occupant?

For the investigation of the mentioned questions, road tests were performed by UVMV in Prague in August 2003. The car was a Renault Megane Scenic. Two different types of road tests have been conducted by an experienced driver (VDA ISO 3888-2 and Fishhook).

For the assessment of the muscle activity, surface electrodes were fixed on the skin of the driver respectively the co-driver. These electrodes measure the potential upon a muscle which is proportional to the muscle activity state. This technique is called surface electromyography (EMG).

The aim of this study was to investigate the muscle activity during crash scenarios and the resultant kinematics of the occupants. No literature about EMG measurements during road tests could be found, therefore the results presented in the following chapters should be considered as a first step towards the analysis of EMG data related to accident scenarios.

Methods

The vehicle was equipped with the following sensors for the acquisition of the kinematics:

- Velocity sensor
- Accelerometers
- Rotational velocity sensors

High-speed video cameras and accelerometers fixed on the helmets of the driver and co-driver were installed to record the kinematics of the occupants (for details see UVMV report no. 40325-03).

Muscle activity was logged by fixing surface electrodes on the skin of the occupant. Two electrodes have to be fixed above one muscle for the measurement of it’s electrical activity (see Figure 4); one electrode, the so-called reference electrode has to be fixed at a location with no electrical activity (e. g. brow).

Figure 4: Electrodes measuring activity of the right m. sternocleidomastoideus (left), technical equipment in the car boot (right)

For the experiments we used an EMG-device with 8 channels (Noraxon Inc. Scottsdale, Arizona) and a sampling frequency of 960 Hz. The data is transferred via a telemetry unit to a laptop, where the data is stored online. Both, the sender/receiver and the laptop were in the car.

The following table gives an overview of the muscles measured during the road tests and their physiological function.

Muscle	**Function**
M. sternocleidomastoideus left	Rotation of head to the right, nod of head to the left
M. sternocleidomastoideus right	Rotation of head to the left, nod of head to the right
M. trapezius left	Adduction, stabilisation of shoulder girdle
M. trapezius right	Adduction, stabilisation of shoulder girdle
M. obliqus externus abdominis left	Lateral flexion of torso to the left
M. obliqus externus abdominis right	Lateral flexion of torso to the right
M. rectus femoris left	Extension of left knee, flexion of left hip
M. rectus femoris right	Extension of right knee, flexion of right hip

The muscles given in the table are appropriate for EMG-analysis because of their superficial location.

Summary

1) The kinematics of the driver and the co-driver are different. Due to the active driving manoeuvres the torso and the head of the driver exhibits a higher lateral flexion.

2) Results: VDA-tests

   a) Reproducible EMG-signals can be found for the driver and for the co-driver.

   b) During the first left curve the left m. sternocleidomastoideus is active. The shape of the EMG-envelope for the driver and the co-driver is similar, however the amplitude of the driver EMG is higher.

   c) Activity of the mm. trapezius can be observed. The EMG-amplitude of the driver is higher compared with the signals of the co-driver.

   d) Myocardial muscle activity superposes the EMG-signal of the mm. obliqus externus abdominis. This has to be considered when the data is analysed. Due to active driving manoeuvres the EMG-amplitude of the driver is higher.

   e) The EMG-signals of the mm. rectus femoris show a distinct activation pattern. During a left curve the left m. rectus femoris is active, during a right curve the right m. rectus femoris shows activity.

2) Results: Fishhook

   a) All muscles show activity.

   b) The right and the left m. sternocleidomastoideus, m. trapezius and m. obliquus externus abdominis are activated synchronously. An activation pattern can not be stated.

   c) The left m. rectus femoris is active during the first left curve. At the maximum of the negative acceleration the EMG-amplitude of the left m. rectus femoris decreases and the activity of the right muscle increases.

3) Results of these field tests are going to be compared with our laboratory results (task 2.3).

List of deliverable(s)

The main deliverable from this work package was Report T2.2 – Full scale reconstruction of vehicle & occupant movement during pre-roll phase.

6. Task 2.3: Reconstruction of occupant movement during first phase of roll using a motion base (LMU)

Scientific and technical description of the results

Objectives

The objectives of the Task 2.3 were to assess the kinematics of the occupant in the first phase of roll. The knowledge of occupant kinematics is essential for the design of new restraint systems or for the trimming of current systems for rollover accidents. Many cases were documented in which rollovers were followed by an impact. These demonstrate the importance of the occupant kinematics during the roll for the assessment of possible Out of Position issues.

As opposed to most frontal, rear or side crashes the accelerations acting on the occupants in rollover accidents are usually lower and the duration of the crash is much longer (up to several seconds). Thus, the kinematics of the occupants can be influenced by muscular actions (both reflexive and voluntary).

An experimental setup should be build up; a series of experiments with volunteers and dummies should be performed.

The experiments were designed to answer following questions:

- Do the occupants exert active muscle forces during the first phase of roll?
- In what regions are muscles activated?
- Is the muscle reaction side-specific (i.e. are there differences between the left and the right hand side of the same muscles)?
- Does the muscle activation clearly influence the kinematics of the occupant? How and to what extent?
- Are the laboratory results comparable to the output of the field tests in the car obtained in the task 2.2?
- Does muscle activation (its level or time pattern) depend on the magnitude of the accelerations the body is exposed to?
- Do the occupant kinematics depend on the magnitude of the acceleration the body is exposed to?
- Are there individual differences in the occupant kinematics?
- Are there differences between the kinematics of volunteers and dummies (Hybrid III and SID)?
- Which of the two used dummies is more suitable for the usage in rollover-like scenarios?

- Are there any distinct triggers for the onset of muscle activation in terms of acceleration or jerk of various body regions?

Methods

Experimental setup

In order to imitate the car motion in the first phase of roll a special sled facility with a mounted motion base was constructed by TUG in co-operation with LMU. The sled was allowed to move on rails fastened firmly to the ground. A motion base (i.e. a steel frame with wooden platform) was anchored to the sled by a hinge so that tilting the platform was possible. A current make of a car seat with an integrated seat belt was firmly screwed to the motion base. For safety reasons a safety frame with tight netting was attached to both sides of the motion base (see Figure 1).

Two motion types that represent the dominant features of different rollover scenarios – translational movement (rollover scenarios with dominant lateral acceleration in the first phase – trip over, turn over, collision with another vehicle) and tilting movement (rollover scenarios in which the roll is not accompanied by significant lateral acceleration – flip over, fall over) were simulated with the motion base.

The translational movement was imitated by using the principle of inverse motion. It means that instead of inducing an initial velocity to the sled and braking it as it would be in the real car, the sled was exposed to the same lateral acceleration (originally deceleration of the car) in a standstill position. The sled thus moved in the opposite direction than the (assumed initial) movement of the car, but the effects on the occupant are exactly the same. The translational movement of the sled was driven by a bungee rope, the acceleration of the sled was trimmed by adjusting the initial pull-strength of the rope.

The tilting movement of the motion base was driven by a pneumatic piston; the tilting velocity was determined by the initial air pressure. In this configuration the motion base stood still and only the tilting movement was induced.

Figure 1. The motion base with a seated volunteer

The whole experimental set-up was designed to minimise all potential hazards for the volunteers. An approval of the ethics commission of the LMU was obtained in advance.

Prior to the experiment, each volunteer was given an explanation of all procedures and signed an informed consent. His basic anthropometric data were collected and he put on a tight non-reflective dress.

The skin over chosen muscles was shaved and rubbed with EGM-preparation gel for better conductivity. The Blue Sensor® electrodes were positioned over the thickest part of the selected muscles (overview see Table 1).

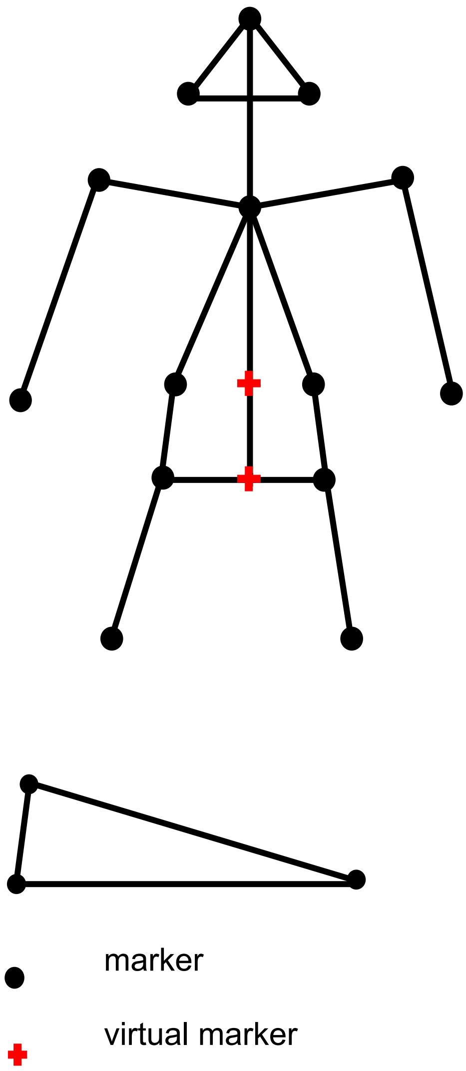
14 reflective markers for the kinematical analysis were positioned on the volunteers' bodies as depicted in figure 2. Please note that the list contains only the markers needed for the analysis, some more were used to facilitate the automatic tracking process. The same set of markers was used for the dummies as well.

Based on the position of the real marker, the position of the so-called virtual markers was computed automatically. These points enhanced the analysis of the subjects movements.

Table 1. Muscles selected for the EMG analysis

muscle	**function**
m. sternocleidomastoideus left	head rotation to the right, head tilt to the left
m. sternocleidomastoideus right	head rotation to the left, head tilt to the right
m. trapezius left	adduction, stabilisation of the shoulder girdle
m. trapezius right	adduction, stabilisation of the shoulder girdle
m. obliqus externus abdominis left	lateral flexion of the torso to the left
m. obliqus externus abdominis right	lateral flexion of the torso to the right
m. rectus femoris left	knee extension, hip flexion
m. rectus femoris right	knee extension, hip flexion

Figure 2. Positions of the reflexive markers on the volunteer's body



markers on the body:

1. head top
2. head left
3. head right
4. sternum middle
5. shoulder left
6. shoulder right
7. elbow left
8. elbow right
9. chest left
10. chest right
11. pelvis left
12. pelvis right
13. knee left
14. knee right

markers on the motion base:

1. sled right 1
2. sled right 2
3. sled left

virtual markers:

1. chest middle
2. pelvis middle

Due to time and cost limitations, experiments were carried out with two volunteers, a Hybrid III and a EuroSID dummy only. The test matrix showing the overview of experiments carried out in the movement science lab is depicted in Table 2.

Table 2. Experimental matrix

Occupant	translational movement		rotational movement	
	"slow"	"fast"	"slow"	"fast"
Volunteer 1	X	X	X	X
Volunteer 2	X	X	X	X
HybridIII	X	X	X	X
EuroSID	X	X	X	X

The variants slow and fast in table 1 are stated in inverted commas because we were not able to reproduce the exact speed of the translational and rotational motion for all occupants. Though both bungee rope and pneumatic piston enabled the regulation of the motion to a certain degree, the kinematics of the sled motion were not exactly reproducible. On the other hand, a construction of a sled facility with a high degree of reproducibility would have been much more consuming in terms of time and resources and the results achieved with our motion base proved to be meaningful. The acceleration levels in the experiments were chosen so that they comply with two requirements – they should represent the accelerations observed in the first phase of real rollover accidents (as documented by the accident reconstruction and the field tests done in the task 2.2) and at the same time the experiment had to be safe for the volunteer. The peak lateral (inertial y-) accelerations achieved during the translational movement as well as the peak roll-rates achieved during the rotational movement are listed in table 3.

Table 3. Peak accelerations/roll-rates of the motion base in the experiments. The peak acceleration values are accompanied by the maximum linear velocity achieved (in brackets, m*s^{-1})

Occupant	y- acceleration peak (g)		roll-rate peak (grad*s^{-1})	
	“slow”	“fast”	“slow”	“fast”
Volunteer 1	0.8 (2.0)	0.9 (2.5)	56	62
Volunteer 2	0.7 (2.1)	0.9 (2.8)	36	60
HybridIII	0.6 (1.3)	1.0 (2.6)	44	58

The peaks stated in table 3 were found from filtered kinematical data (low-pass filter with cut-off frequency 15Hz). It should be noted that acceleration data are computed as second derivative of marker positions and as such they are extremely sensitive to filtering. A different filter may have lead to different peak values.

Table 4. shows the first peaks of lateral accelerations and roll-rates for the first 21 cases of the database created in work package 1. It demonstrates that our experimental values are comparable to the real data. However, one has to keep in mind that rollover accidents distinguish themselves with a very wide variety of kinematics (not only the heights of the accelerations vary in time, but also their directions) and as a result only a small part of possible scenarios has been dealt with.

Table 4. First acceleration ($m*s^{-2}$) and roll-rate ($grad*s^{-1}$) peaks in the reconstructed cases

case	TUG 1	TUG 2	TUG 3	TUG 4	TUG 5	TUG 6	TUG 7
accel.	1.8	2.4	2.8	n. a.	n. a.	n. a.	0.6
roll-rate	57	78	105	n. a.	170	n. a.	110
case	TUG 8	TUG 9	TUG 10	TUG 11	TUG 12	TUG 13	TUG 14
accel.	n. a.	n. a.	5.0	0.8	0.4	0.6	n. a.
roll-rate	n. a.	50	85	77	155	61	87
case	TUG 15	TUG 16	TUG 17	TUG 18	TUG 19	TUG 20	VSRC 1
accel.	0.7	1.1	n. a.	6.0	n. a.	EOE	5.1
roll-rate	69	92	58	29	76	EOE	498
Legend:	n. a. ... data not available EOE ... end over end rollover type, not relevant						

The experimental peak values correspond well with the lower values of the reconstructed cases and are thus realistic. Higher accelerations and/or roll rates would have been dangerous for the volunteers.

In all experiments the occupant was seated and the seat belt properly fastened. After a check-up of all safety measures and a proper function of all measurement devices the propulsive devices were loaded (bungee rope pulled or pneumatic piston filled with air). The motion of the sled followed after a countdown, they were aware of the motion onset.

For each occupant at least two measurements were carried out for each motion, i.e. the slower and the faster modus.

Instrumentation

The surface EMG was measured by using an 8-channel telemetric measurement device (NORAXON, Scottsdale, Arizona). The measurement device was triggered simultaneously with the kinematical analysis system by the same external trigger.

For the kinematical analysis the EVa Real Time 2.1 (Motion Analysis, Santa Rosa, California) motion capturing system was used with 8 Falcon cameras. The recording frequency was set to 240Hz. The positioning of the cameras as well as the calibration of the measurement space was done according to the recommendations of the system manufacturer.

Evaluation and analysis

The EMG data were rectified and plotted at the same time as the voltage scale in order to facilitate the assessment of the total amount of muscle activity. Because the position of the electrodes did not change between various test runs, it is possible to evaluate activation differences of the same muscles in various situations. However, a comparison between various muscles of the same subject is not possible because of likely differences in the amount of muscle units recorded.

The trajectories of the markers on the subjects' bodies and on the motion base were tracked by using the EVa software and then low-pass filtered with a cut-off frequency set to 15Hz. The positions of the virtual markers were computed in the system as defined by the investigator.

For the evaluation of the occupant kinematics, screenshots from the animations were made in the overall (near to frontal) view and in the top view (xy plane).

The motion capturing system records the positions of the markers in individual frames, velocity, acceleration and jerk data are computed as the first, second and third derivative, respectively. Thus, these data are very sensitive to the filtering as well as to artefacts caused by the vibration of the sled, the movement of the markers on the skin etc. The jerk and acceleration data are therefore to be assessed with great caution.

Results

<u>Translational movement</u>

Muscle activity analysis

Both subjects showed a considerable amount of muscle activity during the simulated first phase of roll in the slow as well as in the fast variant of the test. Active were apparently all the considered body regions – the neck, abdomen as well as the legs.

The onset time of muscle activity does most likely not depend on the velocity of the sled movement – we found approximately the same values for the slow and the fast variants in both tested subjects. The fastest response is shown by the neck muscles (sternocleidomastoideus) with the onset at approx. 0.1 sec. A little bit slower reaction time was found for the abdomen muscles and the upper leg muscles followed with a minor delay (reaction time up to 0.2sec). The response of the trapezius muscle was inconsistent and varied between 0.1sec and 0.2sec.

These findings correspond with our expectations – the neck muscles react first as the head is accelerated with respect to the torso and the muscular actions are presumably aimed at its stabilisation. The stabilisation of the torso follows and because the legs are supported by the floor, no actions are needed until the torso has deviated from its upright position.

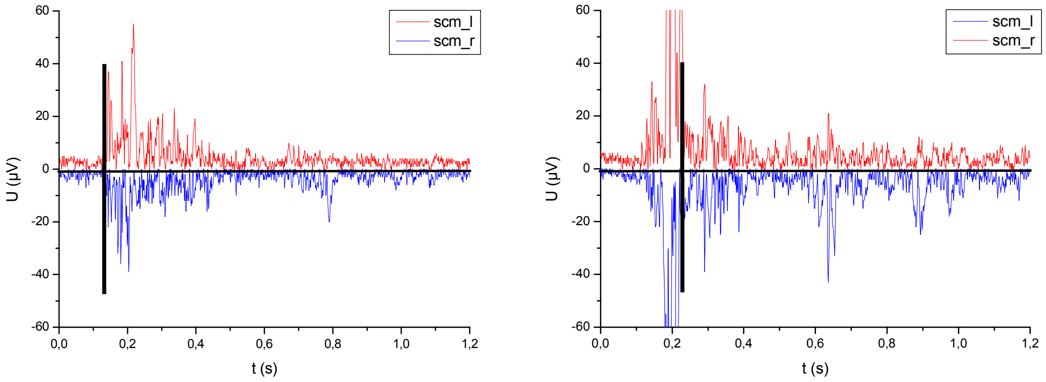
Though the translational movement of the sled was oriented from the left to the right hand side of the sitting subject, relatively little lateral differences in the muscle activation were found. The abdominal muscles showed about the same reaction on both sides in both subjects. It means that the muscles stabilise the torso regardless of the direction of acting forces (accelerations). The neck muscles showed concurrent activation as well. However, in the first subject there was completely the same activation onset time on both sides of the body whereas in the second subject there was a shift towards the right hand side (i.e. the right muscle was activated earlier and a concurrent activity followed, see Figure 2). It is apparent as well that there is more activation on the right hand side at the beginning of the movement – the muscle counteracts the tendency of the head to move to the left. After approx. 0,2sec there is no difference between the left and the right hand side of the neck musculature.

Also evident from Figure 3 is a higher amount of muscle activity in the faster variant of the movement. Though it is impossible to quantify the force exerted by the muscles (that is only possible to a certain degree in isometric contractions), the amount of muscle activity can be compared because the positions of the electrodes were exactly the same for both measurements. These results are also plausible, because higher sled accelerations bring about higher accelerations of the head and therefore more muscle force is required for stabilising.

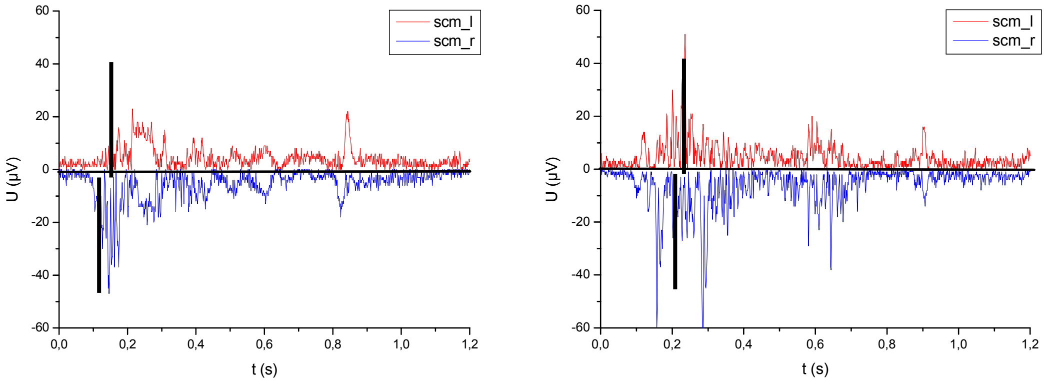
Similar tendency (i.e. more muscle activation in case of higher accelerations) has also been observed in other muscles except for the upper leg muscles.

Figure 3. Comparison of the muscle activation on both sides of the human body – translational movement, m sternocleidomastiodeus left (red) and right (blue)

Volunteer 1, slow (left) and fast (right) motion of the sled



Volunteer 2, slow (left) and fast (right) motion of the sled



Occupant kinematics analysis

The kinematics of all measured occupants (volunteers as well as dummies) recorded as 3D – trajectories of selected points on the surface of various body segments is a very complex phenomenon. A simple synchronisation of all trials does not make sense because accelerations induced to the sled vary and the sled position as well as acceleration level in various trials differ one from another at the same point of time. Thus, two space locations of the sled were chosen and the positions of the occupant at these configurations were evaluated. The sled locations were chosen approximately at the beginning and at the end of the sled acceleration phase, the sled travelled 0,76m between the two screenshots. In the following, only the most interesting screenshots are presented, the complete set of pictures from all measurement runs can be found in the Attachment.

It is apparent from the figures that only very little movement of the head and shoulder relative to the hip and chest occurs. Volunteer 1 as well as both dummies stayed upright with their trunk and head only volunteer 2 showed some bending in the trunk. It means that there is most probably a high degree of individual variability in the response of human subjects to low lateral accelerations. Different kinematics of both volunteers correspond well with the deviations found in the EMG signal as discussed above.

The dummy response met our expectations – both dummies are too stiff in the neck and shoulder region and tip over without bending the neck. With higher accelerations the trend observed in volunteer 2 would probably become more apparent in both volunteers whereas the dummy response would most probably stay the same. Due to safety reasons it was impossible to expose the volunteers to higher accelerations.

No rotation about the longitudinal axis was found in any of the evaluated segments in all occupants, no signs of movement forward or backward of the upper torso or the head were recorded. Thus, in this scenario the movement of the occupant can be considered planar in the frontal plane.

With respect to crash testing there is no preference to which dummy type should be used – both Hybrid III and EuroSID show the same (very stiff) behaviour.

Our results are in agreement with the findings of the study carried out by DELPHI and DSD presented in the technical report (Task 2.3, Volunteer and Dummy Head Kinematics in Low Speed Lateral Sled Tests). They also found differences between the dummy and human subject in low-impact situations in the head region.

Rotational movement

Muscle activity analysis

Similarly to the translational movement, all the selected muscles responded to the rotational motion of the sled. However, some differences in the response were observed.

The onset of the muscle activity corresponded roughly to the one found in the translational movement except for the upper leg muscles which were activated significantly later in the second volunteer.

The most striking difference between the two volunteers was found in the activation of the m. obliquus externus abdominis as shown in figure 4.

Whereas the first volunteer activates the muscles on the left hand side of the body much sooner than on the other side, there is no lateral difference in the response of the abdominal muscles in the second volunteer. These reactions show two different strategies of the human subjects:

- an active effort to stabilise the trunk by means of concurrent muscular actions on both sides of the trunk (the second volunteer)
- bending of the torso actively back to the vertical position after its deviation due to the sled rotation (the first volunteer). The tilting motion of the sled was oriented clockwise from the point of view of the subject so the left hand side of the abdominal musculature was employed in the correction.

In spite of the huge difference between the left and right side found in the first volunteer in the abdominal muscles, all other muscles showed exactly the same activation timing. The effort of the subject was possibly concentrated on the straightening of the torso whereas other body regions were stabilised.

The concurrent activity of abdominal muscles of the second volunteer was in turn followed by higher activity of the left hand side musculature of the neck (m. trapezius) and legs (m. rectus femoris). Thus, this subject presumably corrected the position of the head more in the shoulder region as opposed to the first volunteer.

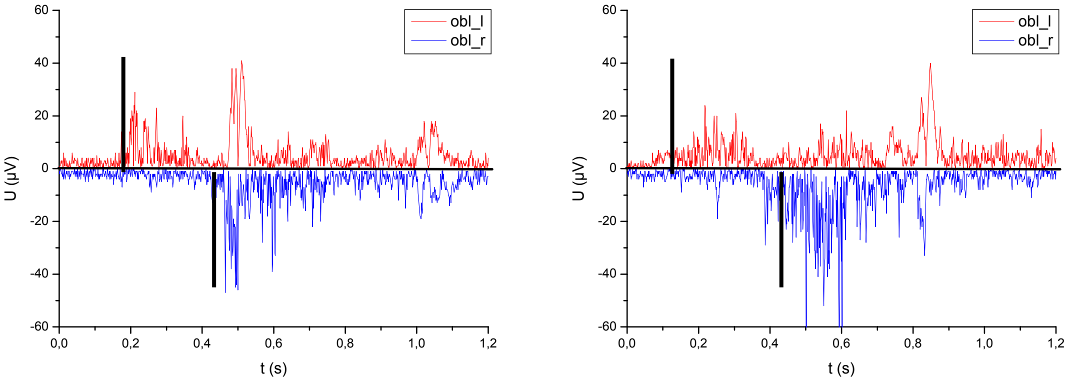
To what extent these different approaches influence the kinematics of the volunteers cannot be assessed solely from the EMG data. This will be discussed in the final task report. It should also be stressed that both subjects were not exposed to exactly the same motion of the sled because of the reproducibility issues as stated above. The found results thus may be influenced not only by individual reactions but also by the quality of the movement itself.

A minor increase of the activation volume can be observed with higher sled acceleration in all measured muscles.

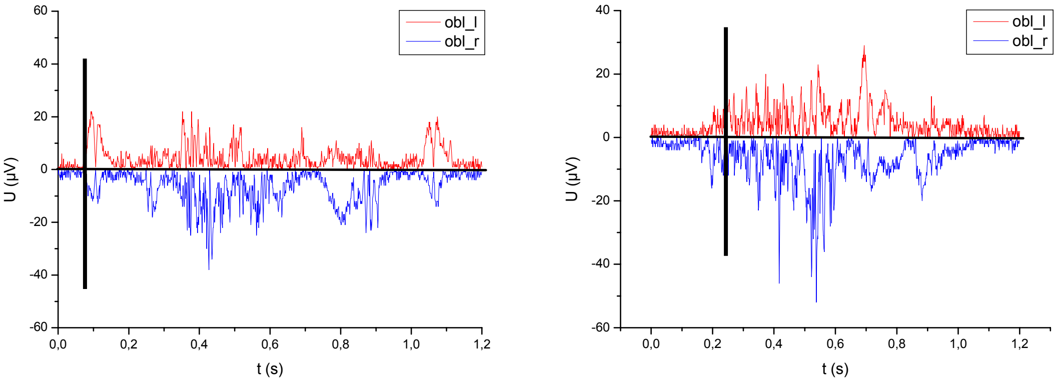
As mentioned above, it is impossible to assess quantitatively the amount of muscle activation in various muscles. Any conclusion regarding the exerted muscle forces and their influence on the kinematics of the subjects would therefore be misleading. However, the measurements provide valuable information about the response of human subjects to the movements in the first phase of roll.

Figure 4. Comparison of the muscle activation on both sides of the human body – rotational movement, m. obliquus externus abdominis left (red) and right (blue)

Volunteer 1, slow (left) and fast (right) motion of the sled



Volunteer 2, slow (left) and fast (right) motions of the sled



Occupant kinematics analysis

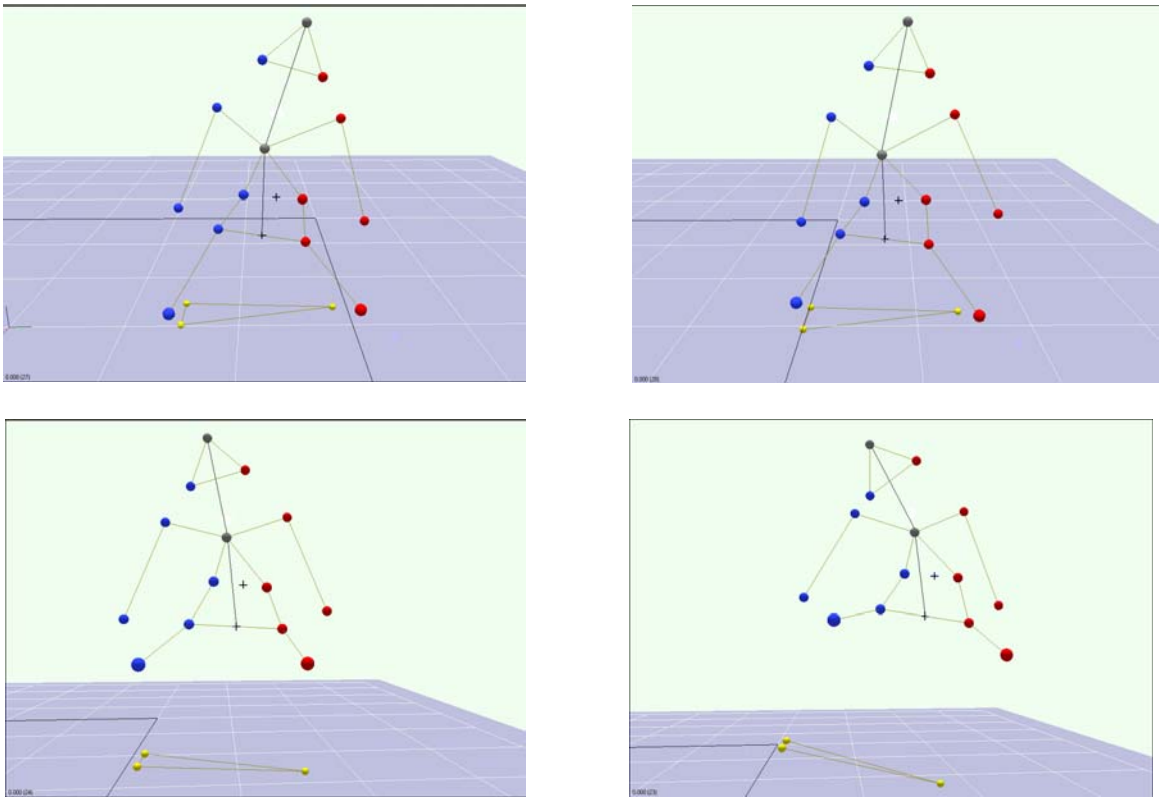
It is important to note that though the rotational movement of the motion base represented the first phase of other rollover types as discussed above, the overall rollover direction stayed the same (i.e. if a car slid laterally as simulated by the translational movement, it would roll in the same direction as simulated by the rotational movement).

The kinematics of both dummies were according to our expectation the same as in the translational movement – their whole bodies just tipped over in the direction of the motion base rotation without any relative movement in the torso or neck regions. As apparent from the figures, there are no differences between the two dummies. Consequently, no preference regarding the usage in a rollover crash-testing can be recommended.

There were significant differences found in the kinematics of human subjects between the translational and rotational movement of the motion base. The bending of the torso and neck is oriented opposite to the one found in the translational movement. Figure 5. shows the comparison between the two movement types in volunteer 2.

In the fast variant of the test the bending of the upper torso and neck becomes even more pronounced.

Figure 5. Bending in the torso and neck regions in volunteer 2 in the translational (up) and rotational (down) movement of the motion base, the early (left) and late (right) phase of the measurement, fast variant.

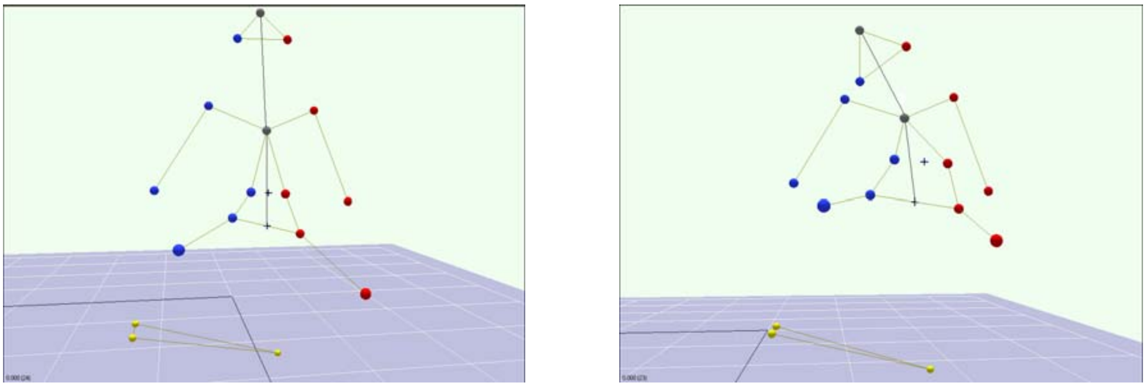


Though the above described lateral flexion of the upper torso and the neck occurs in both volunteers, the situation is similar to the one found in the translational movement, i.e. volunteer 1 tends to stay more in an upright position and the bending is only slightly indicated whereas volunteer 2 shows a much higher range of flexion. This fact is probably interrelated with the differences found in the muscle activation as described above and it indicates a huge individual variability of the response in human subjects.

Another difference is the rotation of the head of both volunteers about the longitudinal axes of their bodies. Both volunteers rotated the head relative to the rest of the body (clockwise from the top view) during the test. The orientation of the shoulder, chest and hip regions did not change. The initial positions of the head markers were checked as well and deviations of the marker placement were excluded. The heads of both volunteers rotate from the initial position and the rotation angle increases with time and/or rotation angle of the motion base.

Figure 6 shows the difference in the head/neck and upper torso bending between the volunteers and the dummies in the late phase of the rotational movement. Evidently, the volunteers exert lateral flexion so that the head bends against the direction of the roll whereas the heads of the dummies stay parallel to the longitudinal axis of the body. The relative movement of the head thus shows to the opposite direction. Please note that for practical reasons the positions of the markers on the volunteers differ slightly from the dummies so that the points in the top view do not overlap completely. However, the relative movement of the segments of interest is demonstrated very clearly.

Figure 6. Difference in the lateral flexion of the head and upper torso of the volunteers and the dummies – late phase of the fast rotational movement. Top left volunteer1, top right volunteer 2, bottom left Hybrid III, bottom right EuroSID



Jerk vs. EMG Analysis

Possible relationships between motion parameters that may presumably trigger the muscle activity (i.e. acceleration and jerk) and the recorded EMG signals were investigated. Table 5 shows time points of muscle activity onset as seen in the EMG curves and time points of acceleration and jerk peaks of the sled movement (represented by a marker attached to it). Whenever there was a small peak in the EMG signal followed by a bigger one, time points of both are stated in the table. Similarly, for both acceleration and jerk the first three peaks are listed for each movement. As apparent from the table, it is impossible to discern a clear triggering of the muscle activity in the acceleration or jerk signal.

It is important to mention two important factors that may explain the lack of relationship found between the movement parameters and the muscle activity.

Firstly, the acceleration and jerk curves represent the movement of the sled, but the human subject reacts on its own perceptive signals, i.e. on its own movement. On top of that, there are much more parameters that presumably influence the response of human subjects to similar stimuli – all the visual and perceptive signals of all body regions, past experience, etc. The existence of a single parameter threshold based solely on the subject's movement is very unlikely.

Secondly, the acceleration and jerk signals are the third and fourth derivatives of the position data obtained by the motion analysis system and as such they are very sensitive to filtering. A very small change in the filter used for the positional data leads to huge differences in the acceleration and jerk output. Moreover, any measurement error is amplified by the derivation. We intended to use acceleration sensors in order to obtain the sled accelerations directly, but for technical reasons we could not use them. On top of that, the vibration of the sled results in a big number of acceleration and jerk peaks as demonstrated by means of an example in figure 7.

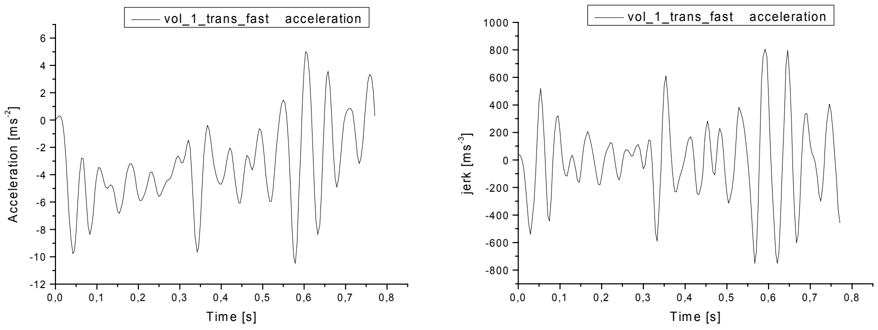
Table 5. EMG onset versus acceleration and jerk peaks

Motion	s_l	s_r	t_l	t_r	o_l	o_r	f_l	f_r	acc.	jerk
Vol1_r_s	.152 .327	.137	.225	.112 .185	.167	.416	.201	.142	.033 .058	.017 .046

									.083	.075
Vol1_r_f	.155	.148	.073 .213	.201	.215	.234 .380	.173	.154	.017 .067 .092	.009 .041 .054
Vol2_r_s	.093	.071 .158	.071 .292	.308	.067	.068	.489	.281	.029 .063 .087	.017 .050 .075
Vol2_r_f	.133	.203	.129 .255	.206	.196	.163	.460	.223 .397	.095 .120 .150	.054 .066 .087
Vol1_t_s	.126	.127	.189	.120	.165 .344	.134	.150 .187	.145	.046 .071 .096	.029 .054 .075
Vol1_t_f	.110	.128	.193	.179	.191	.134	.216	.175	.046 .067 .083	.029 .054 .071
Vol1_t_s	.127 .160	.087	.144	.152	.183	.134	.068 .226	.238	.073 .066 .104	.016 .041 .079
Vol_t_f	.109	.089	.089	.140	.092	.093	.180	.239	.050 .079 .112	.033 .062 .096

Legend: s_l, s_r … the left and right m. sternocleidomastoideus
t_l, t_r … the left and right m. trapezius
o_l, o_r … the left and right m. obliquus externus abdominis
f_l, f_r … the left and right m. rectus femoris
Vol1_r_s … volunteer1, rotational movement of the sled, slow variant
Vol1_t_f … volunteer1, translational movement of the sled, fast variant

Figure 7. Example of a typical acceleration and jerk curve of the sled motion – volunteer1, the fast variant of the translational movement.



Conclusions

- Both volunteers exerted in all tests active muscle forces, i.e. active movements of the occupants in the first phase of roll are very likely.
- Muscle activity was registered in all regions taken into account

- Differences between the activity of the left and the right hand side of the same muscles were found, i.e. the direction of the movement influences the muscle activation pattern.
- The muscle activity influences the kinematics of the occupant. The response to various movements (rotational versus translational movement) is different.
- The results of this study are in very good agreement with the output of the field tests carried out in the Task 2.2 (EMG measurement in the car).
- With increasing accelerations the response pattern does not change significantly, but the volume of muscle activity increases.
- The relative movement of the shoulder and head/neck regions (i.e. lateral flexion) in the rotational and translational motion differ substantially from each other – the directions of the lateral flexion are opposite. The occupant kinematics is thus highly dependent on the rollover type.
- The occupant kinematics does not change substantially with increasing acceleration (i.e. the same trends can be observed), but the trends become more apparent.
- There is a high degree of individual variability in the occupant kinematics.
- Relevant differences were found between the kinematics of human subjects and the dummies.
- Both the Hybrid III and the SID dummies show the same kinematics in the first phase of roll. Therefore, there is no preference with respect to their usage in rollover scenarios.
- No unambiguous trigger of the muscle activity in terms of acceleration or jerk of the sled was found. The existence of such a simple trigger is not likely taking into account the complexity of motor control processes.

List of deliverable(s)

D2.3: Report on typical pre roll movement of occupant during first roll phase.

Comparison of initially planned activities and work actually accomplished

For a better understanding of the performed work and to make it consistent with the title of the task the report on task 2.3 was called "Reconstruction of occupant movement during first phase of roll using a motion base" instead of "Report on typical pre roll movement of occupant during first roll phase".

7. Task 2.4: Summary of Rollover Scenarios (Classification & Description) (TUG)

Scientific and technical description of the results

Introduction

Rollover accidents are a possible scenario that can occur to passenger vehicles. Until now,this scenario has not been investigated on an European level. Investigations on this accident scenario have mainly been carried out in the US and a classification based on these investigations was derived. For the US classification eight different scenarios are known (Asic [1]), based on typical sequences in the case of rollover. These scenarios are: *Trip-over* – when the lateral motion of the vehicle is suddenly slowed or stopped inducing a rollover. The opposing force may be produced by a curb, pot-holes, or pavement dug into vehicle wheels. *Flip-over* – when the vehicle is rotated along its longitudinal axis by a ramp-like object such as a turned down guardrail or the back slope of a ditch. The vehicle may be in yaw when it comes in contact with a ramp-like object. *Bounce-over* – When a vehicle rebounds off a fixed object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected. *Turn-over* – when centrifugal forces from a sharp turn or vehicle rotation are resisted by normal surface friction (most common for vehicle with higher centre of gravity (COG)). The surface includes pavement surface and gravel, grass, dirt, etc. . There is no furrowing or gouging at the point of impact. Note that if rotation and/or surface friction causes a trip, then the rollover is classified as a turn-over. *Fall-over* – When the surface on which the vehicle is traversing slopes downward in the direction of movement of the vehicle COG such that the COG becomes outboard of its wheels (Note: The distinction between this code and flip-over includes a negative slope.). *Climb-over* – when the vehicle climbs up and over a fixed object (e.g. guardrail, barrier) that is high enough to lift the vehicle completely off the ground. The vehicle must roll in the opposite direction from which it approached the object. *Collision with Another Vehicle* – When an impact with another vehicle causes the rollover. The rollover must be the immediate result of the impact between the vehicles. For example, this could occur at an intersection where a vehicle is struck in the side and the momentum of the struck vehicle results in a rollover. *End-over-end* – When a vehicle rolls primarily about its lateral axis.

Based on these scenarios it was investigated, if they are also applicable for European rollovers. For choosing real world accidents for in-depth studies, basic studies of the statistics were analysed and resulted in the following characteristics of rollover accidents.

Statistical analysis

Sferco et al. [2] found out that the German In-Depth Accident Study (GIDAS) and the Co-operative Crash Injury Study (CCIS) in the UK show, that rollover account for 5-15% of all accidents. Single rollover events, without any multiple impacts account for up to 5% of all accidents in Europe. This is one third of all rollover accidents. For multiple rollover accidents the first event is the impact rather the rollover. So a rollover can be regarded as a consequence of an impact rather than an initiator. Most vehicle rollovers involve one complete roll or less and they occur about the longitudinal axis of the vehicle, approximately half in each direction. When an impact follows an initial roll, it is frequently against a fixed object (rather than a vehicle) and appears to randomly involve all parts of the vehicle. In cases where rollover follows an initial impact, the impacts are split between those against cars and those against fixed objects. A disproportionate number of the initial impacts are against the sides of the vehicle that rolls over (rather than the fronts).

Analysis from the British national accident data (STATS 19) from Kirk [3] shows that 6% of all car casualties were injured in cars with an element of rollover and 12% for killed and severe injured car occupants (KSI). Of all cars that have a fatal occupant or occupants, 15.1% have an element of rollover. For cars that have an element of rollover, accidents that occur whilst negotiating a bend are far more common than for non-rollover cars, although overall normal going ahead accidents are most common. For cars that have an element of rollover, 77% are single vehicle events. For single vehicle crashes from crashes with another vehicle the most commonly vehicle struck is another car. Of all cars, 3.9% that have an injured occupant have a rollover and do not impact another vehicle. For cars with killed and severe injured occupants, frontal impacts are clearly the most common. A higher proportion of vehicles that have an element of rollover leave the carriageway, for KSI cars 81.9%. This also correlates with an increased proportion of objects hit off the carriageway for cars with an element of rollover, for KSI, 67.7%. An increase in KSI rate is evident when the car leaves the carriageway. For cars with an element of rollover, the most commonly struck object off the carriageway is a tree followed by entering a ditch. The most common car rollover accident scenario is for the vehicle not to impact any other vehicle or vehicles and to hit a fixed object off the carriageway and no object on the carriageway, accounting for 45.5% of all vehicles that have an element of rollover and an injured occupant. Of all severity rollover cars, 18.9% have no other vehicle impact or any codeable impact with an object on or off the carriageway.

Sferco et. al [4] were looking at differences of rollover data for US and Europe and it was shown that rollovers, as a single event (rollovers without the occurrence of any impact) are rare events in Europe. Fay [5] found that rollovers occur more frequently as part of more complex accident sequences involving multiple impacts. In most of these multiple impact cases, the first event in the sequence is an impact rather than a rollover. In the US, rollovers were identified as a significant safety issue, because a rollover crash is far more likely to result in fatalities than a non-rollover. Although only 3 percent of all passenger vehicles involved in crashes in 2000 experienced rollover, 20 percent of passenger vehicles involved in fatal crashes rolled. In particular, Sport Utility Vehicles (SUV), Multi Purpose Vehicles (MPV) and other Light Trucks are over-represented in rollover accidents.

Real world accidents for in-depth studies

For this investigation a database containing about 150 real world passenger vehicle rollover accidents was used. The strategy for choosing these cases for in-depth studies is based on the results of the statistical investigations as well as the quality of documentation of the cases. These cases were reconstructed numerically using the accident reconstruction software tool PC-Crash [6].

Method

Relevant mechanical parameters

The PC-Crash reconstruction files of the reconstructions provided mechanical data on tire side forces of all four wheels, velocities in x, y and z direction, the roll angle, the roll rate and the angular acceleration as these seemed to be of importance for detecting a rollover. After studying the provided data it seemed promising to further assess the importance of the roll rate for categorisation as it is used in state of the art technologies. For the general analysis it was focused on the roll rate and the roll angle as the relevant parameters.

This focus seemed plausible as a high roll rate at a low roll angle might not lead to a rollover whereas even a low roll rate at a large roll angle with the centre of gravity nearly above the wheels will cause a rollover. There should be a direct interrelation between the parameters roll rate and roll angle and a rollover case.

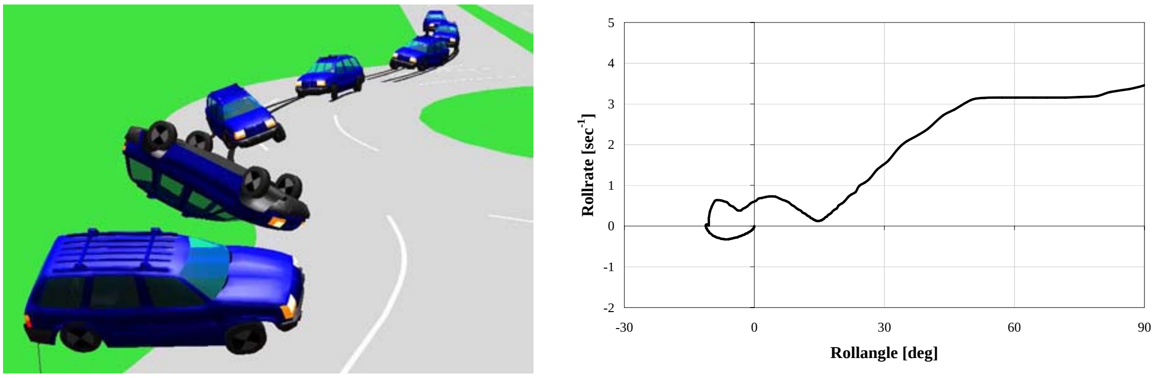
In-depth analysis of relevant cases

General Analysis from Point of Conflict to End of Rollover

The first step of analysing the PC-Crash data was to plot the roll rate [deg/s] as a function of the roll angle [deg]. As the different rollover cases analysed vary widely in their roll angle, the roll rate – roll angle graphs show very different patterns in the latter stages of the roll. The vehicle behaviour during the rolling phase (i.e. after the initial event) seems to happen at random.

As many graphs showed similarities at lower roll angles, the roll rate – roll angle graphs were plotted from the roll angle at the initial event ($\varphi_{t=0} = 0°$) to a roll angle of $\varphi = 90°$. This range also includes the relevant phase for detecting a possible rollover and for triggering possible safety systems.

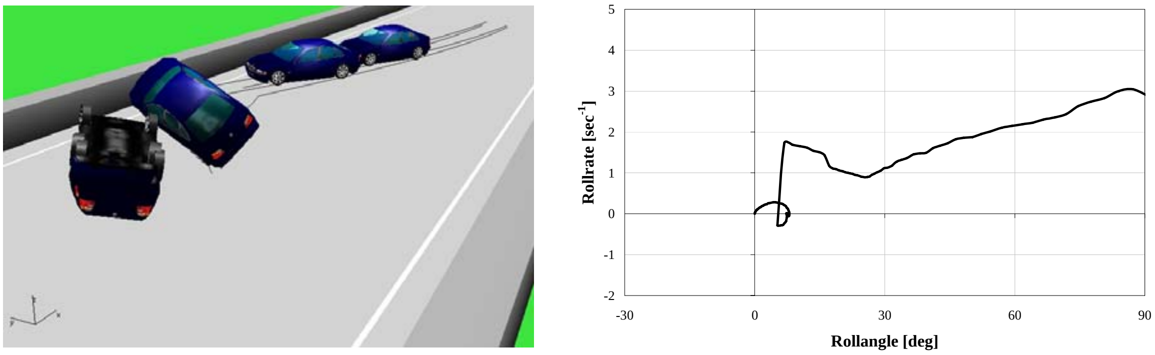
Figure 5. Example for basic analysis of a whole rollover event up to 90° roll angle



When compared, groups of these graphs ($\varphi = 0°\ldots90°$) showed distinctive similarities and could be sorted into a categories. The most obvious group is formed by cases with an impact. The graphs show distinctive differences between cases without impact or with impact.

Category 1: Rollover caused by some kind of impact (other vehicle, tree, or other)

Figure 6. Example for category 1

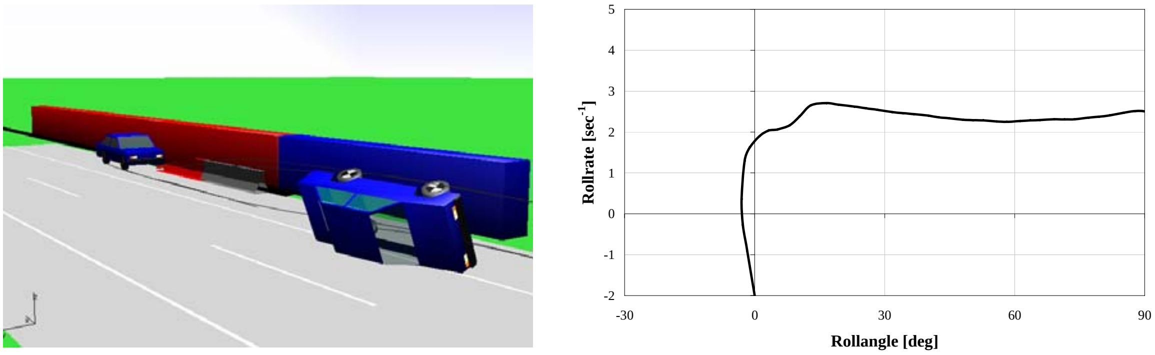


The initial roll rate jumps to form a high peak and rapidly decreases afterwards before increasing again at roll angles of approximately 45°. If the impact is preceded by yawing and / or a sideway skid the graph may show a “γ”-form or encircle the centre of the co-ordination system before it shows the characteristic mentioned above.

Category 2: Rollover caused by ramp like object (e.g. flat car, guard rail, slope)

The roll rate quickly rises to a high level but does not decrease as significantly afterwards as in category 1. The yaw angle remains at low levels (less than 30°)

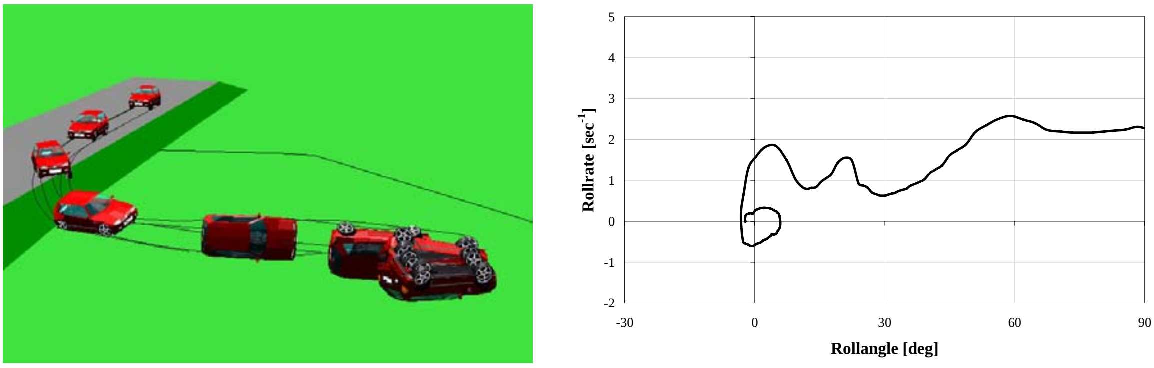
Figure 7. Example for category 2



Category 3: Rollover caused by yawing and skidding sideways with vehicle being affected by a ditch or slope

The yaw angle at the start of the roll action differs widely (0° to over 200°) but on average seems to be lower than in category 4.

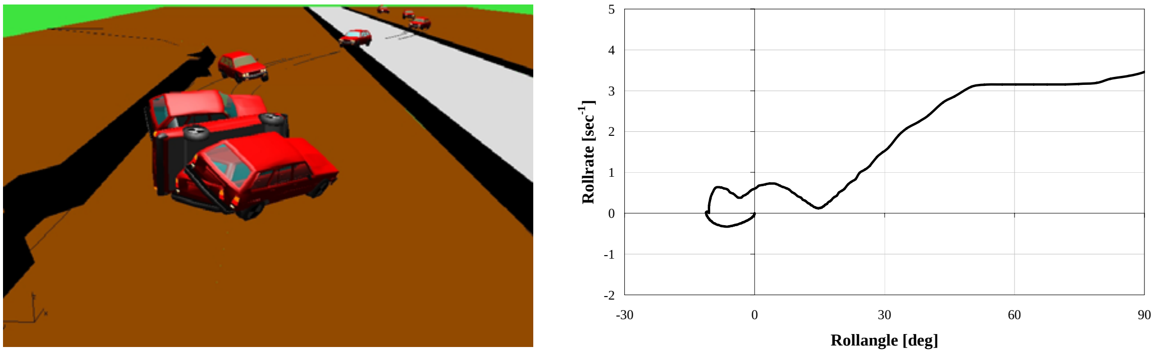
Figure 8. Example for category 3



Category 4: Rollover caused by yawing and skidding sideways on an even surface

The roll rate builds up and the roll angle increases a little until it reaches a constant value. The roll rate then decreases again as far as zero deg/s or below. When the vehicle starts to roll the roll rate rises to a high level. The graph shows a picture resembling the Greek letter "γ". Due to strong yawing the graph may encircle the centre of the co-ordination system. The increase in the roll rate is slower than in cases with impact. The yaw angle at the start of the roll action is mostly in the range between 70° and 90°.

Figure 9. Example for category 4



Category 5: Rollover caused by other causes

The graphs of pitch overs show a very different characteristic in the roll rate –¬ roll angle diagram which does not seem to be comparable to the previous cases

In-depth Analysis for first phase of Rollover

In a second phase the reconstructed cases were analysed from the start of the rollover (as described below) up to 90 degree roll angle. For these analyses the following time-depending mechanical parameters were available for the reconstructed cases:

Rotational motion: angle, angular velocity and angular acceleration for rolling, yawing and pitching (referenced to centre of gravity in a reference coordinate system)

Linear motion: linear movement, linear velocity and linear acceleration in x-, y-, and z-direction (referenced to centre of gravity in a local coordinate system)

Additional: tire forces (side and normal)

For rollovers different parameters were analysed regarding their characteristics over the roll angle. The following parameters show the most significant influence for categorisation for the first phase of rollover:

- Roll rate vs. roll angle
- Lateral velocity vs. roll angle (in a global coordinate system)
- Longitudinal velocity vs. roll angle

Due to the long duration of a rollover the characteristic becomes more and more randomised if the whole rolling phase is used. So the rollover is divided into 4 phases (see Figure 10):

- Pre-roll phase
- Point of no return
- First phase of roll
- Rolling phase

Pre-roll phase

The pre-roll phase is the phase when the vehicle reaches a destabilised driving mode till the “point of no return” where the rollover cannot be avoided. In this phase active safety can be used to stabilise the vehicle and to avoid exceeding the “point of no return”.

The more it seems to be unavoidable to stabilise the car passive safety devices can also be pre-activated in this phase. If possible estimation on the severity of the impending rollover should be done.

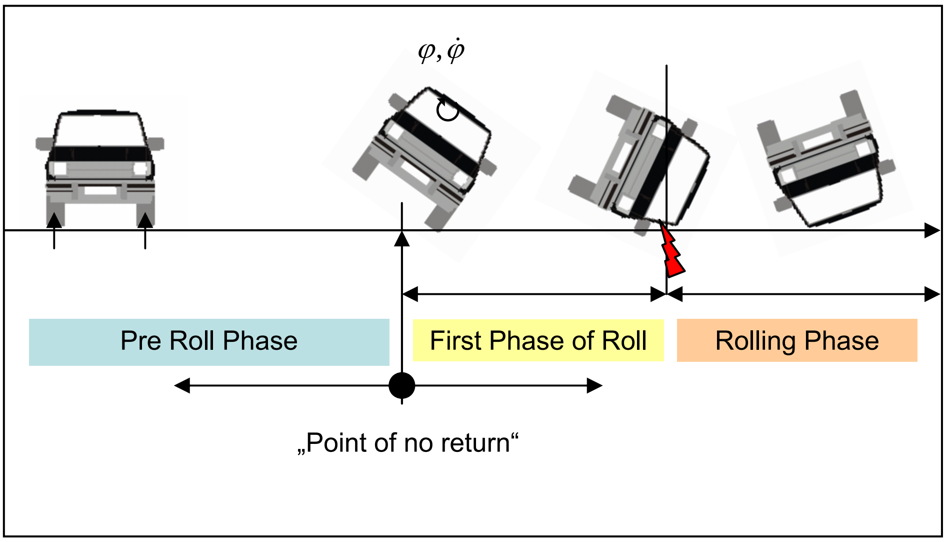
Point of no return

This is not really a time point. It is more a short time interval when the rollover cannot be avoided and passive safety devices have to be activated to reduce the risk of injuries to occupants.

First phase of roll

The first phase of roll starts at the “point of no return” and covers approximately the first 90 degrees of roll angle. It ends with the first impact of the vehicle structure with the ground. The car can always be in contact with the ground or lose the contact (flying phase).

Figure 10. Phases of a Rollover



Rolling phase

The rolling phase is the phase from the end of the first phase of roll until the vehicle's rest position. The most important parameter for this phase is the number of turns.

Figure 11. Determination of first phase of rollover for a 360° left-side rollover

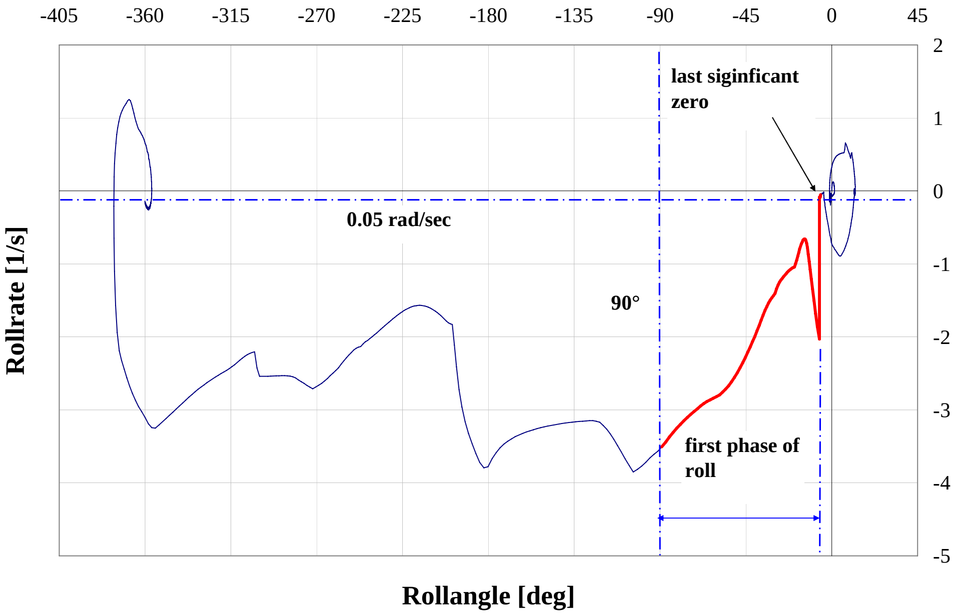
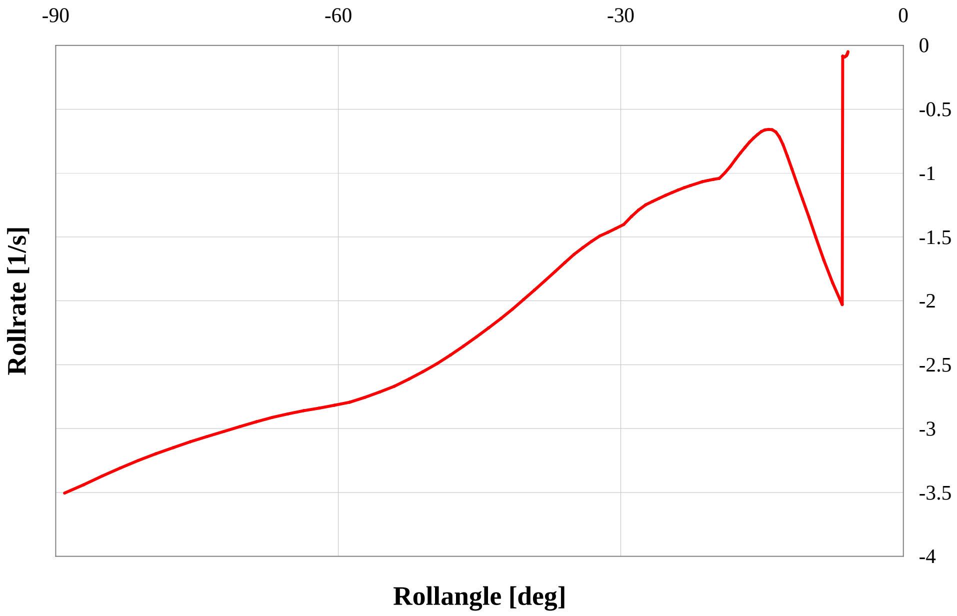


Figure 12. First phase of rollover for a 360° left-side rollover



For the detailed analysis of the rollovers the first phase of roll was used and defined in a little modified way. The start of this phase – the point of no return – was defined as last significant zero of the roll rate vs. the roll angle. Due to the numerical data a threshold for the zero of the roll rate of 0.05 rad/sec was used. For the end of the fist phase of roll the 90 degree roll angle criteria was used due to the difficulties in finding the first impact in the rolling phase.

Results

Based on the procedure described all cases were analysed in detail for their significant roll angle – roll rate behaviour for the first phase of rollover. Also the longitudinal and lateral velocity characteristics were investigated and the following results were gained.

The main rollovers can be classified by the following categories:

- Impact induced Rollovers
  - o $\Delta v < 30$kph
    $\Delta v > 30$kph
- Ramp-like object induced Rollovers
- Skidding & Yawing
  - o Trip induced Rollover
  - o Vehicle dynamic induced (Turning and Rollover)
- Others

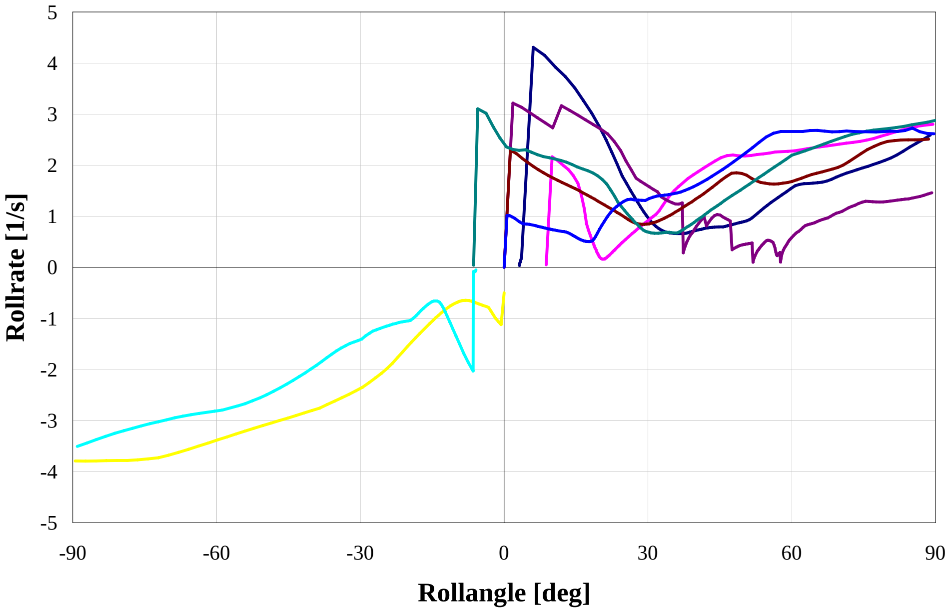
Impact induced Rollovers

Rollover accidents induced by any kind of impact (mostly with another vehicle but also with other object). This type of rollover scenario is divided into tow sub-categories depending on the change of velocity (*Δv*) during the impact. For high *Δv* values the impact inducing the rollover is considered as more harmful event than the following rollover.

Δv < 30kph

For this scenario the *Δv* for the rolling vehicle is less than 30 kph. This is based on the analysis of the real world accidents. Figure 13 shows the characteristics for this type of rollover. The initial roll rate jumps to form a high peak caused by the initial impact. For increasing roll-angles the roll-rate decreases fast and then increases moderately.

Figure 13. Characteristics of Rollover induced by an impact with Δv < 30kph for different real world accidents



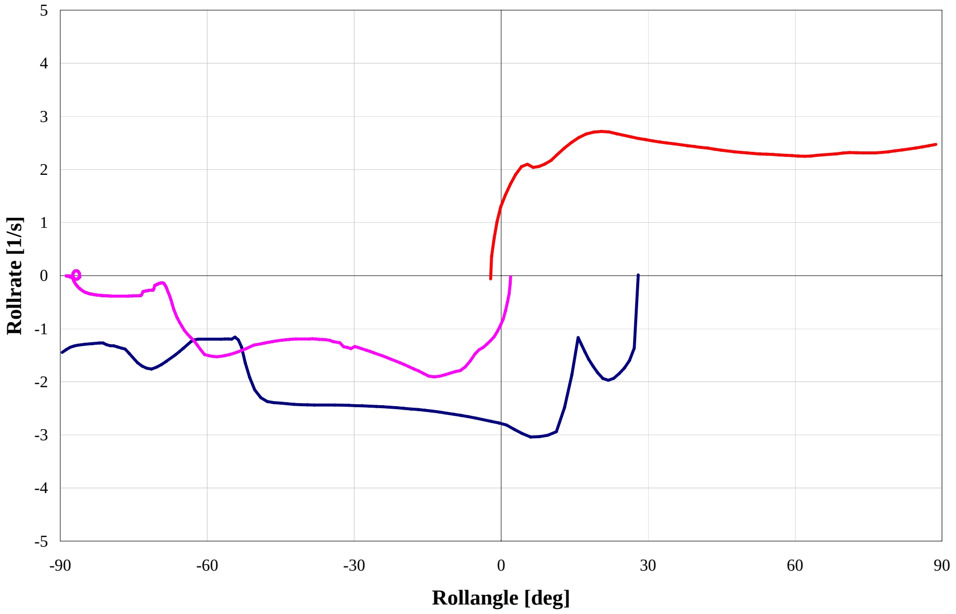
delta v>30kph

Rollover accidents with a Δv higher than 30 kph are considered to have a sever front or side impact. Therefore it is necessary to activate the passive safety system for this kind of impact. The following rollover is not as harmful as the initial impact.

<u>Ramp-like object induced Rollovers</u>

This type of rollover is induced by any kind of ramp-like object. This could be a guardrail, the end of a concrete barrier as well as an embankment, slope or the bonnet of an opposing car. As can be seen in Figure 14 the roll rate rises quickly to a high level and stays nearly constant for the increasing roll-angle. The analysis also shows that the longitudinal velocity is high and the lateral velocity is on a low level.

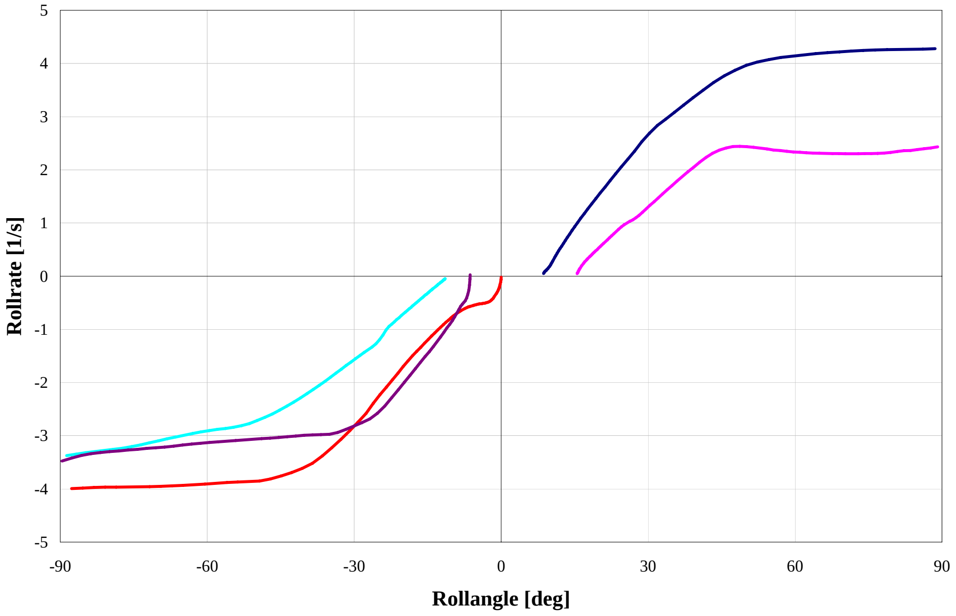
Figure 14. Characteristics of Rollover induced by ramp-like object



Skidding & Yawing - Trip induced Rollover

This scenario happens when a car trips e.g. the tires dig into gravel or soil. This is equal to a higher friction acting in the tire-ground contact and therefore a higher lateral force can be obtained. Figure 15 shows that the roll rate increases moderately to a constant value. The longitudinal velocity decreases to a constant value and the lateral velocity decreases to a constant value rapidly.

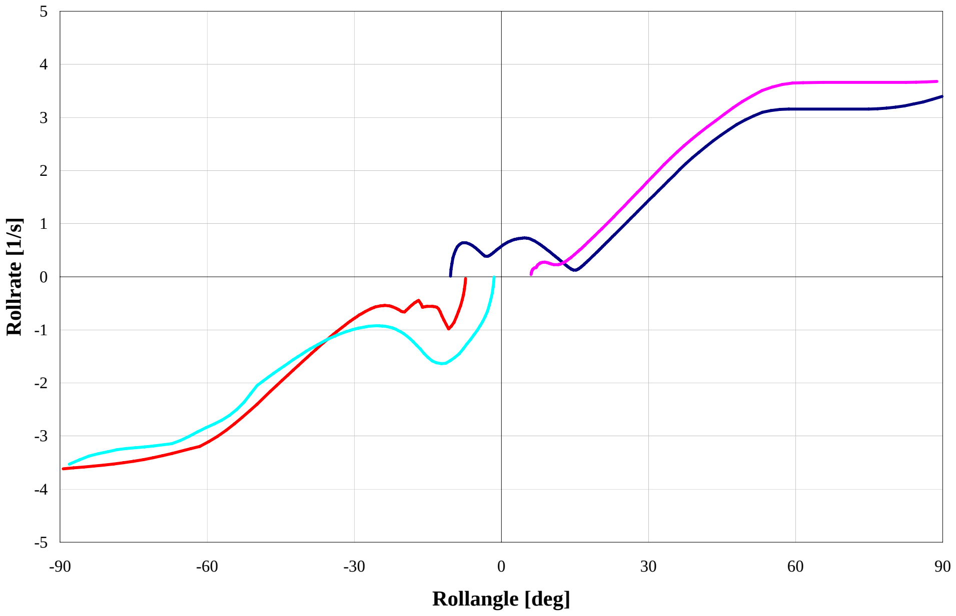
Figure 15. Characteristics of a Rollover induced by tripping



Skidding & Yawing - Turning and Rollover

In this type of rollover the vehicle is normally driven on an ordinary surface. Due to the driving manoeuvres and the dynamic characteristics of the vehicle the car reaches an unstable mode resulting in a rollover. The friction in the tire-ground contact is not increased as in the case of tripping. Figure 16 shows that there is a significant initial oscillation in roll-rate caused by the unstable driving mode. The over all behaviour is the same as in the case of a tripped rollover.

Figure 16. Characteristics of a Rollover induced by turning



Others / Special Others

For the remaining rollovers its not easy to categorise them particularly as they are very rare events e.g. the end-over-end rollover, where the roll-axis is lateral. Some other special cases are the free fall of a vehicle e.g. down from a bridge or cases where the car yaws and the back of the car is tripped when contacting the soil on the road side.

Discussion

The rollover cases chosen for reconstruction represent the statistical results from the survey laid out in the introduction as follows:

According to the STATS 19 77.3 % of all rollovers are single vehicle events. From the 73 reconstructed cases 59 (81%) were single vehicle event cases which is the same proportion as found out by Sferco et al [2] and Kirk [3]. 43% of the reconstructed cases have an initial impact before the rollover which is a little less than Fay's [5] (58%) findings. In 12 reconstructed cases (16%) the vehicle impacts an object off the carriageway. According to Kirk this proportion is 46 %.

In most rollover cases the vehicle turns around its longitudinal axis and makes 4/4 turns or less. The proportion of rolls to the right or to the left is half / half. Accordingly, of the reconstructed cases only 5 vehicles (7%) turned around their lateral axis. Of the others, 49 vehicles turned 4/4 or less (67%). In 16 cases (22%) the vehicles turned more that one turn (5/4 to 30/4). For 7 cases it was not possible to account for the number of turns around the longitudinal axis as they were either pitch overs or the reconstruction file did not give enough information. Of the vehicles turning around their longitudinal axis 32 turned to the right and 31 to the left.

According to GIDAS and CCIS analysis by Sferco et al [2] only around one third of all rollovers occur as single, isolated events in the UK and Germany. The remainder occur during more complex multiple impact crash sequences. 43 of the reconstructed cases had no impact and can be regarded as single isolated events. This proportion (59%) is about twice as high as stated by Ford.

Conclusions

The rollover categorisation defined in this work can be used either by non-professional analysts for pre-categorisation of an accident. The rollover can be compared easily to the four main categories: impact induced, ramp-like object induced, skidding and yawing or others. When reconstructing a real world accident a final classification can be done when analysing the vehicle trajectory and its kinematical data. The selected real world accidents represent the statistical finding from other authors.

List of deliverable(s)

D2.4 Overview and description of different rollover categories

Acknowledgements (if appropriated)

These results were published on the ESAR – Expert symposium on accident research, Hannover, in 2004. They are printed in the conference proceedings.

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2 R Sferco, P Fay, Vehicle Rollover in Europe - A Real World Overview, Presentation, Ford Motor Company, European Community – R&TD-Project – 5th Framework-Programme “Growth” – Project “Rollover” G3RD-CT-2002-00802, 2003

3 A Kirk, Great Britain Statistics , Report Work package 1 – Task 1.1, Vehicle Safety Research Centre, European Community – R&TD-Project – 5th Framework-Programme “Growth” – Project “Rollover” G3RD-CT-2002-00802, 2003

4 R Sferco, P Fay, S Asic, Comparison of US and European Rollover Data, Report Work package 1 – Task 1.1, Ford Motor Company and Delphi, European Community – R&TD-Project – 5th Framework-Programme “Growth” – Project “Rollover” G3RD-CT-2002-00802, 2003

5 P Fay, R Sferco, R Frampton,. Vehicle Rollover - An Important Element in Multiple Impact Crashes, ESV 2003, Japan, 2003

6 PC-Crash User Manual, Dr. Steffan Datentechik Linz, Austria, 2003

8. Task 3.1: Component tests (Concept)

Scientific and technical description of the results

The main aim of this task was to determine the dynamical, unidirectional performance of different roof crush scenarios to validate occupant space intrusion for simulation

Therefore BOLTON INSTITUTE performed a quasi static roof crush test, MIRA a dynamic roof crush test and CONCEPT TECHNOLOGIE free-motion-headform tests.

Secondly material behaviour of the interior was to be determined to validate computer modelling of occupant impacts.

Body-in-white component tests performed by BOLTON INSTITUTE and seat tests done by CONCEPT TECHNOLOGIE should help to reach this aim.

Roof crush scenarios

Static roof crush test

A Ford Fiesta 3 door body-in-white was used as a test specimen. The car body-in-white was fixed to the ground at an angle of 6°. The load was applied by a platen under an angle of 8°; the rotation axis of the platen was offset about the longitudinal axis of the body-in-white. (Figure 17 and Figure 18)

Figure 17: Roof Crush Test Setup

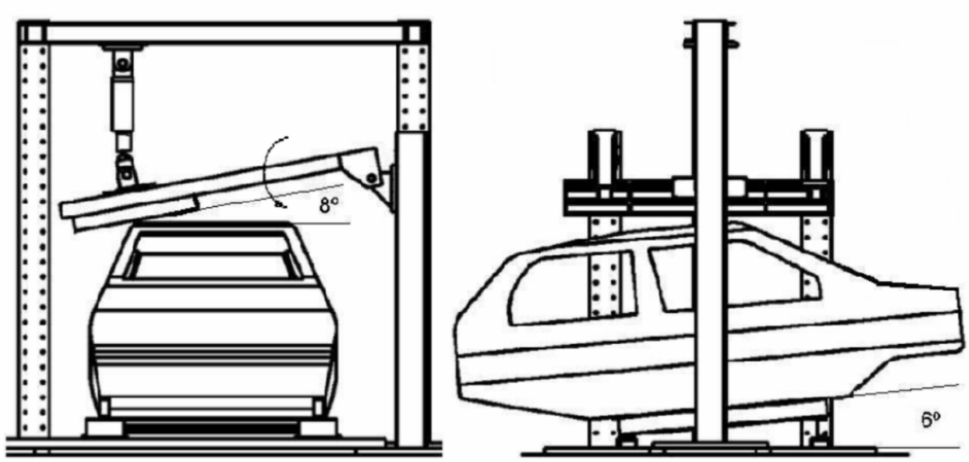


Figure 18: Pre and post test front view

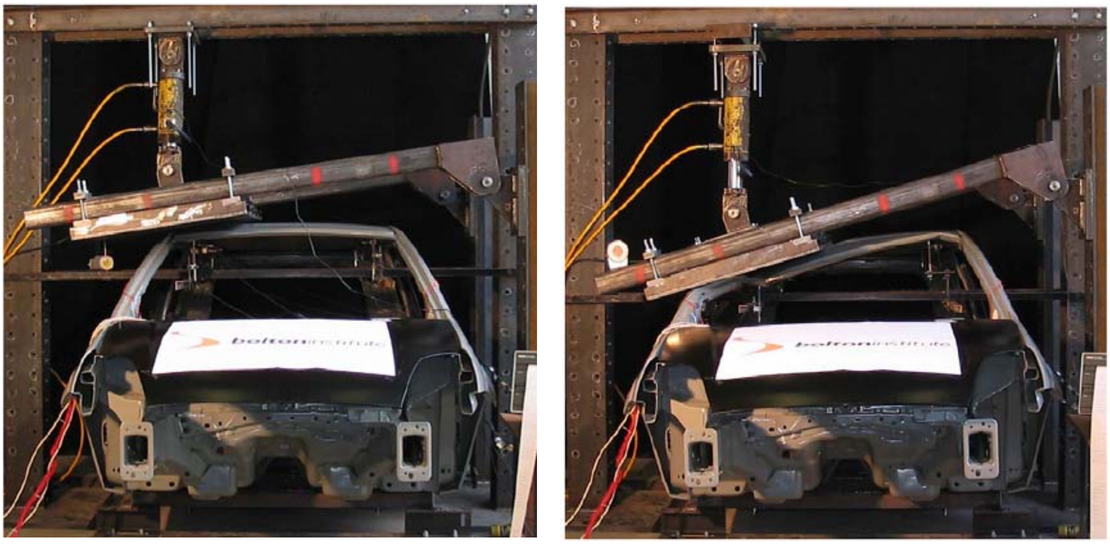
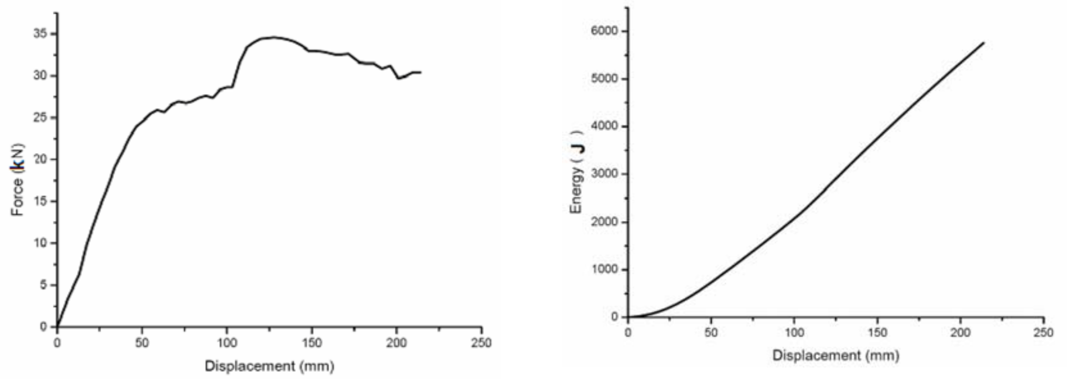


Figure 19: Force-displacement and Energy-displacement curve



The maximum force was 3460 KN and the energy absorbed was 5760 J after 213 mm roof deformation (Figure 19). The displacement inside the car was measured at three points. (Figure 20)

Figure 20: Roof deformation measuring points

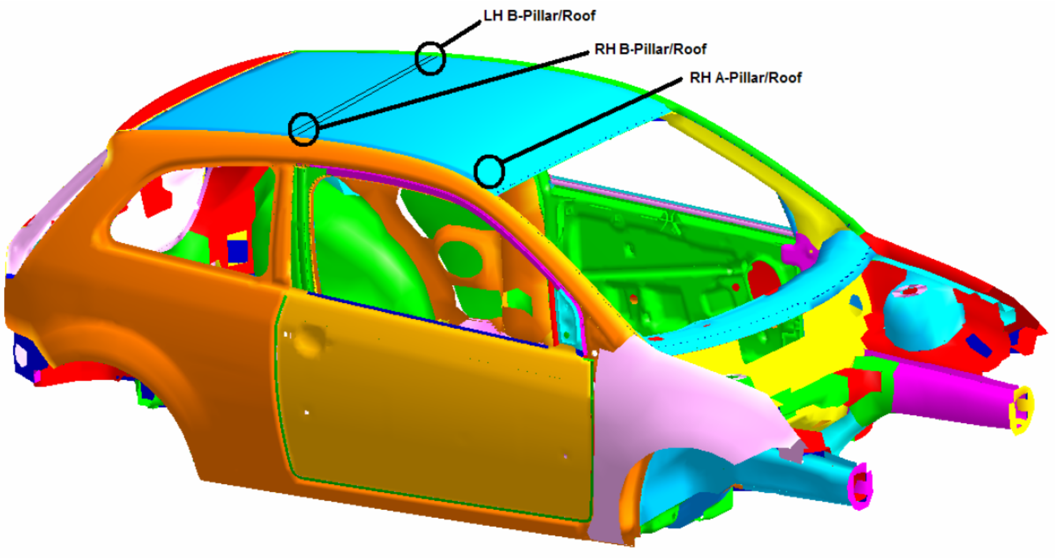
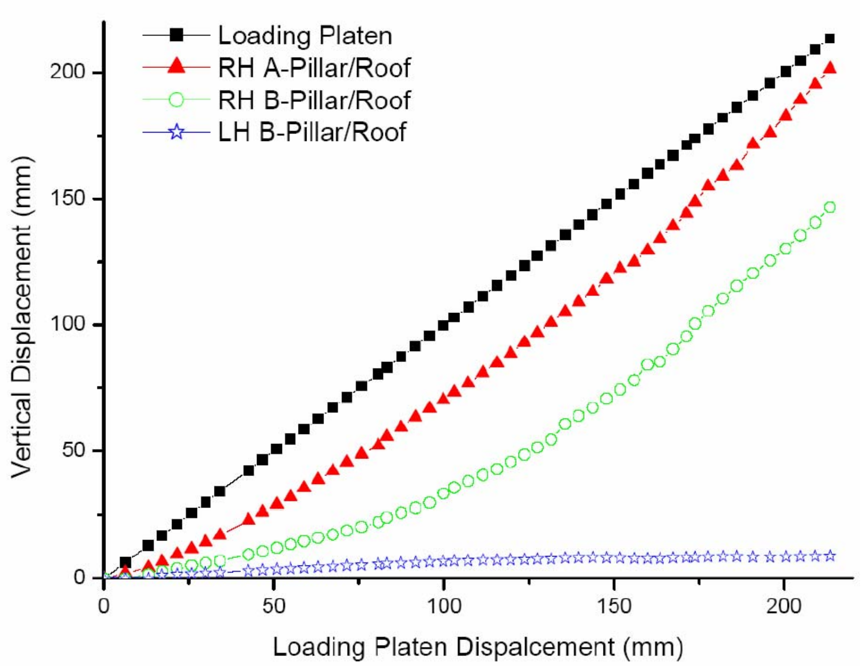


Figure 21: Roof deformation



The most deformed part is, as expected, the right A-pillar, followed by the right B-pillar and the left B-pillar. (Figure 21)

Dynamic roof crush test

A Ford Fiesta 3 door body-in-white was used as a test specimen. It was mounted on a sled and rotated to 40° roll and 10° pitch. A fixed steel plate was used as a barrier. (Figure 22)

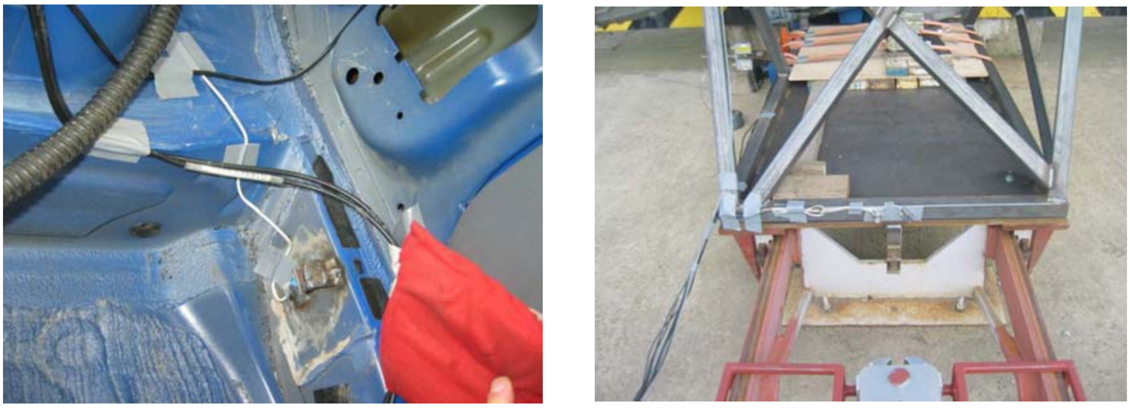
Figure 22: Pre-test rear and post test front view

Several accelerometers were attached to the car and the sled:
(Figure 23-Figure 25)

Figure 23: Left: Accelerometer 'car1' (LH A-Post by base of windscreen); Right: Accelerometer 'car2' (Top of A-Post by header rail)

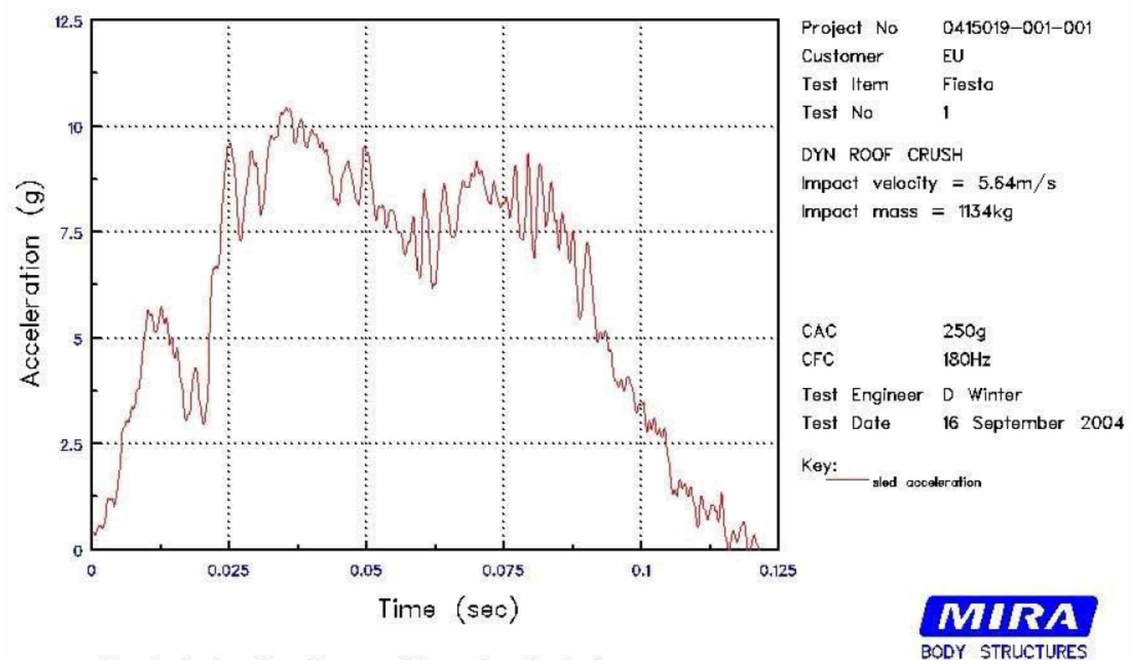
Figure 24: Left: Accelerometer ’car3’ (Top of B-Post cant rail); Right: Accelerometer ’car4’ (Rear of cant rail by tailgate)

Figure 25: Left: Accelerometer ’car5’ (Sill by B-Post); Right: Accelerometers ’sled1’and ’sled2’ (Rear of sled)



The test results are shown in Graph 1, Graph 2 and Graph 3.

Graph 1: Acceleration vs. Time for sled



Project No 0415019–001–001
Customer EU
Test Item Fiesta
Test No 1

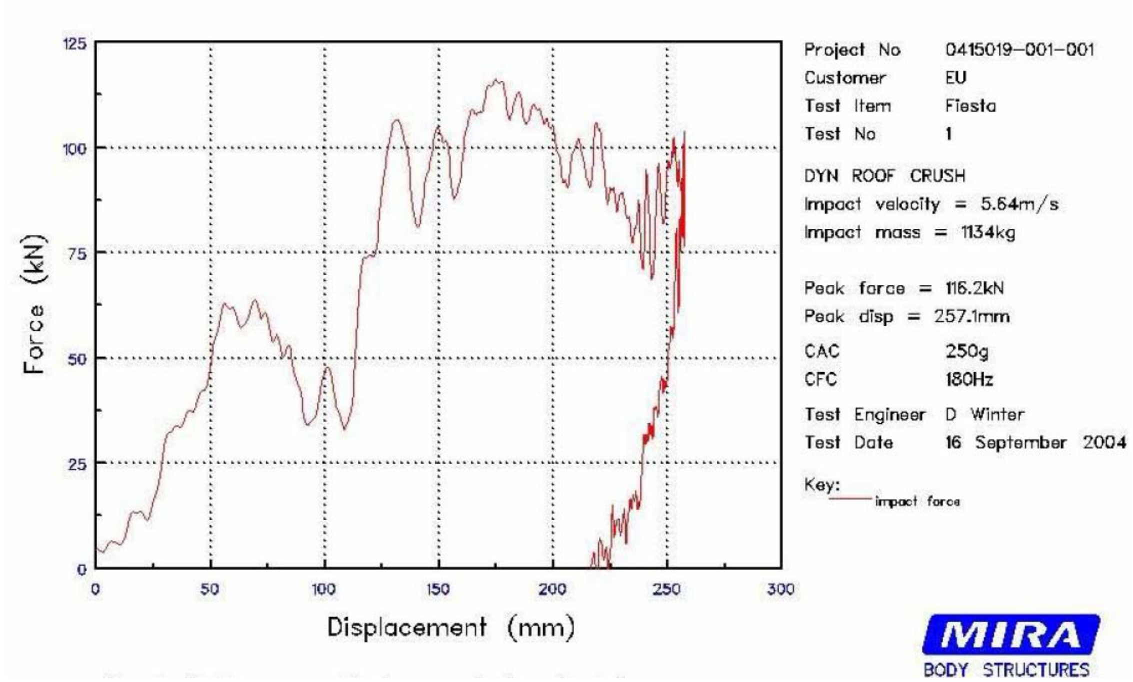
DYN ROOF CRUSH
Impact velocity = 5.64m/s
Impact mass = 1134kg

CAC 250g
CFC 180Hz

Test Engineer D Winter
Test Date 16 September 2004

Key:
sled acceleration

Graph 2: Force vs. Displacement



Project No 0415019–001–001
Customer EU
Test Item Fiesta
Test No 1

DYN ROOF CRUSH
Impact velocity = 5.64m/s
Impact mass = 1134kg

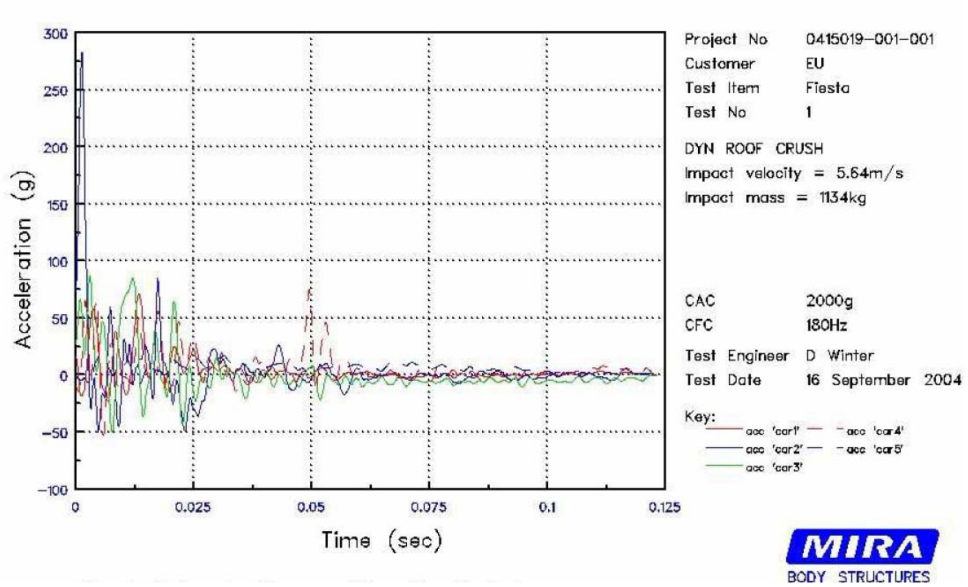
Peak force = 116.2kN
Peak disp = 257.1mm

CAC 250g
CFC 180Hz

Test Engineer D Winter
Test Date 16 September 2004

Key:
impact force

Graph 3: Acceleration vs. Time for car accelerometers



Free-motion-headform test

Two different scenarios with a Ford Fiesta were tested. First normal FMH-tests according to FMVSS 201 were performed. Secondly two FMH-tests were performed, which should simulate a “car is lying on the roof”-scenario.

Therefore a weight was putt on the cars roof. (Figure 26) The vehicle interior was impacted using a Free Motion Headform, m = 4,5 kg ± 0,05, a speed of 6,7 m/s and a free-flight of at least 25 mm. The acquired HIC(d) must not exceed a value of 1000. The tests were analysed according to the current status of FMVSS 201u.

Figure 26: FMH-testing points: Left: Normal test points; Right: Weight (300kg) on roof of the car

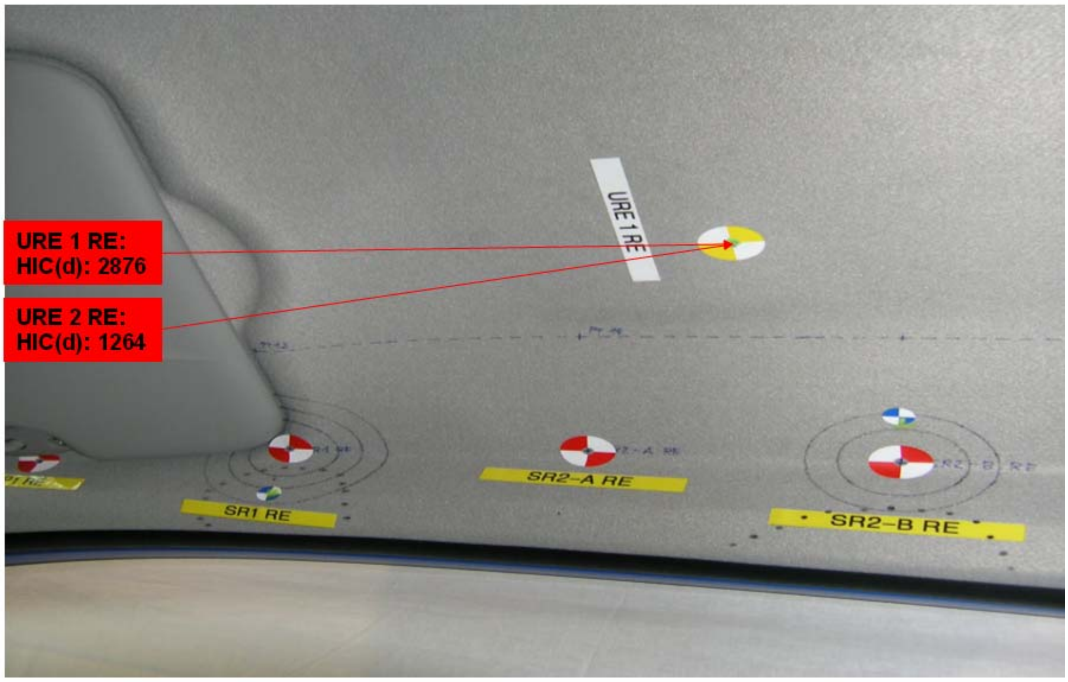
The test results are shown in Figure 27 and Figure 28.

Figure 27: Test Results for FMH-tests on right side of vehicle

Figure 28: Test Results for FMH-tests on left side of vehicle

The FMH-test for the rollover scenario was once performed with normal test conditions and once with a weight on the roof. As expected the HIC-value was significantly higher with the blocked roof. (Figure 29)

Figure 29: Comparison of HIC values for blocked and non blocked roof

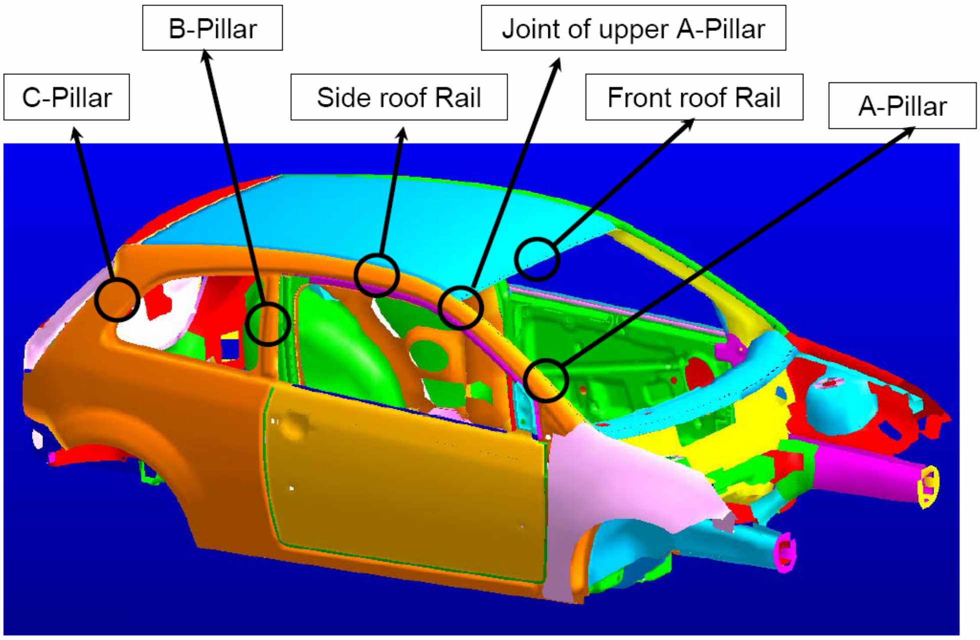


Material behaviour tests

Body-in-White Components tests

Purpose was to investigate the deformation properties and failure mechanisms of Body-in-White structural components. For that purpose bending tests were carried out with the pillars, the header and the side roof rail and the cross bar. The tests were performed with parts of a Ford Fiesta. The analysis of the static roof crush test lead to the following selection of components: (Figure 29)

Figure 30: Components to be tested



For each component the most significant type of deformation in the roof crush scenario was selected and tested with the single component. (Table 1)

Table 1: Component test matrix

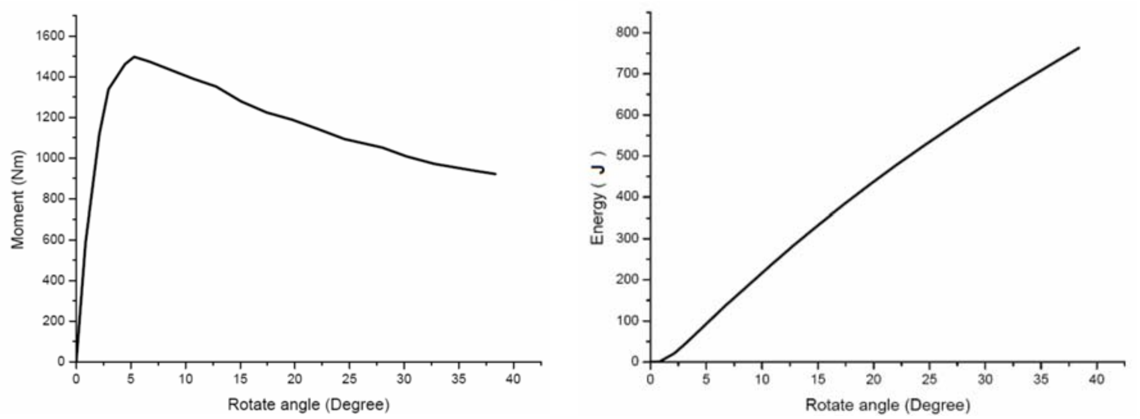
	Lateral bending	Vertical bending	3-Point bending	Compressive load / bending
A-Pillar	√			
B-Pillar	√			
C-Pillar				√
Header Rail			√	
Side Roof Rail			√	
Cross Bar			√	
Joint of upper A-Pillar		√		

The tests and their results are described in Figure 31 to Figure 44.

A-Pillar Lateral Bending:

Figure 31: Pre Test A-Pillar

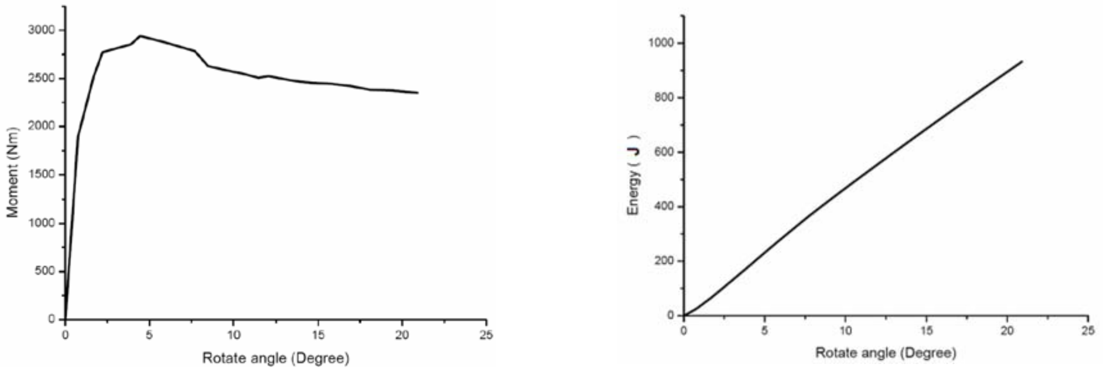
Figure 32: Test results Test A-Pillar



B-Pillar Lateral Bending:

Figure 33: Pre Test B-Pillar

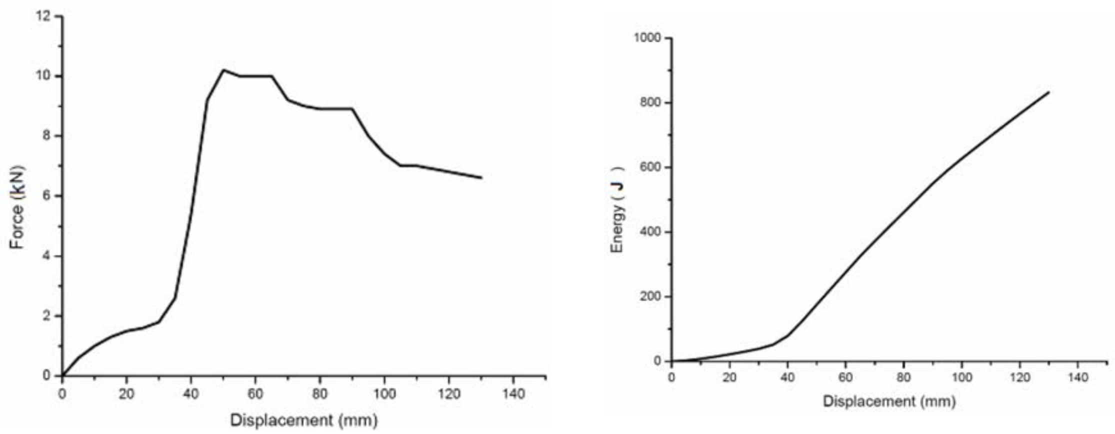
Figure 34: Test results B-Pillar



C-Pillar Compressive Load:

Figure 35: Pre Test C-Pillar

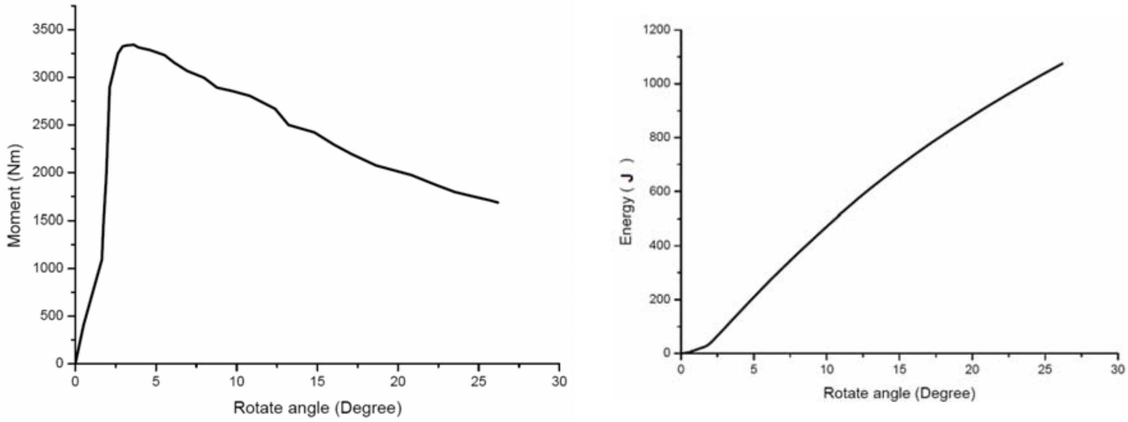
Figure 36: Test results C-Pillar



Upper A-Pillar joint bending test:

Figure 37: Pre Test Upper-A-Pillar

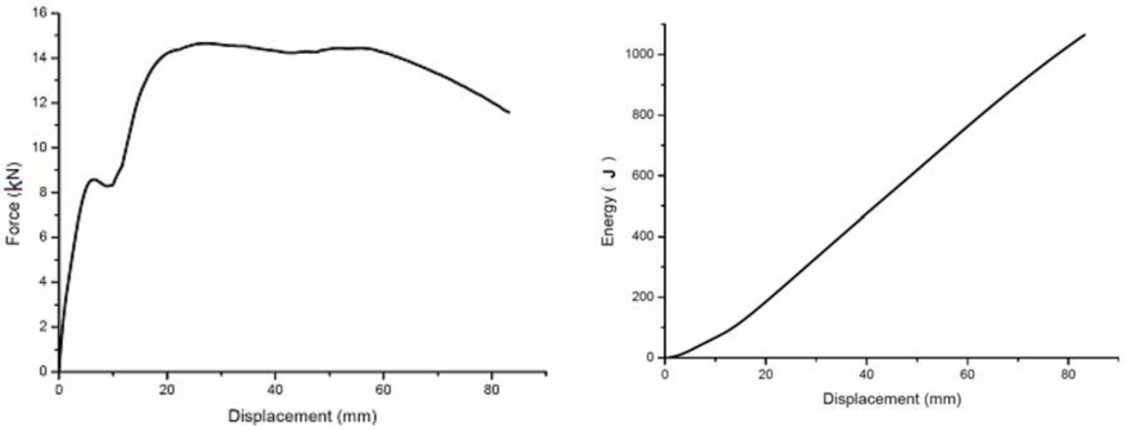
Figure 38: Test results Upper-A-Pillar



Side roof rail bending test:

Figure 39: Pre test side roof rail

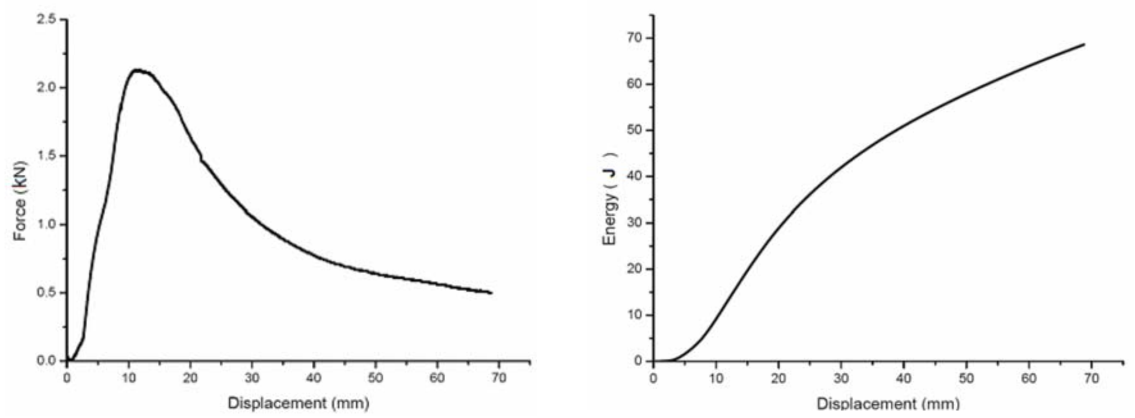
Figure 40: Test results side roof rail



Header rail bending test:

Figure 41: Pre test header rail

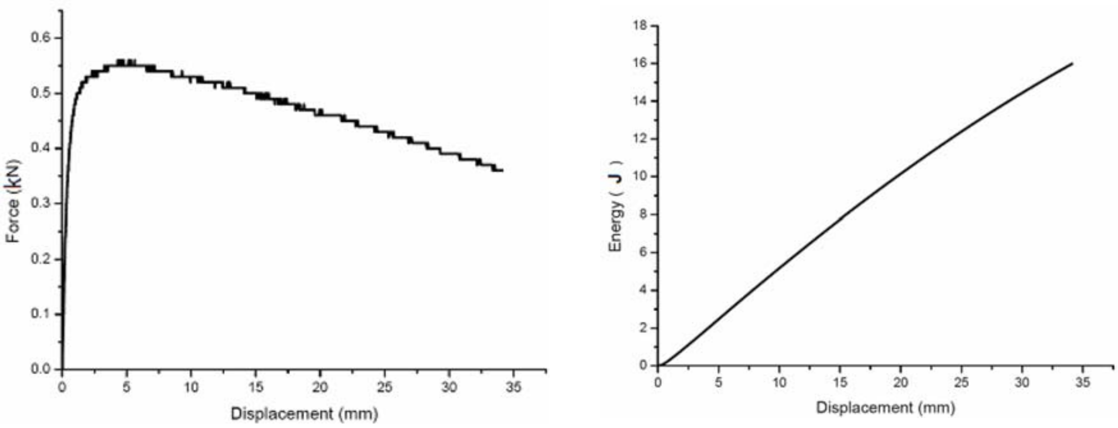
Figure 42: Test results header rail



B-Pillar crossing bar bending test:

Figure 43: Pre test B-Pillar crossing bar

Figure 44: Test results B-Pillar crossing bar



These tests were performed to characterise the structural behaviour of the seat for finite-element-validation. Seats from a Ford Fiesta were used.

The seat was fixed on a rack and a ball-shaped head on a hydraulic piston was used as an impactor for the static tests. (Figure 45)

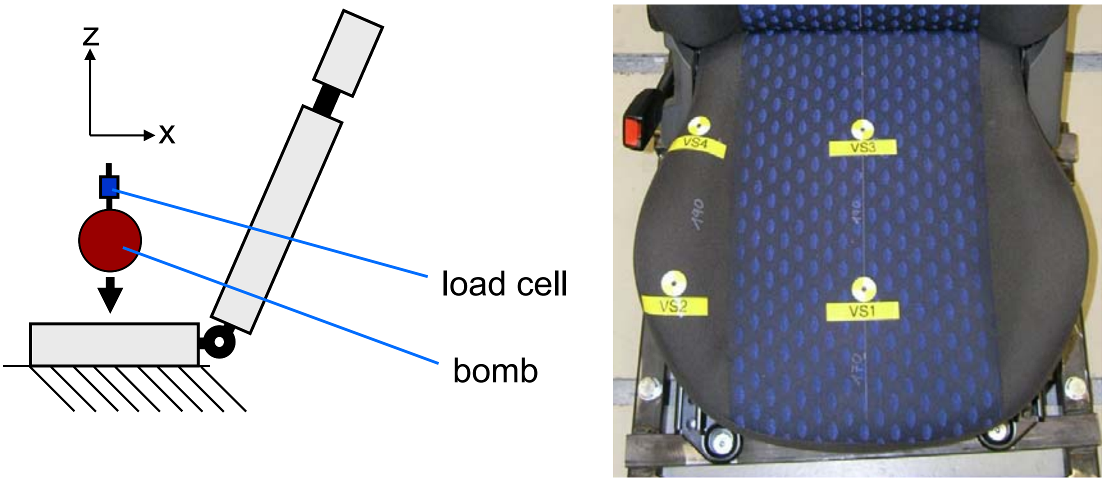
The load-displacement curves of the seat shell and the seat back and the bending moment of the joint of these parts were measured.

Figure 45: Left: Test points on Seat; Right: Test Setup

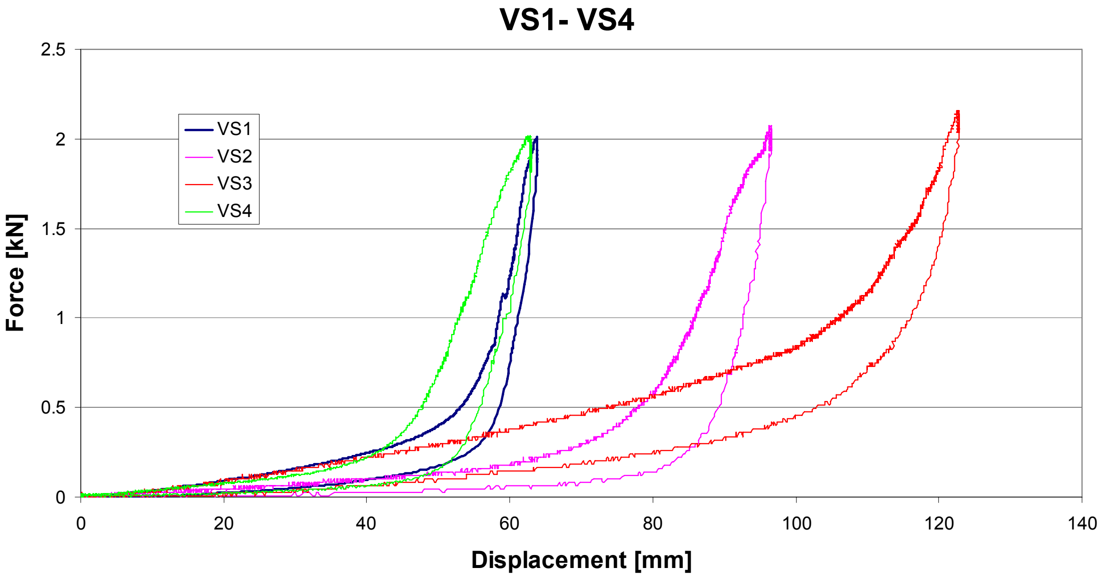
The ball shaped impactor was pushed into the seat with a load of up to 2000N and released afterwards.

Test of seat shell:

Figure 46: Left: Test setup; Right: Test points on Seat shell

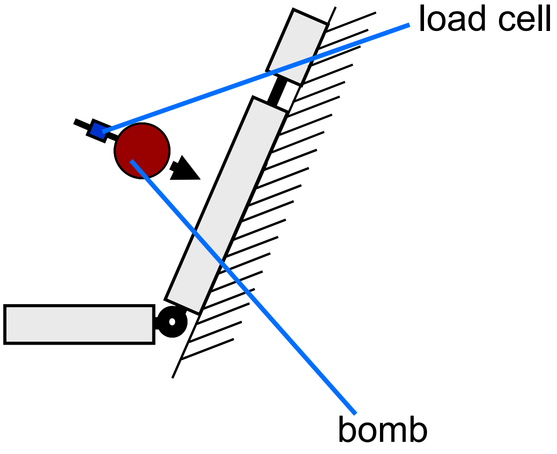


Graph 4: Force vs. displacement for seat shell



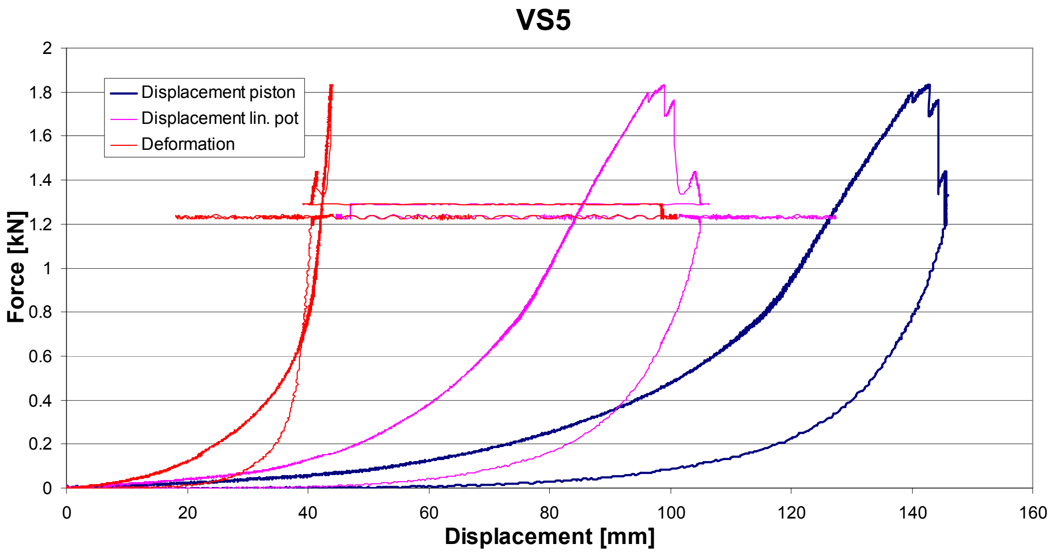
Test of seat back:

Figure 47: Left: Test points on Seat back



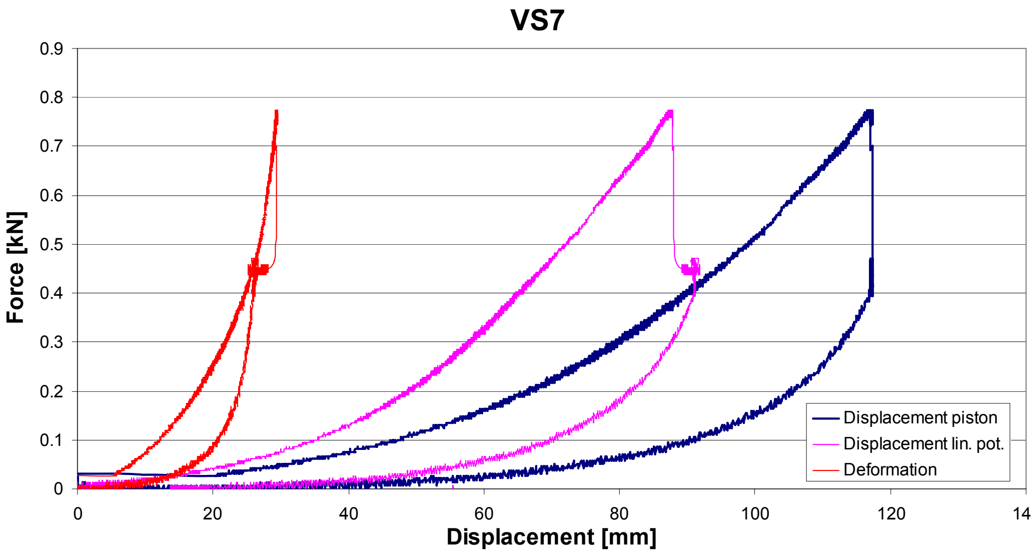
The backside in the middle was not restrained in its displacement by a supporting structure as is the case at the edge. To measure the deformation of the middle structure the displacement of the backside was measured with a linear potentiometer.

Graph 5: Force vs. displacement for seat back test point 5



The linear potentiometer lost contact during the test, but could be fixed to the backside again.

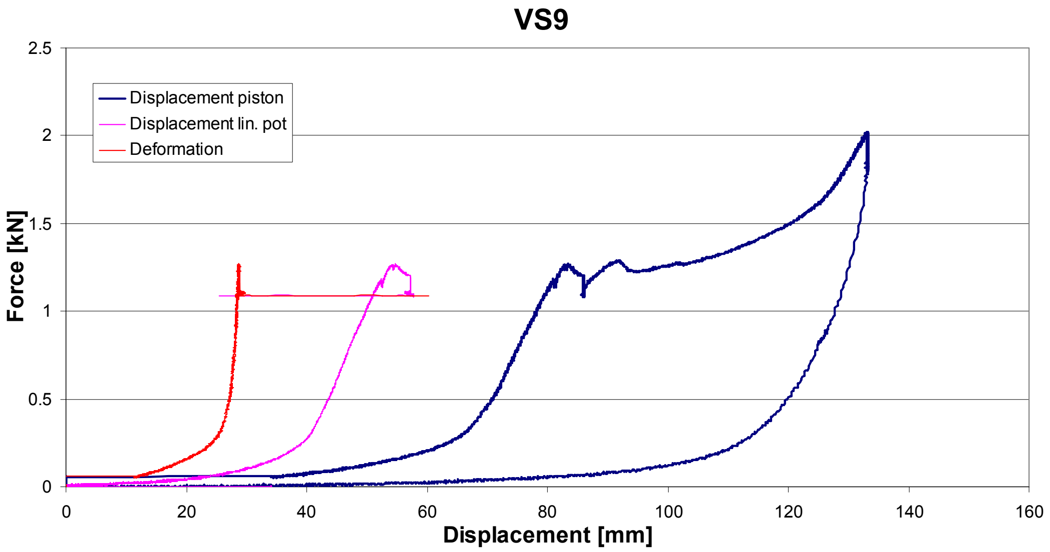
Graph 6: Force vs displacement for seat back test point 7



The test was stopped when the linear potentiometer reached its maximum.

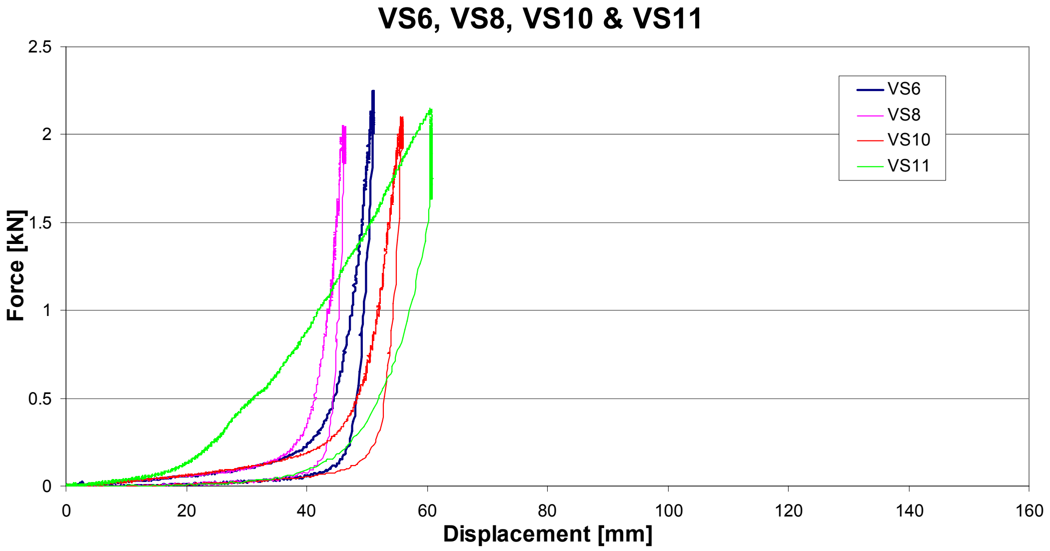
Before that point the breaking of some material that could not be defined was heard.

Graph 7: Force vs. displacement for seat back test point 9



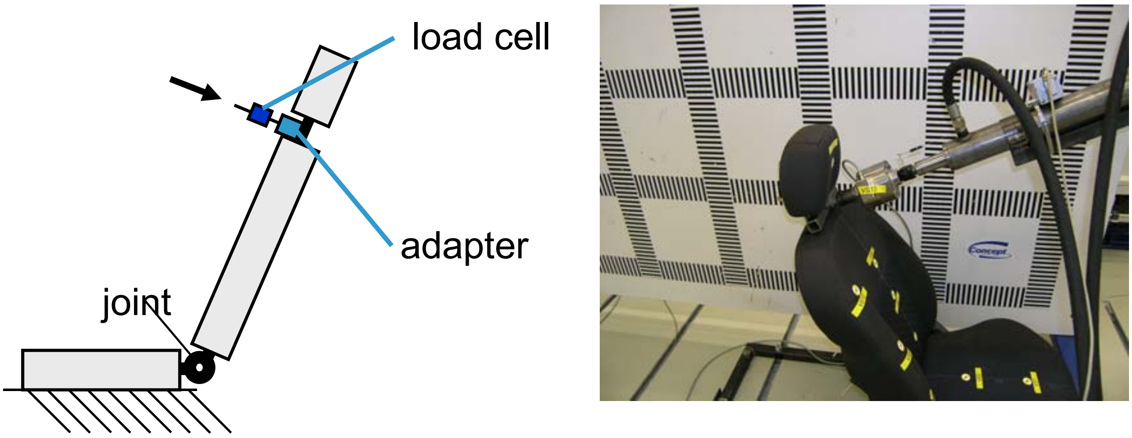
At a displacement of 60mm the potentiometer lost contact with the backside and could not be fixed again. The test could also not be repeated because the supporting structure was already damaged.

Graph 8: Force vs. displacement for seat back test points 6, 8, 10 and 11



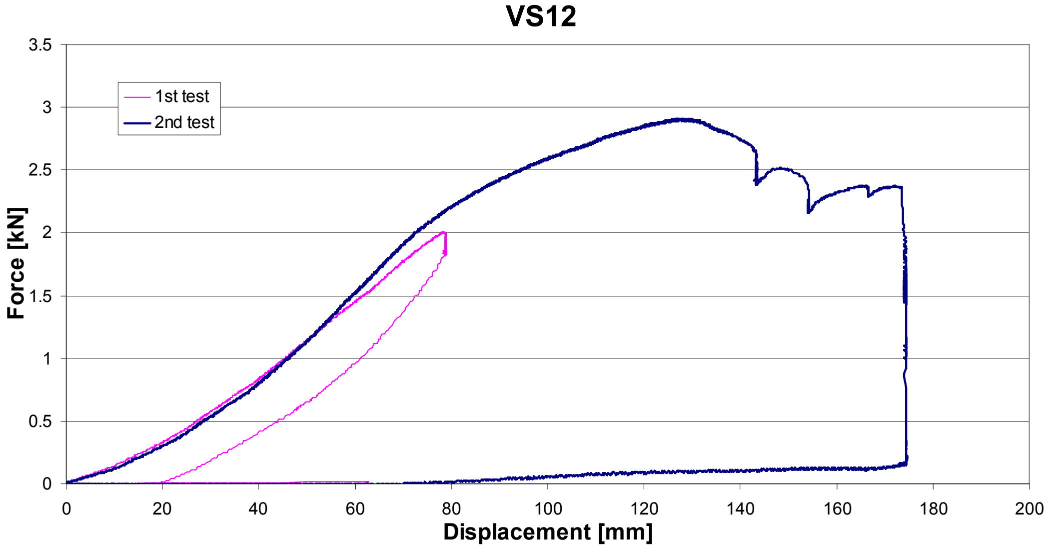
Bending moment of joint seat shell-seat back:

Figure 48: Left: Test points on Seat back



The first test was carried out with a load of up to 2000N. Afterwards a second test up to the breaking load of the joint was performed.

Graph 9: Force vs. displacement for test point 12



12 tests were performed to characterise the material behaviour of the seat. The tests with a maximum load of 2000N could only be performed once per seat, because of the occurring plastics deformations.

List of deliverable(s)

D3.1: Report on Component tests

9. Task 3.2: Full scale reconstruction (Mira)

This section summarises the results and findings of the accident reconstructions conducted in Task 3.2 as part of the Rollover project.

Aim

The aim of Task 3.2 was to investigate the viability of conducting rollover accident reconstructions using the available information from the accident scene to determine their usefulness as a research tool in future rollover investigations. The important factors pertaining to achieving reproducible rollover accident reconstructions were to be highlighted as part of this Task.

Deliverable

The deliverable for Task 3.2 was a report on specifications for crash rollover tests, but it was discovered that a single reproducible test based on an accident reconstruction was not a practical option. The report detailed the findings of these reconstructions and stressed the importance of the information extracted for sensor specifications and development.

Comparison of Initially Planned Activities and Work Actually Accomplished

It was initially specified in Annex 1, Description of Work of the Rollover Consortium Agreement that about seven accidents would be reconstructed. The outcome was that only four cases were selected for reconstruction. This was due to the following issues:

- The availability and number of vehicles needed for the tests
- The amount of time, cost and effort required to perform the reconstructions was far higher than expected

Selection of Accident Reconstructions

Data and analysis conducted in Work Packages 1 and 2 were used as a basis to select suitable accident reconstruction cases. The accident cases were grouped into categories, as described in Work Package 2. The number of cases in each category was reduced to about two or three, subject to the reliability of the PC Crash reconstruction, crash scene data and injury levels. These remaining cases were discussed in detail and the final selected reconstructions allocated to the relevant Partner involved in Task 3.2.

It was recognised by all Consortium members that it could be difficult to replicate the actual accident and that there was a risk that they may not be accurately reproduced, given the chaotic nature of these accidents. In general there were a number of concerns:

- Accident scene replication. The use of test rigs and fixtures could detract from the actual accident site.
- Occupant vs. dummy response. The difference in responsiveness caused by the inability of the ATDs to replicate human muscle movement was an unknown factor with respect to injuries recorded from the accident. The HIII was chosen because it had full length arms.
- Difference in test vehicle to accident vehicle. Due to financial constraints, the Consortium was restricted to the use of Ford Fiesta MY2003 vehicles, rather than being able to purchase vehicles to the same specification as that of the accident.

Even with these concerns, it was considered useful to continue with the accident reconstructions for the following reasons:

- If the test did not closely replicate the accident, it should at least exhibit the characteristics for that particular category of rollover accident.
- The response of the ATDs could be compared to the accident injuries to assess the suitability of using ATDs as part of a future test procedure or protocol.
- The influence of side and curtain airbags could be examined. This would be useful in determining Design Guidelines for Work Package 6.
- The addition of a sensor box by Delphi to record data for the analysis of restraint systems firing would aid in determining sensor performance characteristics for Work Package 6.

Reconstruction of IDIADA 3, Impact Induced Rollover, $\Delta_v < 30$km/h

This was an impact induced rollover with a $\Delta_v < 30$km/h accident reconstruction performed by MIRA. The accident involved a Mercedes SLK skidding on a bend in the road on to rough ground rotating anti-clockwise about its Z axis as it did so. The rear right hand side of the vehicle struck a rock at approximately 70km/h at the top of an embankment, which induced the rollover down the bank. The vehicle rolled two quarter turns and landed on its roof. There were two occupants in the vehicle both suffered severe head injuries, one of which was fatal.

The reconstruction used the FMVSS208 sled to propel the Ford Fiesta vehicle into a fixed rigid barrier which simulated the rock. The vehicle was set at an angle and position to approximately represent the same configuration from the accident estimated from photographs.

After impacting the barrier, the Fiesta rotated about all three axes for three quarter turns before landing on its left hand side. A reliable reconstruction of this particular accident has proven to be extremely difficult. Overall, the test has shown that a complex dynamic rollover event is hard to replicate in a test facility.

The deployment of the side curtain bags in the Fiesta provided a useful insight into how they might operate in a rollover. It should be noted that the passive safety provisions in the Fiesta were developed for front and side crash, not rollover. Both curtain bags fired in response to an impact. Initially the passenger curtain bag fired upon impact with the barrier. However, later in the impact, the passenger ATD head was partially ejected through the side window and the curtain bag appeared to offer the potential to restrain the occupant in that unfavourable position. The driver curtain bag fired upon contact with the ground and appeared to offer the potential to prevent a serious head injury with the vehicle structure or the ground.

Reconstruction of TUG 12, Ramp-like Object Induced Rollover

The accident case TUG 12 was reconstructed by IDIADA and involved a Nissan Primera travelling on a three lane road in a tunnel. The vehicle mounted the curb, hit the tunnel side wall and remained in contact with it for several meters before the near underside of the vehicle struck a sloping steel impact barrier on the curb. The vehicle then rode up over the barrier at approximately 77km/h, which subsequently caused the vehicle to roll. It rolled for two quarter turns and slid across all three lanes of the road on its roof before coming to rest. The vehicle contained two occupants who sustained minor to moderate injuries. The driver suffered contusions to the spine, knee and wrist, the passenger abrasions to the right arm.

IDIADA used their cork screw rollover facility to conduct this reconstruction using the Ford Fiesta at a velocity of 77km/h. The test vehicle rolled two quarter turns, landed on its roof and slid across the test area. Although the heads of both ATDs contacted the roof of the vehicle, injury levels were low, which is comparable with the injuries recorded from the accident. There were no side airbags in this vehicle. Before conducting the reconstruction, IDIADA used the Fiesta test vehicle to conduct two near rollover tests at lower speeds of 25 and 50km/h.

Reconstruction of Delphi 1 Skidding and Yawing – Trip Induced Rollover

Rollover accident Delphi 1 involved a Toyota Corolla travelling at 105km/h on a straight road with four elderly occupants aged between 64-85 years of age. The driver fell asleep at the wheel and the car drifted to the left and off the road. He over corrected the steering to the right, which caused the vehicle to cross the road on to the soft dirt shoulder. He then attempted to correct the steering to the left which caused the vehicle to rotate anti-clockwise. The right side of the vehicle then dug into the earth, which induced the rollover. The vehicle rotated four quarter turns and landed on its wheels. The PC Crash simulation calculated vehicle velocity at the time of roll to be 32km/h.

All four occupants were injured. The driver suffered various skin contusions. The front passenger suffered rib fractures and contusions. The rear female passenger suffered cervical spine fracture and lacerations. The rear male passenger also received cervical spine fracture along with a number of abrasions and contusions to the upper body.

TNO attempted to conduct the reconstruction using their rollover test facilities in Delft. Although it was possible to replicate the trip obstacle and the vehicle velocity, it was not possible to get the Fiesta to roll. Even after a number of parameters were changed, including modifications to the vehicle suspension. It was decided by the Consortium in December 2004 to stop this particular reconstruction and allow TNO to concentrate their efforts on working with Delphi to investigate numerical experimental sled simulations to optimise airbag triggering times for rollovers.

The unsuccessful reconstruction tests, which were near rollover events, were not wasted as information from the Delphi sensor recorder was used in sensor performance developments for fire/no fire conditions.

Reconstruction of GDV6 (GDV7) Skidding and Yawing – Turning Induced Rollover

GDV6 (later renamed GDV7) involved an Opel Corsa in a single vehicle rollover containing four occupants, one of whom was not wearing a seatbelt and was ejected during the roll. The driver lost control of the vehicle on a right hand bend travelling at 80km/h. The vehicle skidded off the road onto the left hand shoulder, rotating clockwise about its Z axis of travel when the rollover occurred. The vehicle rolled over two and a half times, a total of ten quarter turns.

UVMV conducted a large number of tests to induce instability of the Fiesta to cause a roll similar to the GDV6 accident. The Fiesta was put through an increasingly severe series of J-turns and reverse steer (fish hook) manoeuvres up to 90km/h, but the vehicle did not roll.

A number of changes were made with agreement by the Consortium to the suspension of the Fiesta to make it more susceptible to a rollover:

- Front axle stabiliser disconnected.
- Rubber bushes on the suspension shortened
- 50mm spacer added to front suspension height
- 70mm spacer added to rear suspension height.

The vehicle was fitted with a remote control steering robot in the driver’s position. The reverse steer manoeuvre was induced into the vehicle via the steering robot at a vehicle speed of 120km/h. This successfully led to the rollover; however, it was more severe than the accident as the Fiesta rolled five times, a total of 20 quarter turns.

The instrumented ATD led to the conclusion that there was a high risk of neck injuries with a comparatively low risk to head and chest areas. There was also the possibility of a partial ejection through the side window. The vehicle was significantly damaged and the front passenger seat, containing the ATD, collapsed due to a high impact loading between the vehicle and the ground, which forced the ATD onto the seat back.

Conclusions

The tests were generally not able to replicate the accident cases selected. The reconstruction of TUG12 by IDIADA was the closest to the accident, but it was not possible for TNO to replicate Delphi1.

There were two primary reasons for this:

- The use of the Fiesta as a test vehicle for all scenarios compared to the accident vehicles was a major influence in the reconstructions. Suspension performance differences affected its propensity to roll which led to a more severe test in the case of GDV6 and the cancellation of the Delphi1 test. The difference in mass, C of G and inertial distribution between the Fiesta and the SLK from IDIADA 3 caused differences in the trajectory of the vehicle.
- The topography of the ground in IDIADA3, which included a 3m drop down a banking, was a significant factor in the results of the reconstruction.

However, the Consortium does not consider these tests as failures. There were a number of extremely useful results from Task 3.2:

- It was crucial to understand the possibility of including ATDs in possible future test standards. Results from this study showed that it would not be practically possible to include ATDs in test protocols.
- It was also possible to study some aspects of partial ejections from IDIADA3 and GDV6 reconstructions, which supported some of the Design Guidelines in Work Package 6.
- The potential benefit and harm from side curtain airbags was seen in IDIADA3. The air bag showed the potential to reduce partial ejections and protect the occupant, but also increased the potential of this problem if the occupant became partially ejected resulting in the airbag restraining the occupant in the partially ejected position. Note: that these airbags were developed for side impact, not rollover.
- These tests were crucial for providing information on sensor requirements in roll and near-roll conditions from all tests. This work has been used by Delphi and TNO to develop sensor and passive safety systems for rollovers.
- The tests also showed that much more effort and cost has to be put into improving the possibilities of a rollover reconstruction.

10. Task 3.3: Numerical simulation of occupant movement during roll (LMU)

Scientific and technical description of the results

Objectives

The aim of the Task 3.3 was to obtain detailed information about the occupant during real-world rollover accidents: occupant kinematics, injury risk for various body parts, and injury reduction potential of various restraint systems.

Real world rollover accidents should be taken from the accident database developed in task 1.2. These accidents should be reconstructed with PC-Crash and the resulting vehicle kinematics should be used to prescribe the vehicle model in the occupant simulation performed with MADYMO. Beside the occupant simulation of the reconstructed real accident additional simulations with belt pretensioner, without the intrusion of the roof and with a curtain airbag should be performed to investigate the potential of these measures for injury mitigation.

In particular, the work was planned to answer following questions:

- Is it possible to reproduce the occupant injuries (individual injuries as well as the overall injury pattern) occurred in the real accident by numerical simulation?
- What is the potential of a belt pretensioner regarding occupant injury reduction?
- What is the potential of a curtain airbag regarding occupant injury reduction?
- Would a reduction of roof intrusion lower the injury risk for the occupants?

Methods

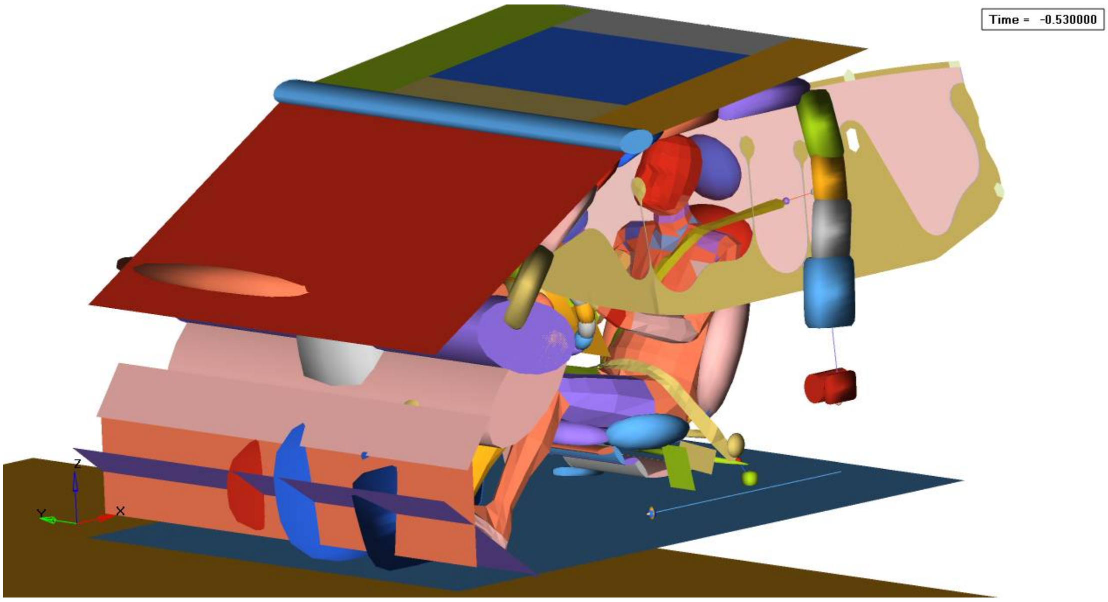
Model development

A generic rollover vehicle model with seat and seat belt was developed by TNO and LMU on the basis of a Ford Fiesta interior model, provided by Ford. In addition a curtain airbag model and a model of a belt pretensioner provided by Delphi were included in the vehicle model (see Fig. 1).

Two 50% Madymo Human Body Models were positioned and belted in the vehicle interior model. The known as well as the expected contacts between the occupant model and the interior were defined and the contact definitions were refined and finalised during the testing phase of the model.

The complete model was tested for numerical stability as well as for its usability in rollover simulation. At the end of the development and testing phase the vehicle model was finalised and the usability in rollover simulation was proven.

Fig. 1: Vehicle model



Case selection

The choice of the cases for occupant simulation was critical. In order to obtain as much information as possible with respect to safety improvement potential of various protection systems as well as for a thorough model validation the cases had to be selected with great care. Based on detailed discussion, the partners set up a list of relevant case selection criteria:

- Simple roll accident – in order to keep the accident complexity as low as possible and thus the degree of certainty about the reconstruction parameters high.
- One vehicle only – in case of a multiple vehicle crash the accident complexity would make it difficult to perform a really reliable reconstruction; many parameters would remain unknown or uncertain.
- Good injury and vehicle data – only cases with very detailed and complete documentation concerning both the occupant injuries and the car damages can be reliably reconstructed and enable a detailed analysis
- Multiple and serious injuries and occupant impacts – because the injury mechanisms/causation was to be investigated, it was necessary to have cases with severe injuries that could possibly be mitigated by passive safety measures. Multiple injuries were preferable because certain injury patterns could be identified.

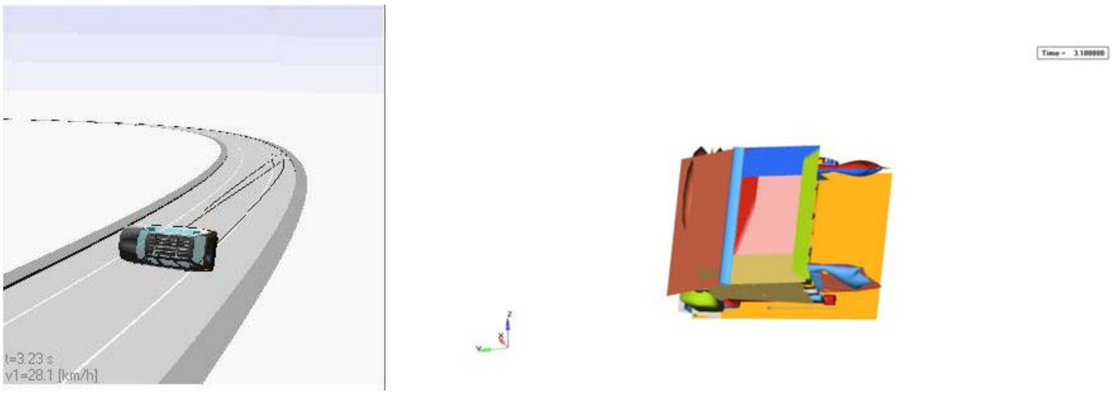
Based on these criteria, the whole ROLLOVER accident library (145 rollover accidents) was searched for the most suitable cases. In the first step, the cases were selected from the database that had complete and detailed medical and technical reports. Further, accidents with injuries of AIS ≤ 2 only were sorted out. At the end of the selection process, only two accidents recorded in the database complied with the set criteria: DELPHI 6 and VSRC 4. It was decided that a detailed analysis of these two accidents should be performed. Simulation of further cases would not be beneficial for the project.

Case reconstruction

The car motions were first reconstructed by using PC-Crash (see left side of Fig. 2) and the vehicle kinematics data were processed and transformed to be used in the Madymo occupant simulations (see right side of Fig. 2). The occupant simulation started at a chosen point of time (the beginning of the pre-crash phase of the accident). The initial position and orientation of the car in the inertial system as well as its initial velocities in all direction were taken from the PC-Crash output; all components of both rotational and translational accelerations of the car prescribed in the centre of gravity of the car were used to define the car motion in the occupant simulation. The simulation ended at the point of time when the car reached a standstill position after the accident.

Prior to the occupant simulation, the vehicle kinematics was validated by means of comparison between the vehicle motion in the PC-Crash simulation and the MADYMO simulation. The PC-Crash output required a small time step (0.001s) in order to achieve a reliable reconstruction of the vehicle kinematics.

Fig. 2: PC-Crash reconstruction (left) and MADYMO occupant simulation (right)



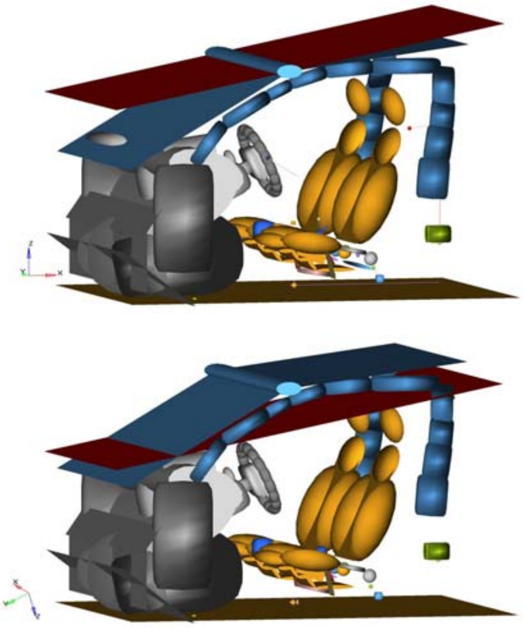
Rollover simulation

Some additional preparation work had to be done in order to simulate the cases DELPHI 6 and VSRC 4. This section gives a short overview of the major preparation issues:

The trigger time for the restraint systems for this particular vehicle motion was calculated by Delphi by using their own internal rollover algorithm. Delphi analysed the motion data and supplied the triggering time for the occupant simulation performed by LMU.

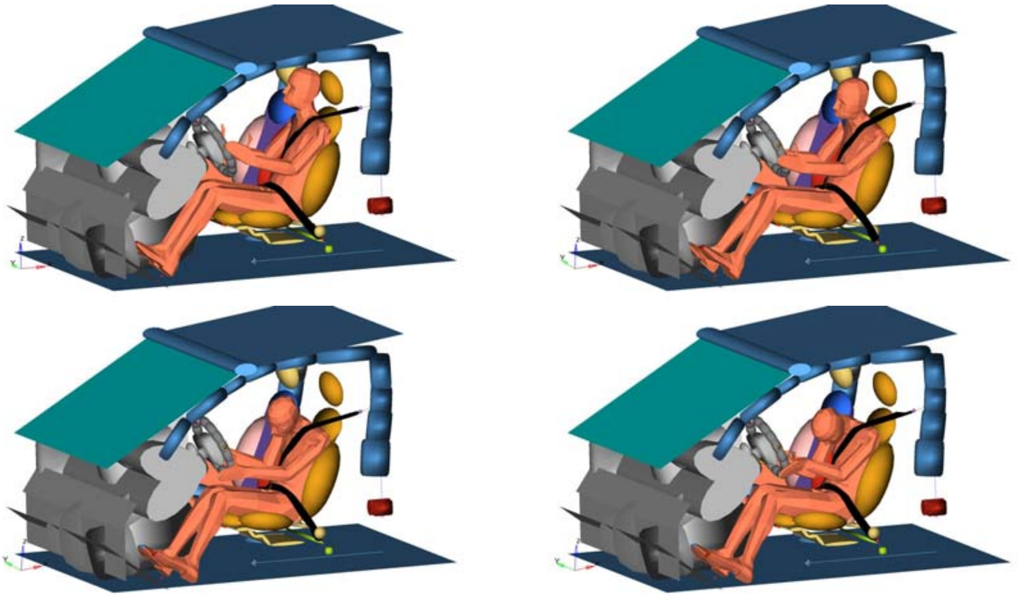
For the simulation of the roof intrusion that was observed in the real-world accidents a plane was modelled which initially lay outside of the occupant compartment but which could be moved by means of a prescribed motion (see Fig. 3). The onset of the roof intrusion was estimated from the vehicle kinematics, i.e. the roof intrusion started when the simulation showed a contact between the roof and the ground. In order to get a realistic roof intrusion the extent of the roof intrusion was estimated from the deformation seen in the accident documentation and the velocity of the intrusion was set according to the data derived from the experiments of task 5.

Fig. 3 Modeling of the roof intrusion – no roof intrusion left, intrusion of maximum 21cm right



The movement of the occupant model was not realistic in the pre-crash phase. The sideward acceleration and the gravity led to a bending of the (predominantly cervical) spine (see Fig. 4). However, the acceleration level in all directions was less than 2g and a living person would have compensated the effects of these accelerations by contractions of the neck and torso muscles. This assumption can be approved by the results of our volunteer tests in task 2.3. As no active occupant model is available at the moment, the bending of the cervical spine was prevented by setting the spine of the model rigid (i.e. all degrees of freedom of the spine were locked) for the time before the start of roll.

Fig. 4 The slack of the occupant due to lack of muscle activity (time interval 0.4sec)



To learn more about the influence of a belt pretensioner, a curtain airbag and a stiffer roof construction, the effect of those measures was evaluated by additional simulation runs. The simulation matrix below shows the performed simulations.

Simulation matrix

Simulation	Roof intrusion	Pretensioner	Curtain airbag
1	+	-	-
2	-	-	-
3	+	+	-
4	+	-	+
5	+	+	+
6	-	+	+

Analysis

The analysis of the occupant simulation was performed in several steps.

1) After the vehicle kinematics was validated, the critical time points were assessed:

- the beginning of the rolling phase of the vehicle (=end of the pre-crash phase) which was important for the unlocking of the spine joints of the occupant
- the beginning of the roof intrusion in order to define the prescribed motion for the intrusion model

2) The first simulation performed represented the real accident, i.e. the protection systems (their usage) were set in accordance with the real accident documentation. The contacts between the occupant and the car interior were analysed and compared to the documented injuries of the real occupant (MIRA report on injury causation)

3) Further simulation runs were aimed to explore the potential of various protection systems for injury mitigation. The impact severity of various contacts was analysed and thus the injury risk assessed. Special attention was paid to the problem of survival space, i.e. the relationship between the roof intrusion, occupant movement and head injury risk.

Results

For the sake of simplicity, the results of the DELPHI6 and VSRC4 cases will be presented separately.

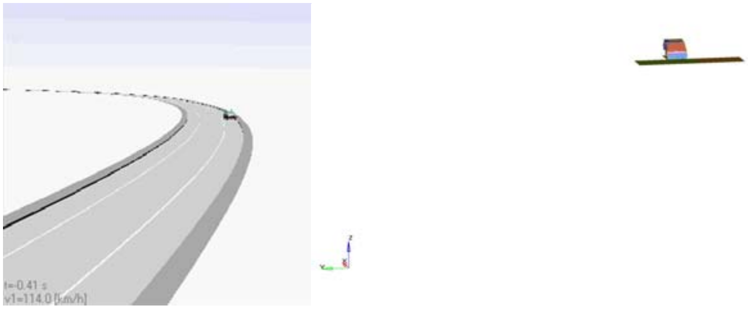
Accident case "DELPHI6"

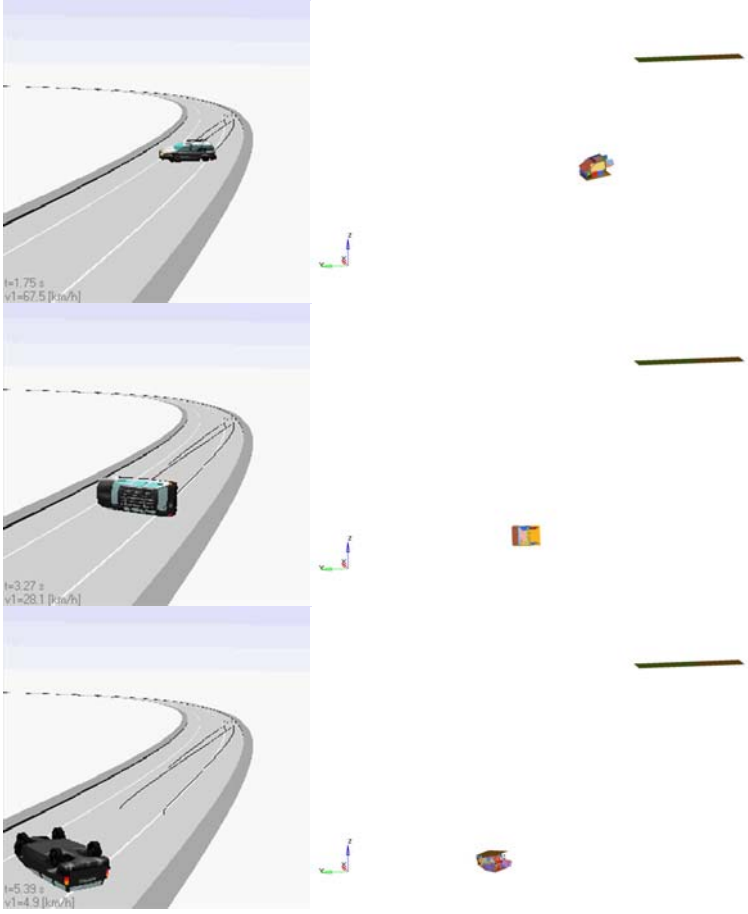
The first step in the analysis of the DELPHI6 case was the verification of the car motion. Figure 5 shows the comparison between the car motion reconstructed by PC-Crash and the motion of the occupant compartment model in MADYMO. Though the vehicle kinematics is not completely reproducible because of a discrete time step of the PC-Crash output, thanks to a small time step (0.001s) the deviations are very small and their influence on the occupant kinematics negligible.

The accident vehicle (Chevrolet Blazer 1999) was equipped neither with belt pretensioner nor with curtain airbag. The rolling phase started at 2.75s (all time points are defined in the simulation time; the simulation in this case started at t = 0.53s). The triggering time for the belt pretensioner obtained from Delphi was 2.98s. The beginning of roof intrusion was estimated from the car motion as the time of first contact between the roof and the ground at 3.64s. The extent of the intrusion was estimated from the deformation of the real accident car – 21.4cm. The spine joints of the occupant were locked till simulation time 1.73s. This time point was chosen based on the analysis of car accelerations.

In the following, the results of individual simulation runs will be analysed with respect to occupant safety.

Fig. 5: The car movement – comparison between the PC-Crash (left) and MADYMO (right) simulation





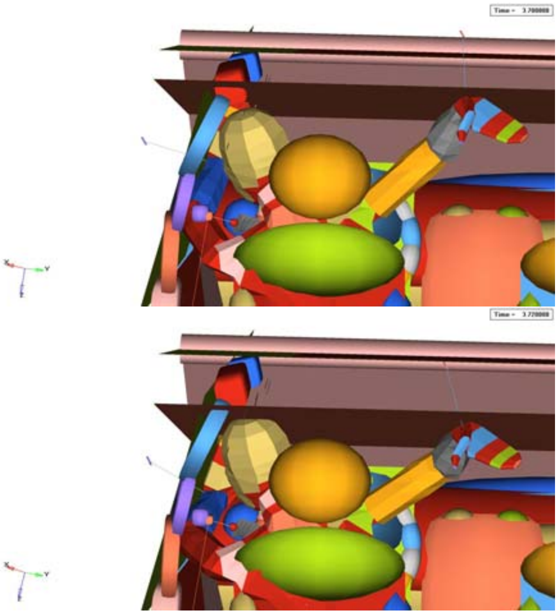
Simulation 1: roof intrusion, no belt pretensioner, no curtain airbag (real accident configuration)

The injury causation analysis performed by MIRA was the basis for the comparison between the simulation and the real accident. MIRA has identified two high energy impacts of the occupant within the occupant compartment, one medium energy impact and five low energy impacts of the occupant.

Head Impact with left Side Roof Rail:

MIRA assumed a high energy head contact against the lateral cant rail producing observed severe injuries of the head (skull vault and skull base fracture, abrasions, cerebrum haematoma). Severe head contact of the occupant was actually observed in the simulation during the roof intrusion phase, but instead of the lateral cant rail the head was impacted by the part of the roof vertically above the occupant position (Fig. 6). However, it should be stated that the kinematics of the head is strongly dependent on the neck muscles that are relaxed in the simulation and thus the head moves "freely" as if the occupant were unconscious. In case of a high energy impact the muscles are not able to counteract the inertial forces, but the initial position of the head at the beginning of the rolling phase might differ from the real occupant head position.

Fig. 6: Roof to head impact (no belt pretensioner)



Face/Eye Impact with Left Side Roof Rail:

Medium energy impact of the upper face with the left hand cant rail causing closed orbit fracture was assumed in the MIRA injury causation analysis. The injury was assumed to occur during the roof deformation. There is no similar contact interaction observable in the simulation. It should be noted that the simulation of roof intrusion is performed by moving a plane into the occupant compartment as opposed to the real accident where various parts of the roof deform to a various extent. The shape of the deformation is thus only a rough approximation of the real situation and it influences the simulation results. On top of that, the above discussed passivity of the model leads to a flexion (bowing) of the head and the head position of the model may thus differ from that of the real occupant.

The insufficiency of the simulation model is a general problem of rollover simulation and cannot be overcome currently .

Shoulder Belt Abrasion to Chest:

The injury most probable was caused by the intensive contact of the chest with the belt during the rolling phase. The injury mechanism proposed in the report of MIRA can be confirmed by our simulations.

Low energy impacts

- Lower Facial Impact with Interior Surface
- Right Hand Impact with Roof
- Left Arm Impact with Left Side Interior Surface
- Left Leg Impact with Interior Surface
- Right Eye Injury from Flying Glass

These impacts are assumed in the MIRA analysis to be caused during flailing of the occupant impacting interior surfaces of the vehicle. The injuries resulting from the above listed impacts are very light (AIS≤1) and can be caused even by a very low intensity impact. The immense complexity of the occupant movement during the very long accident (6sec) makes it impossible to identify unambiguously the cause of these injuries in the numerical simulation. A minor deviation of the initial position during the pre-crash phase or at the beginning of the crash might cause a huge difference of the occupant kinematics (and thus various contact interactions with the environment) later during the crash. The injuries listed above are not relevant with regards to occupant safety; they do not represent a danger to life or persistent health impairment.

Simulation 2: no roof intrusion, no belt pretensioner, no curtain airbag

As opposed to the first simulation reconstructing the real accident, the possible injury mitigation based on reduced roof intrusion was investigated in the second scenario. The only change with respect to the first simulation was thus the absence of roof intrusion, i.e. the occupant compartment did not deform at all.

Head Impact with left Side Roof Rail:

The simulation shows no contact between the head of the occupant and the roof at all, the occupant motion is restrained by the belt and even after the car has rolled onto the roof there is still enough head clearance. It means that by significantly reducing the roof intrusion the head injury risk can be reduced.

Face/Eye Impact with Left Side Roof Rail:

Obviously, since there is no contact of the occupant with any part of the roof the face/eye contact with the left side roof rail could not be observed, no head injuries whatsoever are predicted by the simulation.

Shoulder Belt Abrasion to Chest:

The contact between the occupant and the shoulder belt is very similar to the first simulation, through the absence of the head impact probably even slightly more severe (the contact force acting on the head took some load from the shoulder belt).

Low Energy Impacts:

Similar to the first simulation it should be noted that the low energy impacts produce only minor injuries and are thus considered irrelevant. In addition, it is impossible to reach such a high degree of precision of the accident reconstruction that a meaningful interpretation even of slight contacts of all body parts could be possible.

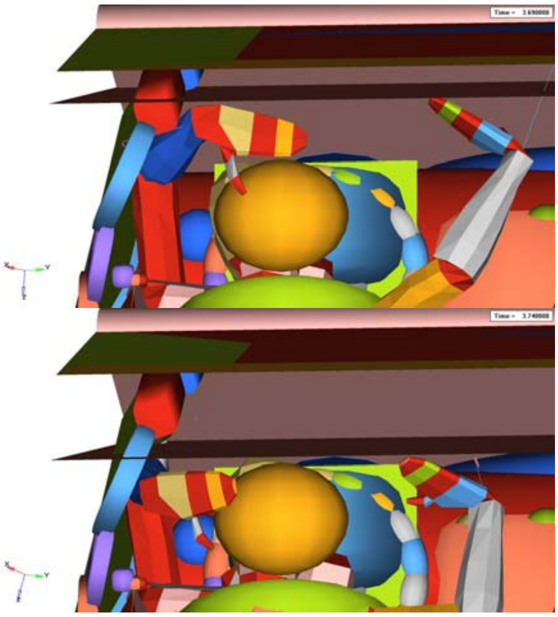
Simulation 3: roof intrusion, belt pretensioner, no curtain airbag

This particular simulation run was aimed at the assessment of the injury mitigation potential of the pretensioner. All parameters stay the same as in the real accident, but the car model is additionally equipped with a belt pretensioner that is fired at a time point ascertained by Delphi by using their rollover-sensing algorithm.

Head Impact with left Side Roof Rail:

A contact between the head and the roof can be observed in the simulation at approximately the same location as in the original simulation. However, the contact occurs later (after the roof has intruded the occupant compartment) and its intensity is much lower. The reason for this is that due to the pretensioner the occupant is better restrained and does not move towards the roof as much as without the pretensioner (see Fig. 7). The contact velocity is much smaller (0.1m/s as opposed to 1.5m/s in the simulation without pretensioner). Impact velocity between head and roof was measured as the relative velocity between the centre of gravity of the head and the plane representing the intruding roof. The velocity of roof intrusion was 2.4m/s, but at the time of contact only the occupant is moving. Apparently, the very light contact does not represent relevant danger; the occupant would not suffer serious head injury in this case.

Fig. 7 Improved head clearance by using a belt pretensioner



Face/Eye Impact with Left Side Roof Rail:

No contact was observed between the head of the occupant except for the one described above, so there is no risk of any head injury.

Shoulder Belt Abrasion to Chest:

Obviously, the increased restraining effects of the belt pretensioner can cause even higher contact forces between the belt and the occupant. Thus, the potential for chest injuries caused by the belt is even slightly higher than in the previous simulations. However, due to relatively small accelerations of the car during the whole accident (as opposed to severe frontal collisions) and the fact that the belt is tightly wrapped around the occupant so that he is firmly fixed to the seat (due to the pretensioner), no severe injuries should be expected.

Low energy impacts:

The same discussion items stated in the simulations above apply.

Simulation 4: roof intrusion, no belt pretensioner, curtain airbag

Our original intention was to perform also a simulation run focusing on the curtain airbag potential for injury reduction. All simulation parameters would have stayed the same as in the first simulation (real accident reconstruction) but the car would have additionally been equipped with a curtain airbag fired on the driver's side.

Since there was no contact between the occupant and the car interior structures on the left hand side, such a simulation would have been useless. In this particular rollover case, the curtain airbag cannot contribute to occupant safety.

Simulation 5: roof intrusion, belt pretensioner, curtain airbag

Also this simulation turned out to be redundant. No safety enhancements thanks to curtain airbag could be expected in this configuration for the reasons stated above.

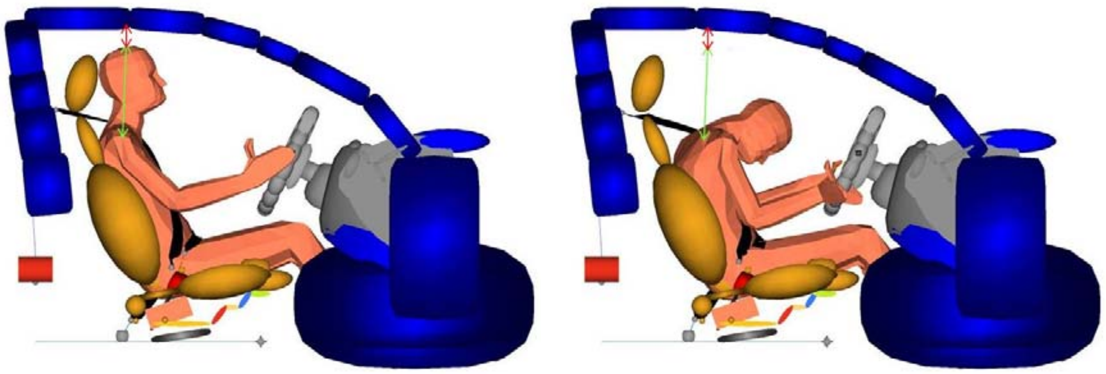
Simulation 6: no roof intrusion, belt pretensioner, curtain airbag

This simulation was not necessary because simulation 2 already showed the safety enhancement due to a stiffer roof. Simulation 3 showed that there would not have been a head to roof contact if the roof had not intruded the occupant compartment and a belt pretensioner had been fired. The curtain airbag will not contribute to the safety of the occupant in this accident case as pointed out above.

Assessment of the necessary survival space

Special attention was paid to the problem of occupant survival space. A frequent measure for the risk of serious head injuries is the negative head room. In this study, a similar approach was used to assess the potential of belt pretensioner for head injury reduction. The relative distance between the head and the roof could easily have been measured but the interpretation of such a parameter would have been very difficult. The reason for this is that in the simulation the head kinematics was driven solely by the accelerations imposed on the occupant, there was no muscle activity. As a result, the head of the occupant experienced large deviations from the upright position allthough the accelerations imposed on the occupant were not high and he would most probably have kept in the upright position by using the neck muscles. To overcome this problem, a point was chosen in the spine region at the height of the first thoracic vertebra and its vertical distance to the top of the head was measured in the upright position. This point was then used for the assessment of the head clearance (i.e. the head clearance is a measure of the distance between the roof and the head in the upright position). The measurement procedure is depicted in Fig. 8.

Fig. 8 Head clearance estimation: the green arrow shows the distance from the defined point to the top of the head in upright position, the red arrow shows the head clearance.



By using this measurement method, the necessary survival space (head clearance to avoid contact with roof) was found to be 1.9cm with and 9.8cm without belt pretensioner. Thus, the belt pretensioner brought a significant reduction of the vertical excursion of the occupant.

Accident case "VSRC4"

Similar to the case DELPHI 6, the first step in the analysis was the verification of the car motion in MADYMO. Figure 9 shows a comparison between the car motion reconstructed by PC-Crash and the motion of the occupant compartment model in MADYMO. As already stated above, the vehicle kinematics is not completely reproducible because of a discrete time step of the PC-Crash output, but due to a small time step (0.001s) the deviations are very small and their influence on the occupant kinematics is negligible.

The car which was involved in this accident (Vauxhall Astra) was equipped neither with belt pretentioners nor with curtain airbags. The start of the rolling phase was at 1.68s. At 1.95s the belt pretensioner was triggered according to the calculations from Delphi. The estimated beginning of roof intrusion took place at 2.4s. As in the previous accident case the extent of the intrusion was estimated from the deformation of the real accident car – 11cm. To keep the occupant in an upright position throughout the pre-crash phase the spine joints of the occupant were locked till simulation time 2.26s. This time point was chosen based on the analysis of car accelerations.

The Vauxhall Astra had its steering wheel on the right side of the car but the injured person was the co-driver sitting on the left side of the car. Thus the injured person was sitting on the far side of rollover.

In the following, the results of the vindividual simulation runs will be analysed with respect to occupant safety.

Simulation 1: roof intrusion, no belt pretensioner, no curtain airbag (real accident configuration)

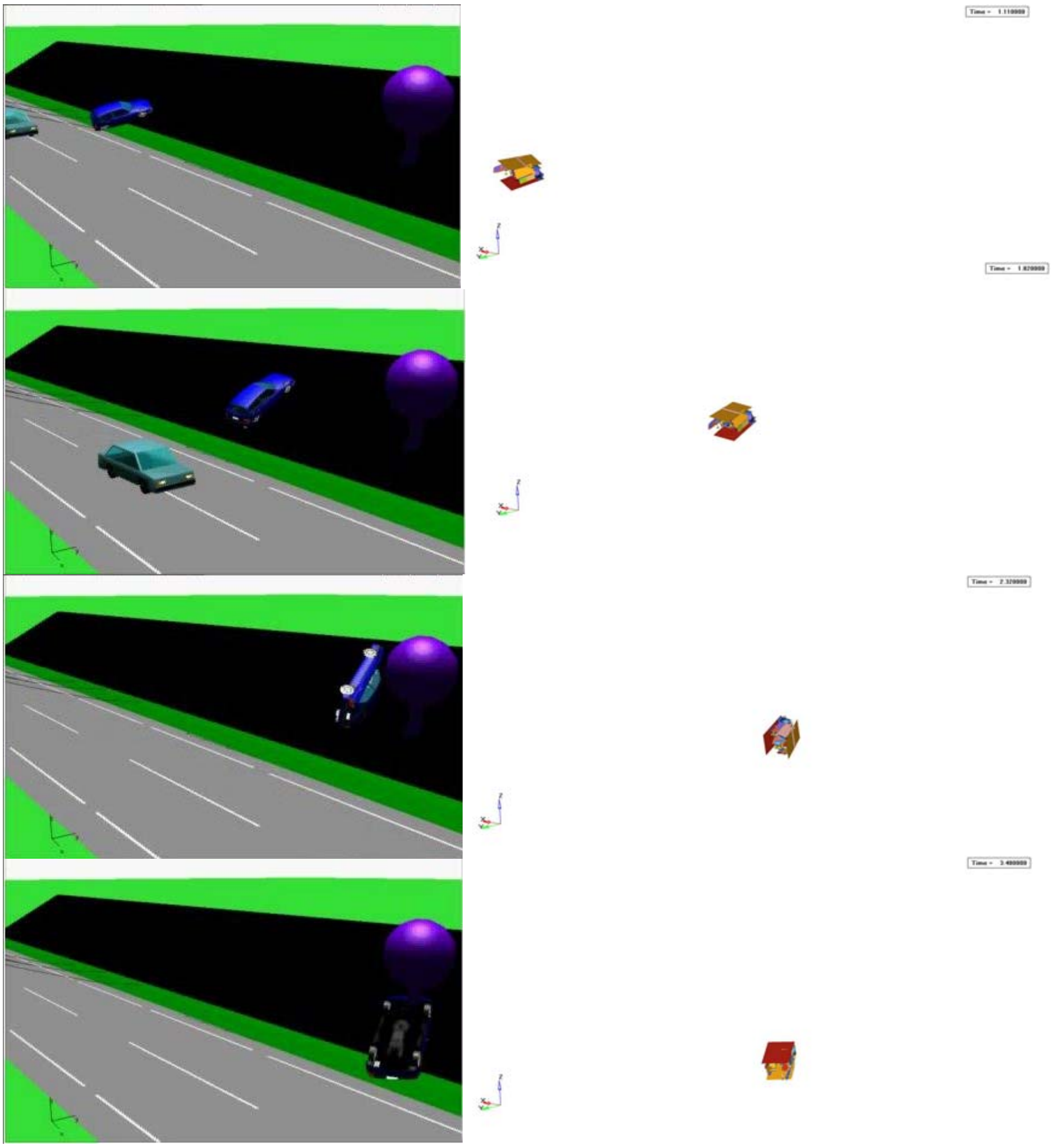
In the VSRC4 case, MIRA identified 6 impacts, but only two of them resulted in an AIS2 injury, the rest were minor injuries (AIS1).

Head Impact with Side Glass and Roof/Grab Handle:

A severe impact of the head against the side glass as well as against the grab handle was identified in the simulation. The impact to the side screen occurred while the roof was deforming and the impact against the grab handle happened shortly after the roof intrusion had stopped (see Fig. 10 and 11). Thus, the impact was caused only by the motion of the occupant's body. However, the impact severity seems to correspond to AIS2 injury because the whole mass of the occupant goes into the contact.

The head contacts the side screen at the time 2.45s, the contact with the grab handle follows at the time 2.59s.

Fig. 9 Car motion reconstructed with PC-Crash (left) and prescribed in MADYMO (right)



Arm Impact with Side Door:

An impact of the left forearm against the door structure was observed in the simulation. The impact severity and its responsibility for styloid and triquetral fracture is difficult to assess, but on principle it can be stated that the simulation brought results that enable to retrace the occupant impacts that might be responsible for the injuries suffered.

Fig. 10 Head impact against side screen

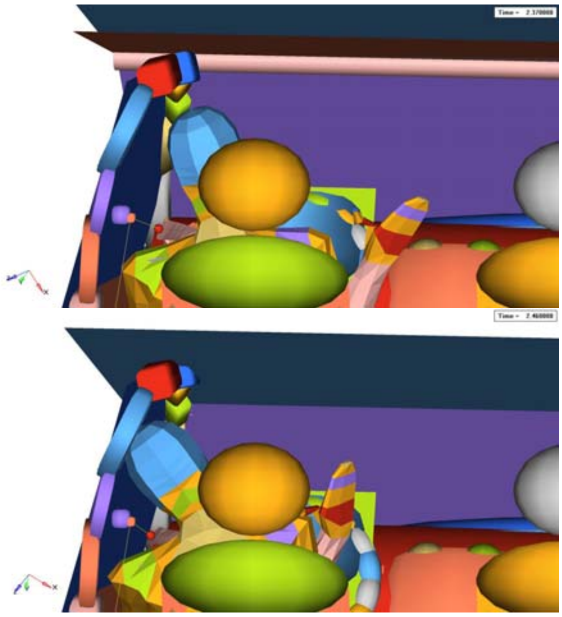
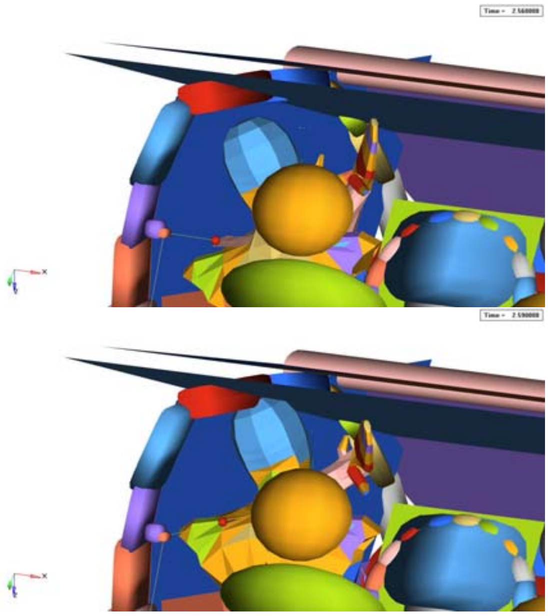


Fig. 11 Head impact against grab handle



Seat belt loading:

Presumably due to seat belt loading the real occupant suffered some bruising in the shoulder and hip regions. The possible cause of these (minor – AIS1) injuries can clearly be observed in the simulation – after the car rolls onto the roof, the occupant moves towards the roof and hangs in the seat belt with an intensive contact in the shoulder and hip regions. Thus, the causation mechanism assumed by MIRA can be confirmed by the numerical simulation.

Head Impact with Side Glass:

Multiple lacerations on the head of the occupant presumably caused by the side glass cannot be confirmed in the simulation. The side glass was modelled as a simple plain that cannot brake so no similar injuries can be predicted by the simulation. It should be stated that as described above we identified a severe impact of the head of the occupant with the side window and in case the glass brakes, multiple lacerations can be expected.

Hand Impact with Windscreen:

Because the windscreen was modelled as a plane, similar to the side glass,,it cannot shatter and the described injury (laceration of the head due to low energy impact with the shattered windshield) cannot be found in the simulation. The minor injury of the hand is not relevant for occupant safety.

Impacts with flying glass in the vehicle interior:

The same as for the two latter injuries also applies for the minor injuries of both hands falling into this last group. Even in the MIRA report the injuries are supposed to be caused by chaotic movements of these body segments and thus cannot be exactly reconstructed even if the glass could brake in the simulation.

Because of the low relevance of the injuries caused by the shattered glass (both side and windscreen) as well as the impossibility to represent the shattering of the glass in the simulation, the last three impacts are not going to be explicitly discussed in the following. Basically, the same explanation would be given in all simulation runs.

Simulation 2: no roof intrusion, no belt pretensioner, no curtain airbag

Similar to the case DELPHI6 this simulation is aimed at the assessment of roof intrusion relevance regarding occupant safety in a rollover accident. All parameters of the accident stayed the same but there was no roof intrusion at all.

Head Impact with Side Glass and Roof/Grab Handle:

Since the roof intrusion was rather small (11cm) and occurred mainly in the front part of the roof and the occupant contacted the grab handle deeper in the occupant compartment and after the roof intrusion, the characteristics of the head impact stayed roughly the same as in the first simulation run. Thus, no improvement could be expected even if there were no roof intrusion at all. It should be stated that the car interior model is a general one and even small changes of the interior geometry (i.e. smaller or bigger interior room) could cause different results – especially the shape of the roof intrusion could thus play a significant role.

Arm Impact with Side Door:

The arm impact occurs before the roof intrusion so no change with regard to the original accident configuration can be observed.

Seat belt loading:

Similar to the impacts discussed above, the seat belt loading was not changed by the roof intrusion.

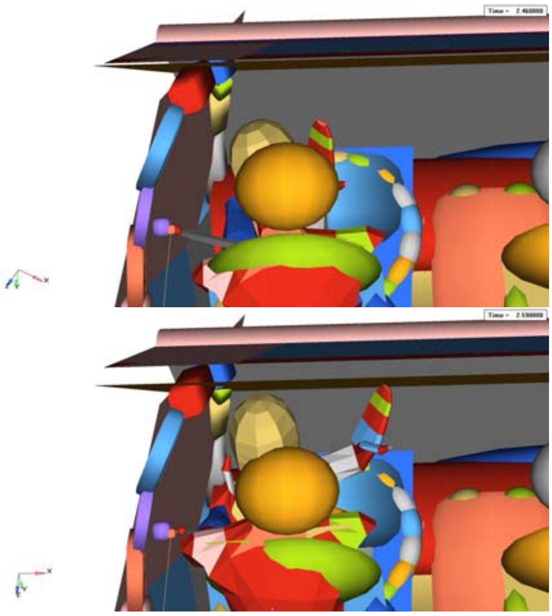
<u>Simulation 3: roof intrusion, belt pretensioner, no curtain airbag</u>

This simulation was aimed at the assessment of belt pretensioner potential for injury reduction in this particular case.

Head Impact with Side Glass and Roof/Grab Handle:

No contact of the occupant model with the side screen or the grab handle could be observed in this simulation. The belt pretensioner prevented the occupant model from hitting the side glass and roof/grab handle (see Fig. 12).

Fig. 12 No head impact with the use of a belt pretensioner



Arm Impact with Side Door:

The simulation showed an impact of the left lower arm with the side door. The impact of the left lower arm could not be prevented by the use of a belt pretensioner.

Seat belt loading:

In the real rollover accident the co-driver suffered some minor (AIS 1) injuries in the shoulder and hip region which are presumably caused by the seat belt. The movement of the occupant towards the roof which can clearly be seen in the computer simulation results in forces on the occupants shoulder and hip due to the seat belt contact. These forces could potentially be amplified by the belt pretensioner thus the injuries caused by the seat belt might be a little bit more pronounced than without the belt pretensioner. But since the vertical motion of the occupant occurs after the belt has been pretensioned the additional loading can be neglected. No severe injuries are to be expected by the use of the belt pretensioner in this particular accident case.

Simulation 4: roof intrusion, no belt pretensioner, curtain airbag

Obviously, the influence of the curtain airbag was examined in this simulation from the point of view of injury prevention/mitigation.

Head Impact with Side Glass and Roof/Grab Handle:

The curtain airbag fired soon enough in order to prevent the head contact with the side window (head to curtain bag contact time 2.28s). Also, there was no impact of the head against the grab handle. However, the head impacted the roof at the time 2.58s. Though the head was kept away from the side structure by the curtain bag, its vertical motion was obviously not constrained so instead of the grab handle the roof was contacted by the head. The contact energy apparently decreased and since the roof surface is flatter and softer in the region of contact than is the case at the side structure, the injury severity could potentially decrease. The contact velocity of the head to roof contact corresponds to the head velocity (the roof intrusion is finished) and is approx. 1ms-1.

Arm Impact with Side Door:

The curtain airbag does not influence the arm impact with the side door because it occurs underneath its lower aspect. Thus, the impact timing and severity stays the same.

Seat belt loading:

The seat belt loading is mainly dependent on the vertical motion of the occupant so only very minor changes can be observed with the use of a curtain airbag (there is a slight contact between the left shoulder of the occupant and the lower aspect of the airbag).

Simulation 5: roof intrusion, belt pretensioner, curtain airbag

This simulation was performed to evaluate the influence of the usage of a belt pretensioner and a curtain airbag on the injury risk.

Head Impact with Side Glass and Roof/Grab Handle:

The additional usage of the belt pretensioner as opposed to the simulation 4 does not seem to bring a huge benefit for the occupant in terms of safety. The same impacts can be observed as without the pretensioner even at the same points of time. However, a minor improvement can be observed. The head impact velocity measured in the simulation was 0.6ms-1.

Arm Impact with Side Door:

The kinematics of the occupant is slightly altered by firing the belt pretensioner and the left upper extremity does not contact the door. Instead, there is a very soft contact with the lower part of the curtain airbag. As a result, no injuries can be expected. The avoiding of the injury should not be interpreted as a clear benefit as the kinematics is just incidentally changed in a way that the contact location is slightly different.

Seat belt loading:

Potentially the seat belt pretensioner could put an additional load onto the occupant but since the vertical motion of the occupant occurs after the belt has been pretensioned, the amount of additional loading will be negligible.

Simulation 6: no roof intrusion, belt pretensioner, curtain airbag

The absence of roof intrusion did not change the occupant motion and the impacts compared to the simulation 5.

Conclusions

The severe injuries mentioned in the medical documentation can be reproduced by the simulation. Although the simulation can reproduce the injuries sustained by the occupant in a global manner, the minor injuries especially on the extremities and the exact position of injuries can not be simulated well. This may be due to the simplified model of roof intrusion, the passive occupant model or the accident reconstruction which is only an approximation of the real vehicle motion. To get more detailed information on the injury mechanisms more sophisticated methods have to be used. A more detailed simulation of the roof intrusion is technically possible but very costly. There is no active human model available at the moment that would take reflexive and voluntary movements of human occupant into account. Though the first attempts to develop such a model have been undertaken, a lot of research effort is still required. The accident reconstruction could be further improved by a better documentation of the accident scenario. Especially an exact measurement of the traces at the accident site would improve the validity of the reconstructed vehicle kinematics. In terms of the validity of the occupant kinematics there is still a white spot in research. A rollover accident is characterised by its long duration and low accelerations. The pre-crash phase up to the start of roll is very important because of the high probability for the occupant moving out of position. More effort has to be put into the analysis of occupant behaviour in the roll- and pre-roll phase and on the valid modelling of active occupants.

Looking at the results of the simulation of the accident “DELPHI6” it can be stated that the driver of the car would never have sustained such severe injuries if the vehicle had been equipped with a belt pretensioner.

Also a stiffer roof which would have resulted in a smaller roof intrusion would have been effective to prevent severe head injuries.

So a combination of a slightly stiffer roof and a belt pretensioner would have been an effective countermeasure to the severe head injuries in the rollover accident case on hand.

The results of the occupant simulation of "VSRC4" also showed the benefit of the belt pretensioner whereas a stiffer roof did not improve the safety of the occupant in terms of injury risk. In case there is no belt pretensioner the curtain airbag can contribute to occupant safety in this specific case.

List of deliverable(s)

D 3.3: Report on numerical simulation of occupant motion comparing MB and FE models as well as human models versus dummy models.

Comparison of initially planned activities and work actually accomplished

The originally planned deliverable D 3.3 was titled "Report on numerical simulation of occupant motion comparing MB and FE models as well as human models versus dummy models". However, the work content of Task 3.3 was amended by the consortium during the course of the project in order to reflect the intermediate project results. Thus, the D 3.3 was renamed to account for its content: "Report on numerical simulation of occupant kinematics of real world accidents and the effectiveness of different countermeasures on the mitigation of the documented injuries”.

11. Task 3.4: Cause of injury summary (Mira)

Aim

The aim of Task 3.4 was to develop a method to identify the cause of occupant injuries in rollover accidents using data available from the Rollover Accident Database and results from occupant simulations.

Comparison of initially planned activities and work actually accomplished

It was planned to use the Rollover Accident Database simulation results from Task 3.3 and the rollover reconstructions from Task 3.2 to evaluate the cause of injuries. In the event, results from the reconstructions were not considered useful for the analysis; however, this did not degrade the outcome of the analysis.

Deliverable

The deliverable was a Cause of Injury Summary report. This detailed the methodology chosen, the injury causation mechanisms and analysis of a selection of case studies from the Rollover Database which detailed the chronology of the injuries. A comparison with occupant simulation results was also discussed.

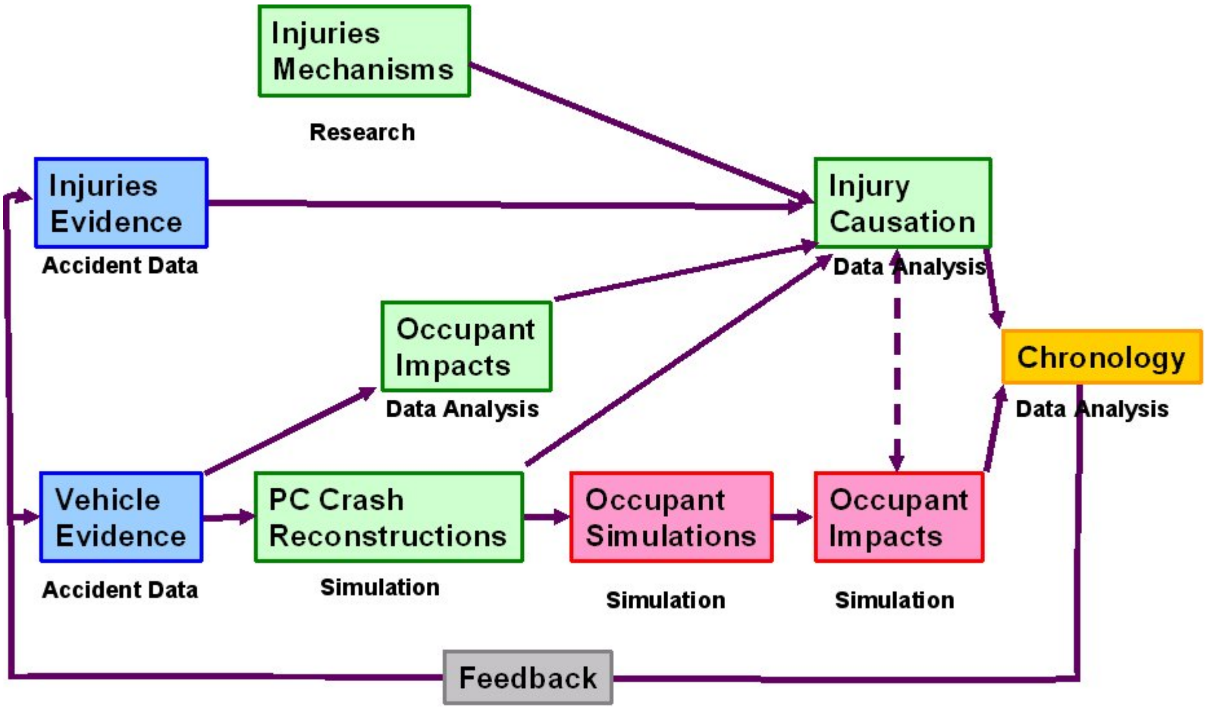
Injury Causation Analysis Process

Figure 1 diagrammatically shows the process that was used to establish the injury causation using data from the Rollover Accident Database developed in Work Packages 1 and 2. Information used from the database included accident reports, photographs, medical reports and reconstruction data from PC Crash.

Research into injury mechanisms was also crucial to ensure reliable causation identification. To avoid confusion from conflicting medical research, a limited number of well known and widely accepted reference sources was used.

Analysis of simulation results from MADYMO modelling in Task 3.3 was conducted on Delphi 6 and VSRC4. The results of the simulations were compared to the real accident injuries to help establish the credibility of the simulation models and provide a useful insight into the timing of events occurring around the occupant, giving a reconstructed chronology of occupant impact events. This was then used to help establish if the simulation results showed the injuries occurring in the right order.

Figure 1: Injury Causation Analysis Process



Injury Causation Methodology

As impact locations are often unknown in rollover events it is difficult to directly link injuries with impact locations and injury causation mechanisms. Instead of linking injuries to impact locations to determine the injury causation mechanism, different types of injury were classified as to their causation mechanism and then an evaluation of their possible impact locations performed.

Four distinct injury causation mechanisms were established:

- Localised injuries caused by a direct impact to a body part. (Localised Injury)
- Remote and diffuse injuries caused by a direct impact to a body part. (Global Injury)
- Load based injuries produced by indirect loading associated with an impact to another body. (Indirect Load Injury)
- Crush based injury produced by crushing of the body part between deformed vehicle structures and/or outside structures (Crush Injury).

For this exercise six main occupant body parts were defined.

- Head and face
- Cervical Spine or neck
- Upper torso including thoracic spine and chest cavity
- Lower torso including the abdomen and pelvis
- Lower extremities including upper leg, lower leg and feet
- Upper extremities including shoulders, arms and hands.

Each injury to the six body parts can be categorised according to the four main impact mechanisms. Using this approach all actual occupant injuries from a rollover accident can be allocated causation mechanisms. Then, for each body part localised and global injuries can be linked to the impact event. Indirect load injuries to another body part can then be linked to loads produced after the initial impact event.

Various injuries and their severity can be linked to individual impact events which then build up to a full sequence of events around the occupant during the rollover accident. The whole series of impact events can be evaluated allowing the probable impact locations within the interior of the vehicle to be deduced. The occupant's kinematics during the rollover can then be proposed from the initial occupant sitting position and the sequence of body part impact locations, which can be compared with the actual vehicle kinematics.

Injuries in Relation to their Causation Mechanism

In order to apply this methodology, all the main injuries that an occupant in a rollover accident may receive must be classified into these four main injury causation mechanisms. Table 1 shows an example of the types of injury associated with the head and face. The injury type is shown against each injury, along with the AIS injury level and injury code. The type of injury mechanisms are also given for each injury.

Application of Injury Causation Tables

The objectives of the injury causation tables are to assign the potential injury causation mechanism to each recorded occupant injury in a rollover accident. Injuries produced from each occupant to vehicle interior or exterior object impact can then be grouped together. For example, a head impact with the roof cant rail grab handle could potentially produce a direct impact injury (depressed skull fracture and lacerations), diffuse global injury (unconsciousness) and indirect loading injury (neck fracture and dislocation). Injuries recorded as a result of a single body part impact may have just one, two or three of the main injury types. Using this methodology, injuries can be linked with known impact locations determined from investigations of the vehicle interior, showing where the majority of injuries were produced in the impacts.

This methodology was applied to the injuries sustained by an occupant in a rollover accident and is presented in Figure 2. The injuries, injury levels and possible impact locations were taken from the accident database. The injury causation mechanism for each injury was evaluated from the injury causation tables. These were linked together for each of the recorded impact locations in the figures. A graphic of the occupant shows the locations of the injuries and the impacting object.

Reconstructions of the vehicle kinematics from PC-Crash can then be linked with the occupant injuries and impact locations to evaluate the occupant kinematics within the vehicle and thus the chronology of the injuries. A number of case studies from the Rollover Accident Database were selected to demonstrate this methodology: VSRC4, Delphi, Delphi5, GDV3 and VSRC2.

Conclusions

Most Rollover accidents have complex three dimensional vehicle and occupant kinematics, in which the occupant has multiple impacts with the interior surfaces, and in some cases external surfaces, producing multiple injuries ranging from minor lacerations and contusions to life threatening ones. An approach using injury causation mechanisms was used to categorise the location and severity of occupant to vehicle impacts in a rollover situation. By understanding the mechanisms, or forces and accelerations, which cause a particular injury it was possible to link a number of injuries to a single occupant impact. For example a high velocity impact to the head will produce localised, force based, skull fracture as well as acceleration based diffuse axonal injury and indirect loading neck dislocations. The technique was used to analyse six rollover accidents reducing as many as twenty five different injuries to just eight occupant impacts. However, for the technique to reach its full potential it is essential that a comprehensive list of injuries is recorded as soon as possible after the accident, as was demonstrated in the Delphi6 accident data. The use of the Abbreviated Injury System (AIS) for documenting injuries is certainly the best system at present, as it not only records the body location and type of injury but also its severity. It has also been proposed that a further suffix could be added to the system, allocating the potential injury mechanism, localised load, indirect load or global acceleration, to each injury which would make analysis considerably easier. Without the use of the AIS, attempting to analyse which injuries are associated with which occupant impact would be very difficult.

Evidence of actual occupant impacts with interior or exterior surfaces is also essential, both in terms of annotated diagrams and photographs, as shown in the VSRC 4 accident data. Therefore in order to improve the accuracy of the technique, improved and consistent recording of occupant injuries and impact locations is required.

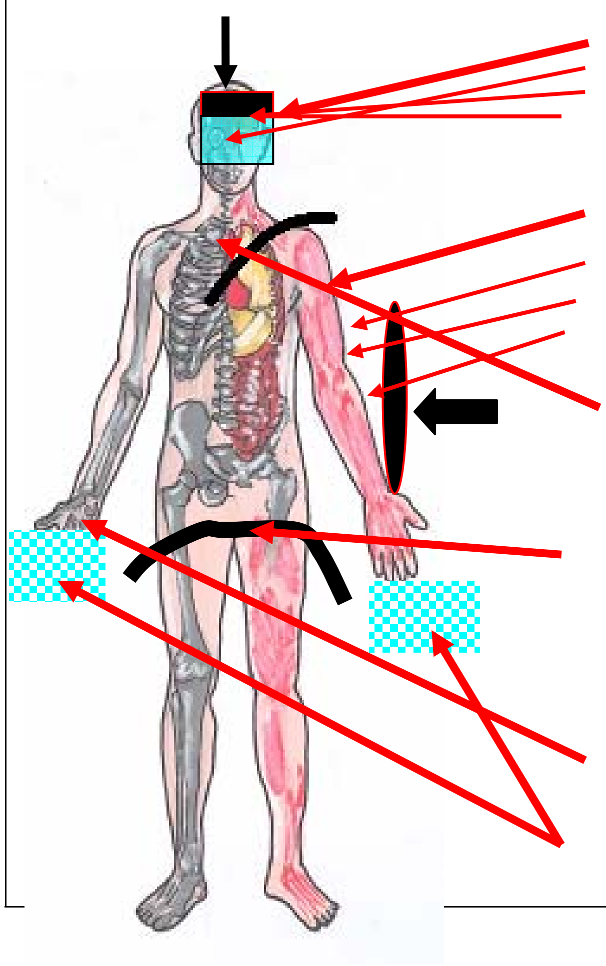
Occupant simulation techniques using MADYMO were used to recreate two of the rollover accidents from the Rollover Accident Database. These simulations were investigated to assess the prediction of occupant kinematics, occupant to vehicle impact locations and injury severity, which were then compared with the actual injuries. The models using 50%ile human models were used rather than the equivalent dummy models which were too stiff to produce the extensive occupant kinematics seen in rollover accidents. In both the Delphi6 and VSRC4 accidents modelled, the head impacts recorded in the accidents were predicted. However the model head accelerations were much lower than would be expected to produce the actual injuries recorded. Although in both cases the head impact velocities were low, both were associated with dynamic roof crush. Further research is required to better understand head injury mechanisms in dynamic roof crush accidents in order to improve vehicle and occupant protection.

Table 1: Injury Causation Mechanisms Head and Face

INJURY	Injury Type	AIS Injury Code	Potential Injury Level	Injury Causation Mechanisms	Current ATD Injury Criteria
Laceration / contusion and avulsion to scalp and face	Direct impact	1102/4/6/800 2102/4/6/800	AIS 1 – 2 AIS 3 High Blood Loss	Direct impact or glancing blow with a sharp / blunt or flat object	None
Penetration Injury to the skull including depressed skull fracture	Direct Impact	116002/4	AIS 3 < 2cm AIS 5 > 2cm	Direct impact by a sharp or blunt object	None
Penetration Injury to the face including facial bone fracture	Direct Impact	216000 2506/800 2512/4/6/800	AIS 1 Minor AIS 2 1 facial bone fracture AIS 3 Multiple fracture with high blood loss	Direct Impact by a sharp or blunt object	None
Coup contusions and Subdural Hematoma	Direct Impact	140600	AIS 3 – 5 Contusions AIS 4 – 5 Subdural Hematoma	Direct impact by a blunt object. Not always associated with skin laceration, penetration injury or depressed skull fracture	None
Cranium vault and basal fractures	Diffuse global injury	150200 150400	AIS 2 simple closed fracture AIS 3 Complex comminuted AIS 4 Complex comminuted and open fracture	Remote fracture associated with a direct impact potentially from a flat object rather than blunt	None
Contracoup contusions	Diffuse global injury	140600	AIS 3 – 5	Remote contusions produced by high accelerations associated with a direct impact	Head Accelerations HIC
Diffuse axonal injury	Diffuse global injury	1602/4/6/800	AIS 5	Diffuse brain injury produced by high rotational and translational accelerations causing lateral shear forces in the brain material	Head Accelerations HIC
Loss of consciousness	Diffuse global injury	160200	AIS 1 Dizziness AIS 2 – 3 Unconscious < 1hr AIS 3 – 4 Unconscious 1 – 6 hr AIS 4 – 5 Unconscious 6 – 24 hr	Produced by high translational and rotational accelerations	Head Accelerations HIC
Massive destruction of cranium	Crush	113000	AIS 6	Massive crush injury with complete collapse of the cranium	None

Figure 2: Occupant Injuries and Potential Impact Locations – VSRC4 – Astra Front Passenger

Incident	**VSRC4**
Vehicle	**Astra**
Occupant	**Front Passenger**
Accident Scenario	
Occupant Kinematics	



Impact A – Head Impact with Side Glass and Roof/Grab Handle

Injury	AIS	Causation Mechanism	Initial Impact Object / Injury Mechanism
Head – Multiple Lacerations	1	Direct Impact	Impact with Side glass
Head – Bruising to forehead and nose	1	Direct Impact	Impact with grab handle (Blood/hair)
Head - Amnesia	2	Diffuse Injury	High Acceleration from impact above

Impact B – Arm Impact with Side Door

Injury	AIS	Causation Mechanism	Initial Impact Object / Injury Mechanism
Left Arm – Bruising left elbow and forearm	1	Direct impact	Impact with side door
Left Arm – Radial styloid fracture	2	Direct impact	Impact with side door
Left Hand – Fracture triquetral	2	Direct impact	Impact with side door

Impact C – Left Shoulder belt loading

Injury	AIS	Causation Mechanism	Initial Impact Object / Injury Mechanism
Left shoulder - Bruising	1	Indirect loading	Shoulder belt

Impact D – Upper leg belt loading

Injury	AIS	Causation Mechanism	Initial Impact Object / Injury Mechanism
Left leg upper anterior - bruising	1	Indirect loading	Lap belt
Right leg upper anterior - bruising	1	Indirect loading	Lap belt

Impact E – Hand Impact with windscreen

Injury	AIS	Causation Mechanism	Initial Impact Object / Injury Mechanism
Right Hand – Dorsum flap laceration	1	Direct Impact	Direct impact with windscreen

Impact F – Impacts with flying glass in the vehicle interior

Injury	AIS	Causation Mechanism	Initial Impact Object / Injury Mechanism
Right hand – Multiple abrasions	1	Direct Impact	Impacts with flying glass
Left hand – Multiple abrasions	1	Direct Impact	Impacts with flying glass

12. Task 4.1: Numerical Simulation of Vehicle Structural Design (ESI)

Scientific and technical description of the results

What was the objective?

The main objective was the identification of effective simulation methods for rollover scenarios.

Description of the work

The work done can be divided into three groups:

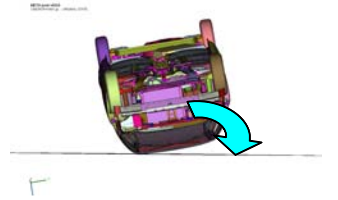
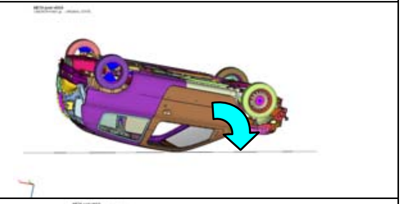
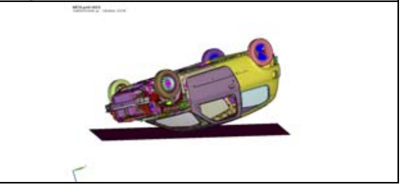
- **First group** – was dedicated to the software requirements from the users point of view.
- **Second group** – was dedicated to the software tools from the software producers point of view.
- **Third group** – was dedicated to the structure how to use the software.

In detail this means that in a first phase of the project the requirements for the software needed in order to simulate rollover scenarios were defined. From the software producer a guideline was developed “How to use PAM-CRASH for full scale rollover simulations”. Finally the software was used by the partners for roof crush and full scale rollover. The outcome of these simulations is documented in the deliverables d4.1.2. This outcome describes the design guidelines for the car body and is the final result of the sub work package.

Software requirements

At first it was investigated what the requirements for numerical software are in order to realistically simulate a rollover scenario.

Different conditions were found. Finally it became clear that for some of the cases static situations and for some dynamic situations are important.

Initials Conditions		
Roll Angle	**170°**	
Pitch Angle	**10°**	
Velocity	**11,27 km/h**	

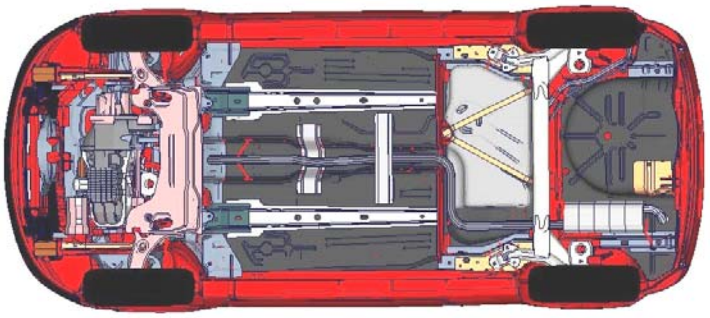
Based on this the user request for the software were found and reported.

Design Guidance for numerical models used to evaluate structures- Rollover Simulations with PAM-CRASH and LS Dyna

Within the EU-project “*ROLLOVER – Improvement of Rollover Safety for Passenger Vehicles*” MAGNA Steyr Fahrzeugtechnik (MSF) was responsible for the development of an efficient, time-saving method to enable a quick and reliable design of the car body already in an early stage of car development.

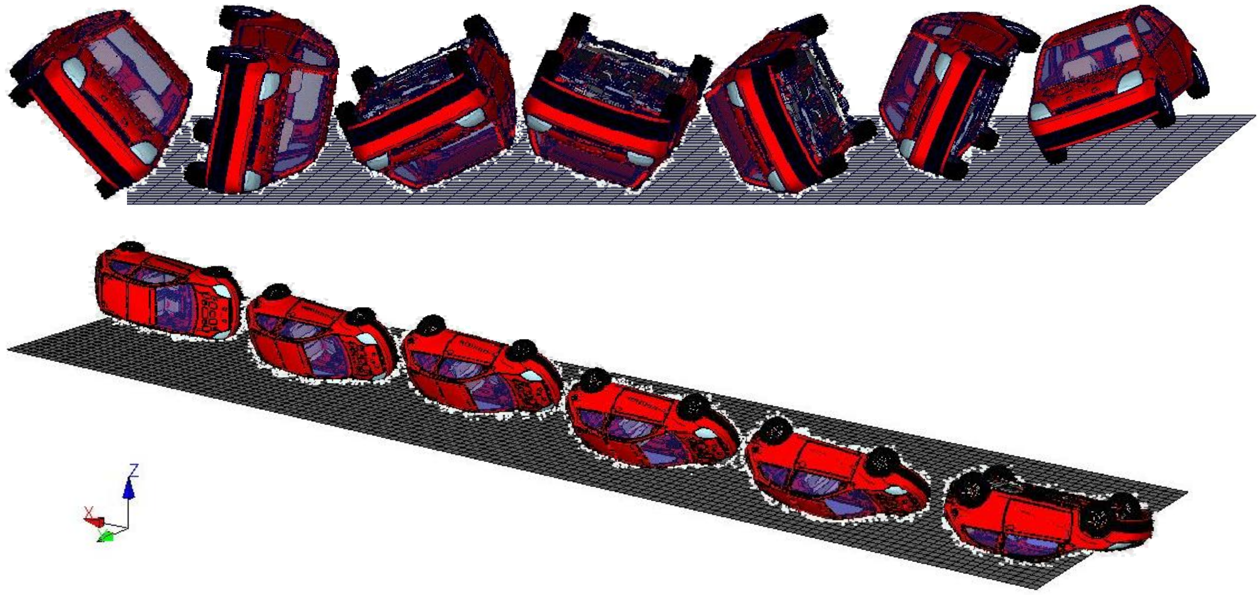
The aim of the part of MSF is to simulate several full-scale rollover scenarios based on an existing Finite-Element-Method (FEM)-vehicle model, to set up parametric studies and to develop a method to evaluate the vehicle structure. Furthermore certain alternative tests, so-called Inverted Drop Tests, are simulated and analysed to find out whether their results correlate to the full-scale scenarios.

The conducted simulations were based on a project car model, which was originally created in RADIOSS and converted in PAM-CRASH Code from ESI.

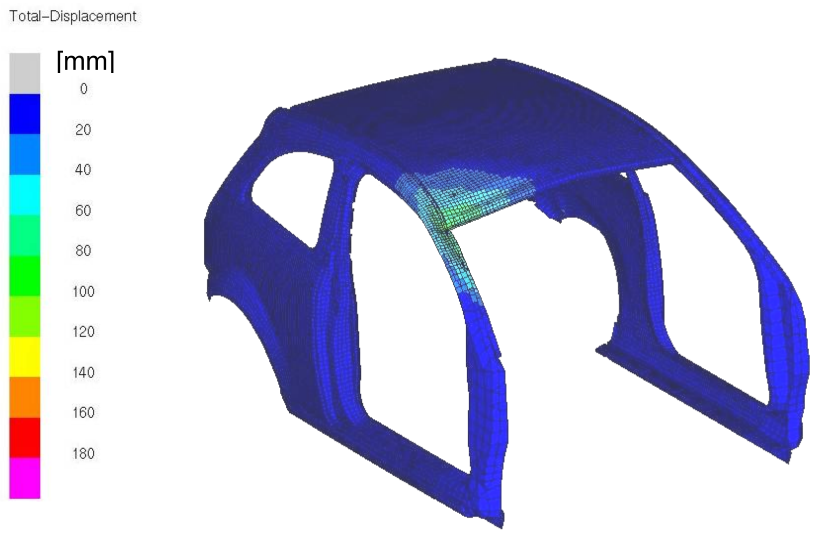


The first step to analyse the model was to check the completeness of the vehicle components. All exterior components were implemented, except for the rear bumper, rear lights and some plastic attachment parts. The model also included the chassis, the engine with drive train, the underbody and windows and tires.

Inside the car model no interior components, except for the front seats, existed. Different scenarios were simulated with PAM-CRASH. Two are shown on the figure below.



The main challenge for these simulations is the long duration of the event (about 2 s). Meanwhile computer processors are so powerful that CPU time is no longer the problem. Due to the experiences we collected in the project now the door is open to wide range of simulations for rollover scenarios.



Roof crush intrusions were studied for the cases and a design guidance was developed based on these simulations.

The simulation done with LS-DYNA were mainly dedicated to the inverted drop test. Here the stiffness of the structure under different loading conditions was studied.

Figure Impact Loading (Roll Angle α = 35°, Pitch Angle β = 5°)

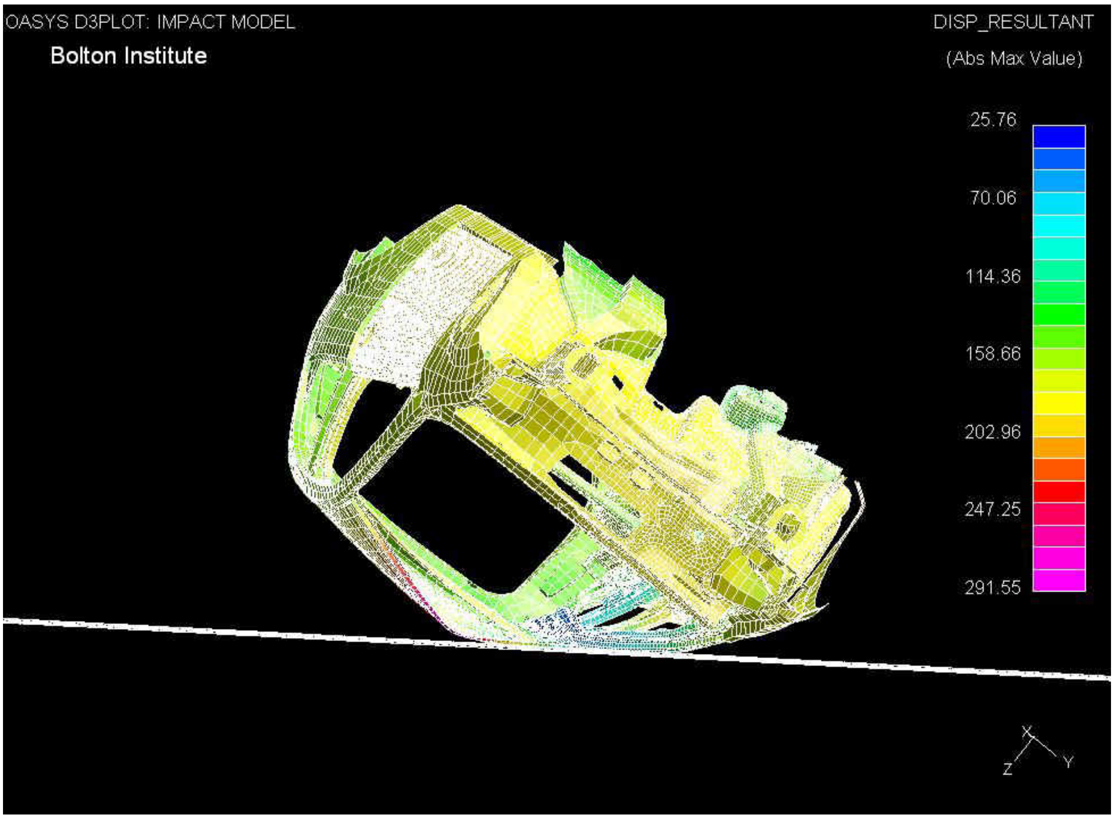
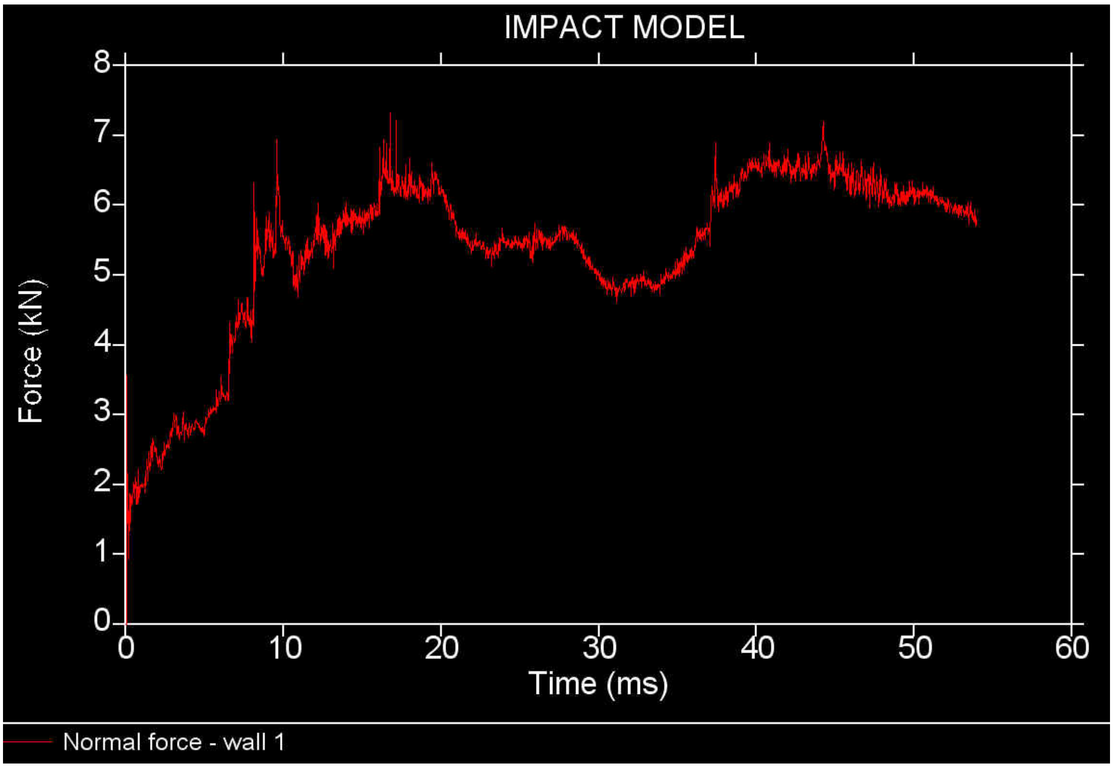
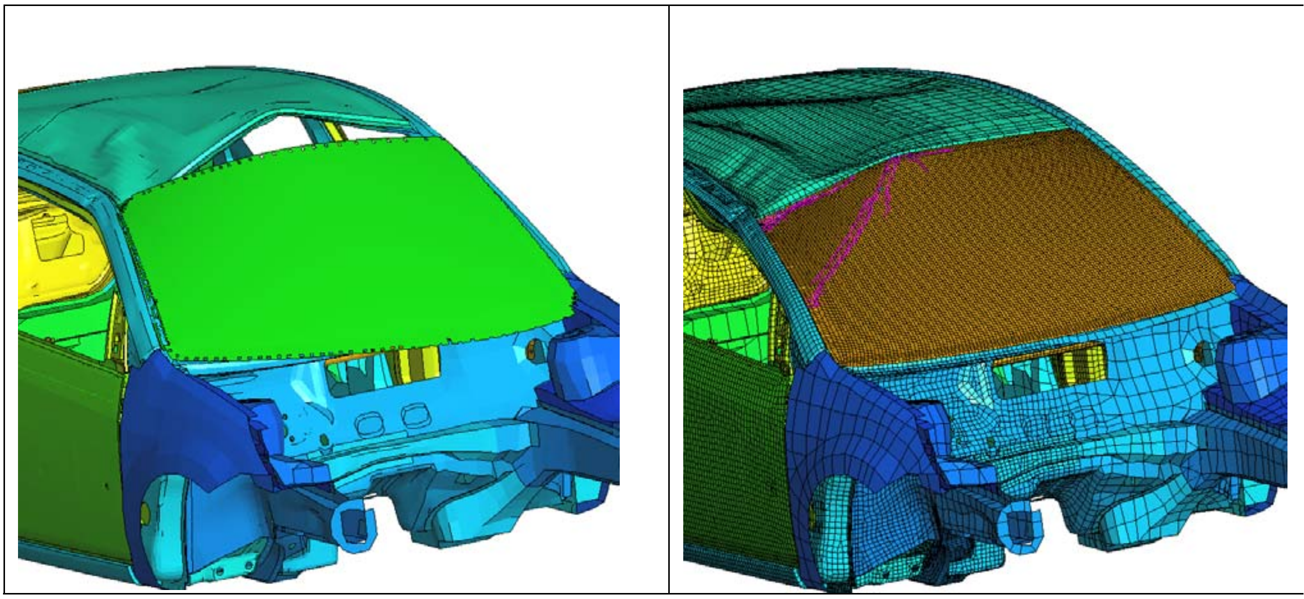


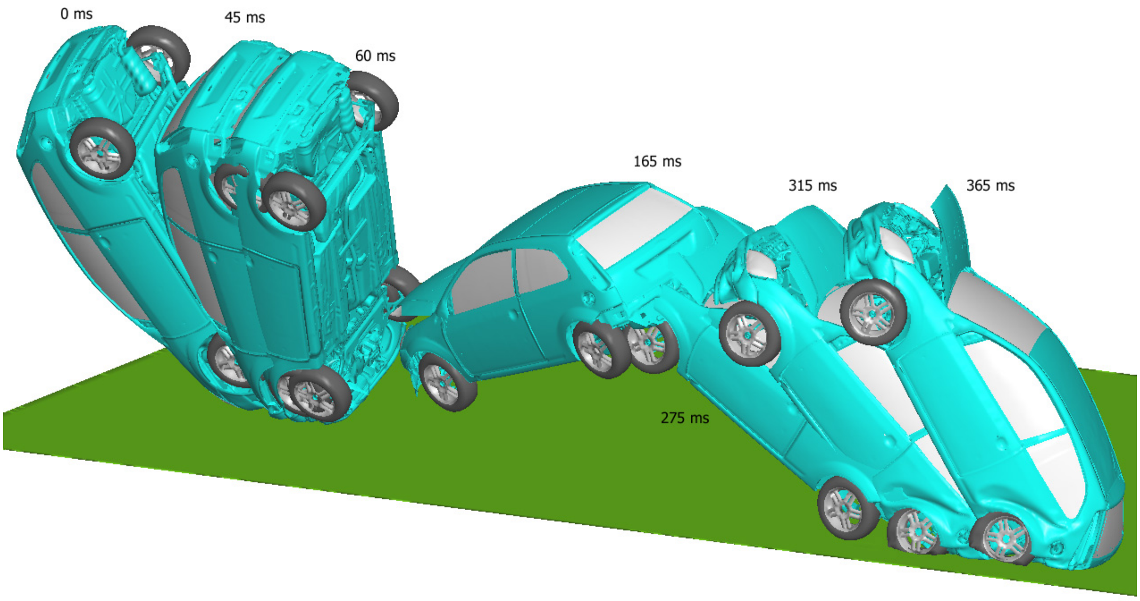
Figure Ground Force/Time for Impact Loading (Roll Angle α = 35°, Pitch Angle β = 5°)



The goal of the roof crush simulations with PAM-CRASH was mainly the development of a glass model for the windshield which gives the realistic response under different loading conditions. The figure below shows the behaviour of the windshield with the old and the new model.



UVMV made additional PAM-CRASH simulations for complex driving situations with a final rollover event. This was also possible with PAM-CRASH.



The figure above shows the simulation results of the important phase of the event were the car is under deformation. These simulations were also done with a dummy inside the car and the injury criteria were studied.

With these studies within the framework of the EU-project “ROLLOVER – Improvement of Rollover Safety for Passenger Vehicles” a simulation procedure was created, which allows a quick and reliable design of the vehicle structure in an early stage of car development. The results could also contribute to legislate an EU-directive, with respect to the occupant safety during Rollover.

List of deliverable(s)

D4.1 Report on design guidance for numerical models used to design and evaluate vehicle structures for rollover protection

Sub-reports:

D4.1.1_p1	Report on software requirements
D4.1.1_p2	User requests for rollover simulations
D4.1.2_p1	Rollover simulations with PAM-CRASH
D4.1.2_p2	Roof crash analysis with LS-DYNA
D4.1.2_p3	Static and dynamic roof crash analysis of the Fiesta model with PAM-CRASH
D4.1.2_p4	FEM analysis of Rollover of Fiesta with PAM-CRASH

13. Task 4.2: Numerical Simulation of interior and restraint system (TNO)

What was the objective?

An assessment will be made of numerical methods for the development and evaluation of restraint systems for rollover protection. The vehicle motion identified in detailed accident reconstructions will be applied to models of the vehicle interior that include models of occupants, padding and restraint systems. Robustness and accuracy issues of the methods will be investigated.

Scientific and technical description of the results

After all and with the support of the partners FORD (MADYMO 5.4 model and test vehicles), UVMV (vehicle test results), DELPHI (accident scenarios) and TRW (airbag model) the main primary research objectives for TNO Automotive within the Task 4.2 were:

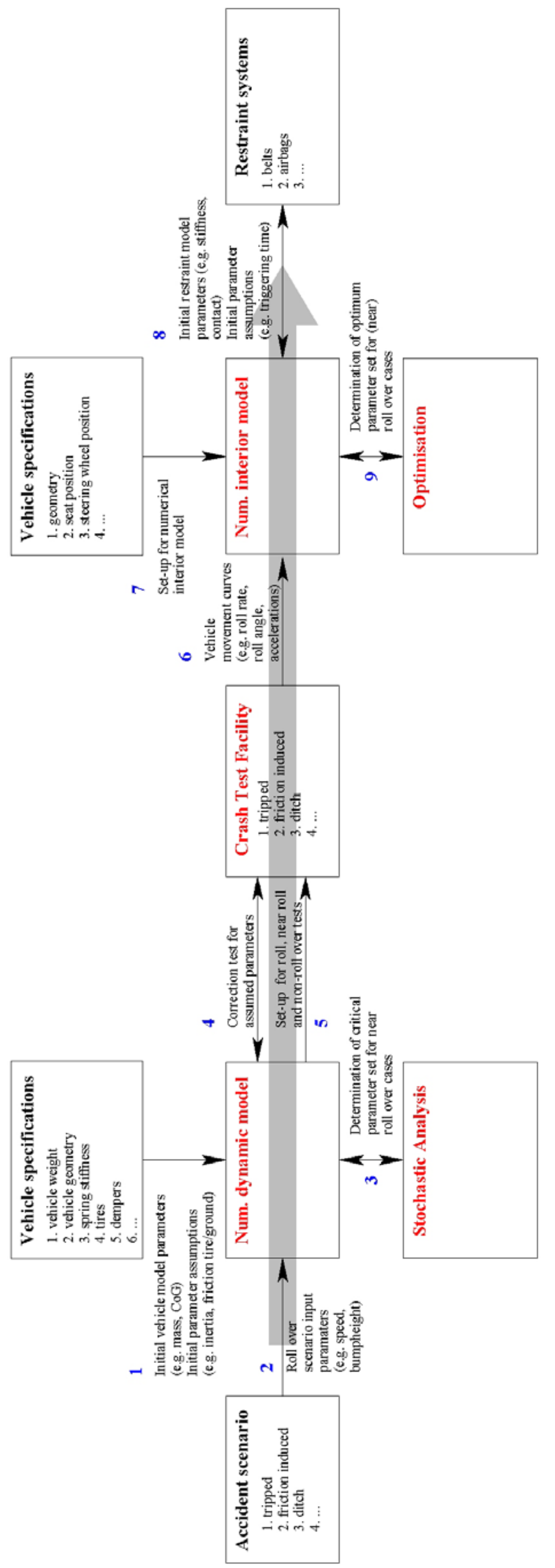
- To investigate the effects of pre-roll vehicle kinematics, to determine worst case vehicle "roll start positions"
- To identify rollover/occupant scenarios worthy of detailed study and to evaluate the issues and likely effects for different use parameters (e.g. belt usage) on those scenarios.
- To identify, create and use advanced computer models and physical testing methods, which allow the effective evaluation and optimisation of such scenarios.
- To generate best practice guidelines to develop and evaluate the functional requirements of rollover occupant protection systems.

The injury mechanics in rollover, however, are not well established. In the past years, safety research has focused on frontal, rear-end and side crash protection due to their higher injury statistics, at the expense of rollover. Consequently, data collection elements, laboratory test facilities, and crash injury countermeasures have been oriented towards planar crashes. The complexity of rollover events makes the characterisation of these accidents much more difficult than for planar crashes [1]. This need for a better understanding and characterisation of rollover has lead to the investigation of the most critical phase during rollover: the near-rollover phase.

Smart restraint development for roll over cases relies on a good prediction of these scenarios. The triggering time (TTF) for restraint systems (e.g. airbags and pretensioners) is based on the analysis of a vehicle’s roll angle, roll rates and rotations. These movements of the car and its expected behaviour in real life scenarios should be clearly identified in controlled environments. In order to reduce costs a great part of the possible range of roll over scenarios should be performed in a virtual world, e.g. by means of numerical simulation. Models used in these numerical simulations are validated in a couple of real life roll over crash tests [2, 3]. When the vehicle behaviour is fully predictable in roll over scenarios, it is possible to include dummies and smart restraints to identify harm and harm reduction. This chain of roll over prediction and injury reduction is further referred to as the roll over tool chain. The figure on next page shows the tool chain.

Figure 13.1 – Roll-over Tool Chain

1. Set-up of the ADVANCE numeric dynamic vehicle model
2. Selection of parameters to represent certain roll-over accidents
3. Numerous simulation with variation of parameters in several ranges
4. Fit the numerical dynamic model with real crash test data
5. Use validated model to set-up input parameters for interesting test scenarios
6. Output of critical crash scenarios is used in interior model
7. Manufacturer’s input of characteristics for MADYMO interior model



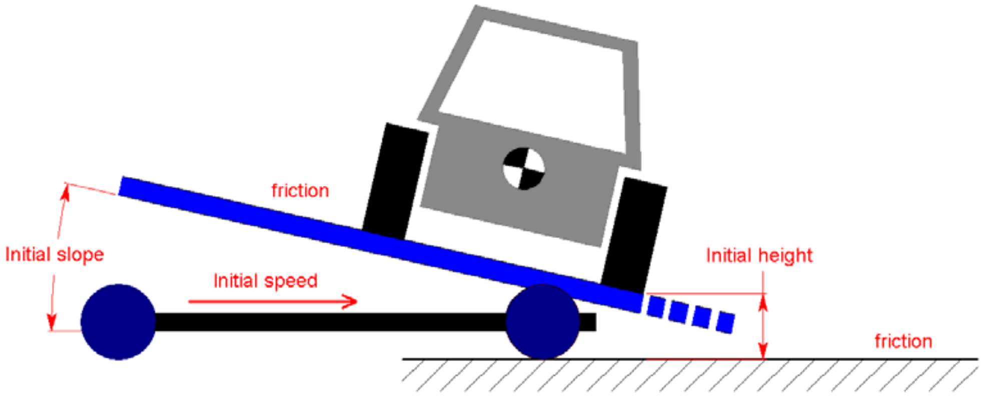
During the setup of the tool chain a parallel path was chosen to setup both dynamic modelling using the TNO Simulink library ADVANCE (developed for vehicle Dynamics studies), the experimental tests in the laboratory and finally a small study with the developed MADYMO model [8].

Whether it is simulated in ADVANCE, MADYMO or real life tested in the crash laboratory, the setup of the lateral vehicle movement is always based on following scenario.

A passenger car is positioned on platform on a sled. Figure 13.2 shows the set-up. The initial slope of the platform can be varied between 0 and 25 degrees. The height between the ground and the platform differs depending on the initial slope within a range of 0 to 350mm. The sled is accelerated to an initial speed of 4 to 20m/s. The sled is stopped after 50m and the car is free to move on.

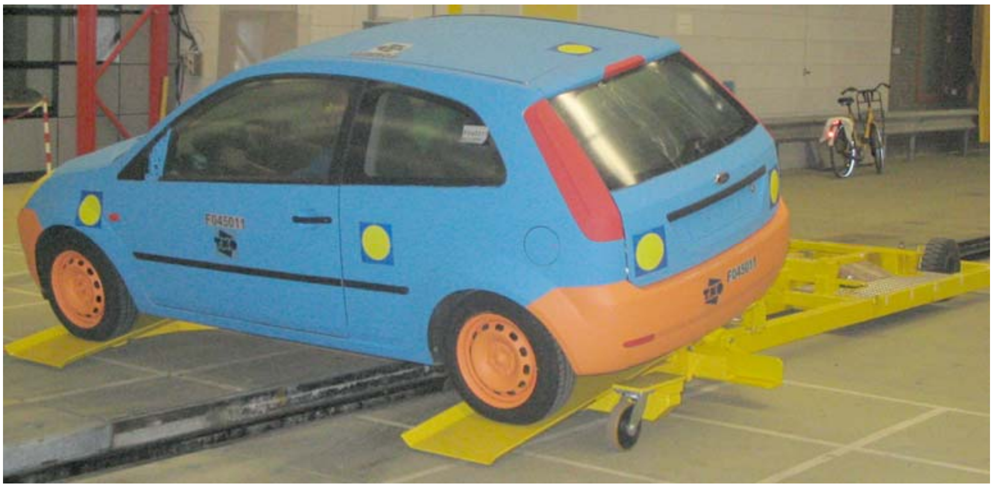
The friction between the passenger car tires and the platform is assumed to be low. The friction with the ground floor is assumed to be a little higher than an average paved road.

Figure 13.2– Sketch of roll over test setup



The main reason to predict roll or non-roll over cases is to generate an accurate and reliable triggering system for restraint systems in order to mitigate the real life roll over crash. Triggering algorithms are based on vehicle signals such as accelerations and roll velocities. Three simulation techniques are used in this study to qualify and quantify the commonly used signals for roll over prediction and to study required restraint system behaviour in order to minimise harm in roll over cases.

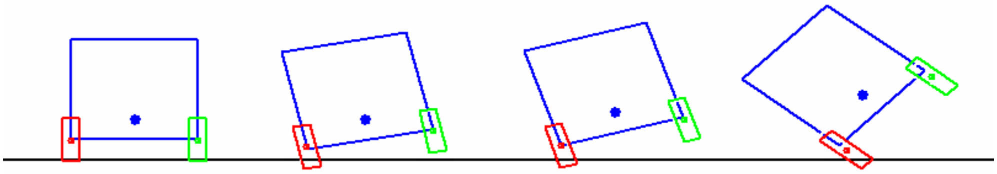
Figure 13.3 **Roll over test setup in crash lab facility**



A friction induced roll over scenario is simulated with a lateral sled test in the crash laboratory. Figure 13.3 shows the hardware used. The vehicle, a 1995 Fiesta provided by Ford Cologne, is equipped with two non-instrumented dummies, several accelerometers and a gyroscope. During the run the vehicle is filmed with several high speed cameras.

The same setup as used in the crash lab is also simulated in ADVANCE. The ADVANCE model is used to obtain the dynamic behaviour of the Ford Fiesta in similar roll scenarios. Figure 13.4 shows a visualisation of the roll over sequence as calculated with ADVANCE.

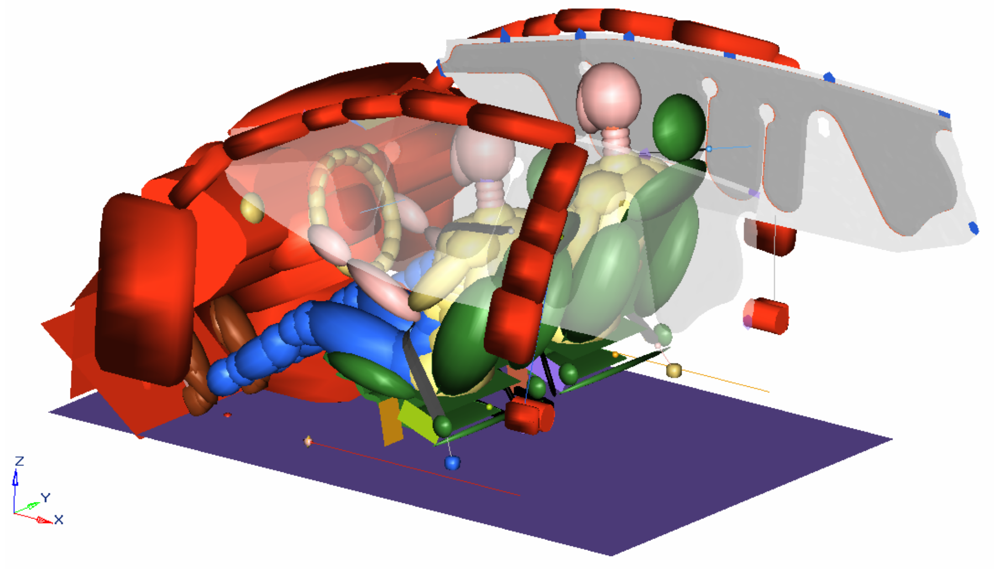
Figure 13.4 **Friction induced roll-over scenario visualized in ADVANCE**



The vehicle motions extracted from the experimental crash tests are used to validate the ADVANCE model. Accordingly, the ADVANCE model is suitable to predict the dynamic behaviour a Ford Fiesta not only in limited handling situations but also in near rollover, or roll over cases.

In the third stage of the roll over tool chain (see number 8 in Figure 13.1), the output of ADVANCE simulations is used as input in a MADYMO multi-body Ford Fiesta compartment model (Figure 13.5). Several restraint systems are included in this model and it also consists of two occupants (either dummy models or human body models).

Figure 13.6 MADYMO Rollover Model



In order to further develop a rollover testing methodology, representative for real world rollover accidents, a stochastic analysis was performed to determine curtain airbag triggering conditions [5]. In this work, occupant simulations have been performed with MADYMO, using a Hybrid III dummy model. The vehicle motions are based on accident reconstructions, divided into different categories (impact induced, ramp induced, skidding and yawing). For each case investigated, a stochastic study was performed in order to find out the required airbag triggering conditions for different parameters used (e.g. belt usage).

It was found that the influence of the different parameters on the required time to fire (TTF) depends on the accident case. However, some general trends could be observed.

"Wearing a belt increases the required TTF, while the shoulder belt height has only minimal influence. The influence of the seat height and dummy size is similar: a higher seat or larger dummy size (both resulting in a higher head position) require a smaller TTF"

Comparison of initially planned activities and work actually accomplished

Planned

During the WP 3 progress (Rolling Phase / Injury Mechanisms, TNO Automotive changed the approach for performing the full scale reconstruction of the selected accident scenario (Delphi 1) as originally planned in the work plan [1]. From several meeting discussions with regard to performing the selected full scale reconstructions (Task 3.2) it became more and more clear that for performing a good and robust numerical simulation of sensor systems not only full scale rollover reconstructions are needed, but also near rollover reconstructions. Today this seems to be a very important statement, because a validated discrimination between rollover- and non-rollover reconstructions is hardly needed for the evaluation of restraint systems (curtains) for rollover occupant protection

Performed

Because of the complexity of the reconstruction of a rollover scenario compared to, for example, a frontal or side impact scenario, TNO Automotive has developed an additional intermediate research step between the in-depth accident study and the full scale reconstruction. With the ADVANCE sled model [2] it should be possible to simulate relevant field rollovers, non-rollovers and extreme driving conditions in laboratory test environments. Based on these simulation results it is expected to develop lab test and uniform test specifications for rollover and non-rollover tests that simulate a majority of the field conditions associated with serious injury.

Figure – TNO Rollover Test Setup

Assessment

A combined numerical-experimental approach has been developed for the prediction of the vehicle dynamics for near-rollover conditions. Prediction of the vehicle dynamics for near-rollover conditions requires simulation models that have validity beyond the common vehicle dynamic motions. This numerical-experimental tool can be used for testing pre-empting rollover sensors and analysis of the injuries and kinematics of dummies.

List of deliverable(s)

The main deliverables of TNO Automotive are:

1. MADYMO Rollover model of Ford Fiesta

Development of a MADYMO Rollover Application, including design guidance and strategies for sensitivity analysis of restraint/protection systems in vehicle rollovers. This will lead to more accurate airbag and restraint system developments, providing a better level of occupant protection during vehicle rollover accidents.

2. ADVANCE Pre-rollover model for estimation of the vehicle motions during the pre-crash phase.

Development of an ADVANCE Pre-rollover Application for the estimation of vehicle motions during the tripping phase.

3. ADVISER Evaluation module for rating of simulation results by objective comparison with test data

Development of strategies for sensitivity analysis of relevant roll-over parameters and implementation in ADVISER.

4. ADVANCE/MADYMO Transfer to occupant simulations

Development of the ADVANCE/MADYMO coupling, sensor box and test method development for rollover (destructive) and non-rollover (non-destructive) experiments.

Acknowledgements (if appropriated)

This research work was performed under responsibility of the department TNO Automotive Safety. The project leader C.G. Huijskens is grateful to the business units TNO Testing and Consultancy (BUT&C) as well as TNO Automotive Safety Solutions (TASS) for supporting this work. The project leader of TNO Automotive also wants to acknowledge the partners FORD, UVMV, Delphi and TRW who provided valuable contributions to this work.

References

Reports:

1. Work Package 3 - Report Task 3.2: Full scale reconstruction
2. Work Package 3 - Report Task 3.2: Vehicle model simulation study for pre-rollover conditions
3. Work Package 3 - Report Task 3.2: Rollover simulations of UVMV tests
4. Work Package 4 - Report Task 4.1: Inventory of current and future requirements for simulation methods
5. Work Package 4 - Report Task 4.2: Rollover Stochastic Analysis
6. Work Package 4 - Report Task 4.3: Overview of simulation tools
7. Work Package 4 - Report Task 4.3: State Estimator for Rollover Prediction
8. Work Package 5 - Report Task 5.2: Methodology for Simulation of Near Rollover Cases

Papers:

- SAE 2006 Paper : Methodology for Simulation of Rollover Cases

- ICRASH 2006 Paper : Stochastic analysis for determination of airbag triggering conditions in rollover accidents.

14. Task 4.3: Numerical Simulation of rollover sensor system (TUG)

Scientific and technical description of the results

Introduction

Rollover sensing is a critical task in improving rollover safety for passenger vehicles. If a vehicle comes into a critical driving mode and the implemented active safety systems (e.g. ESP, ABS, …) cannot stabilise the car, the pre-crash phase begins. This means that possible actions for protecting the occupant from (severe) injuries have to be applied.

In this phase the vehicle's sensing system has to detect the impending rollover accident as well as the status of the car and the occupants. Based on all this information the necessary passive safety actions should be activated:

- Estimation of the severity of the rollover (duration, number of rolls, …)
- Identification and location of the occupant (out of position)
- Decision on the activation of different restraint systems (belt pretensioners, airbags, …)
- Firing or inflation (long time inflation) of the restraints
- Observation of the vehicle's kinematics until the rest position
- Deflation of the airbags (if long time inflated)

The impending rollover should be detected as soon as possible to efficiently run the necessary actions (e.g. slow inflation of the airbags, correction of an out-of-position situation of the occupant …). An optimised sensing system and algorithm is needed to get the best performance of the passive safety system and mitigate the consequences of a rollover.

This document summarises the numerous investigations done within this task.

TUG State of the art report

This report investigates the state of the art for rollover sensing and some basic introductions to rollover sensing.

ECU for Rollovers – The basic hardware system for rollover detection is the electronic control unit (ECU) for rollover detection. Two system are discussed in this report (Autoliv, Mercedes-Benz).

Sensing algorithms – A sensing algorithm including a simplified vehicle model for rollover estimation and prediction is reported.

Algorithm Development Concept – An introduction to the development of deployment concepts is given. A dynamic rollover threshold is described.

Rollover Detection – Rollover sensing systems use lateral and vertical accelerations sensors as well as a roll rate sensor for detection. The hardware demands are investigated in task 6.1 “Performance criteria’s“.

Sensor Systems – A summary of hardware sensors used in rollover systems is given. This includes accelerometers and gyroscopes as well as occupant classification systems. There is also a short introduction to “Future Trends in Sensor Systems”.

Available Simulation Tools – This topic describes the two simulation tools used for numerical analysis for rollover Sensor Systems within this project. These are the ADVANCE tool by TNO and PC-Crash by TUG.

TNO Overview of simulation tools

This report gives a comprehensive collection of simulation tools and internet links. The topics in this overview are:

- Dummy Models
- Crash Solvers
- Structural Analysis
- Vehicle Dynamics
- Crash Reconstructions
- Quality Rating and Stochastic Module

TUG Rollover sensing with PC-Crash

This sub report gives a guideline for using PC-Crash to simulate real world rollover accidents. The output data are used for the evaluation of rollover sensing.

Specific scenarios for PC-Crash

The software package PC-Crash is used for accident reconstruction as well as for basic vehicle dynamic simulations. Regarding the introduced rollover scenarios the simulation method using PC-Crash for rollover sensing system is focused on the scenarios listed in Table 2.

Table 2 Scenarios for rollover sensing with PC-Crash

Category	Sub-Category	Note
Impact induced Rollovers	delta v<30kph	Rollover caused by some kind of impact (other vehicle, tree, or other)
Ramp-like object induced Rollovers		Rollover caused by ramp like object (e.g. flat car, guard rail, slope)

Standard PC-Crash model [1]

The kinetic model takes all dynamic vehicle forces into account. Beside the standard simulation with its implemented models for the different physical effects regarding:

- Tyre-Ground contact
- Suspension characteristics
- Chassis-Ground contact

an open interface allows to include user-defined models and to influence the simulation in order to receive a representation of the real word. The vehicles' kinematics data are used as input in the simulation of the sensing system.

This interface can influence the simulation at 5 interrupts during one time step. Data can be influenced by user definitions in at all 5 interrupts.

Basic simulation of the accident scenario

When an accident scenario is provided for analysing by simulation methods the environment of the scenario, the vehicle data and the driving conditions have to be gained. The environment is modelled by means of different friction sections influencing the tyre forces and polygons with different inclinations to get a virtual scenario.

Focussing on the two mentioned accident scenarios the methodology for basic simulations is described:

Impact induced rollovers ($\Delta v < 30$kph)

For the impact induced rollover scenario the impact can be the result of mainly two different interactions:

- The observed vehicle is impacted by another vehicle inducing a roll momentum
- The observed vehicle impacts an obstacle (mostly with the tyres; e.g. curb)

In the simulation of these cases the impact can be express by the momentum based impact model or the stiffness based impact model.

Momentum based impact model [1]

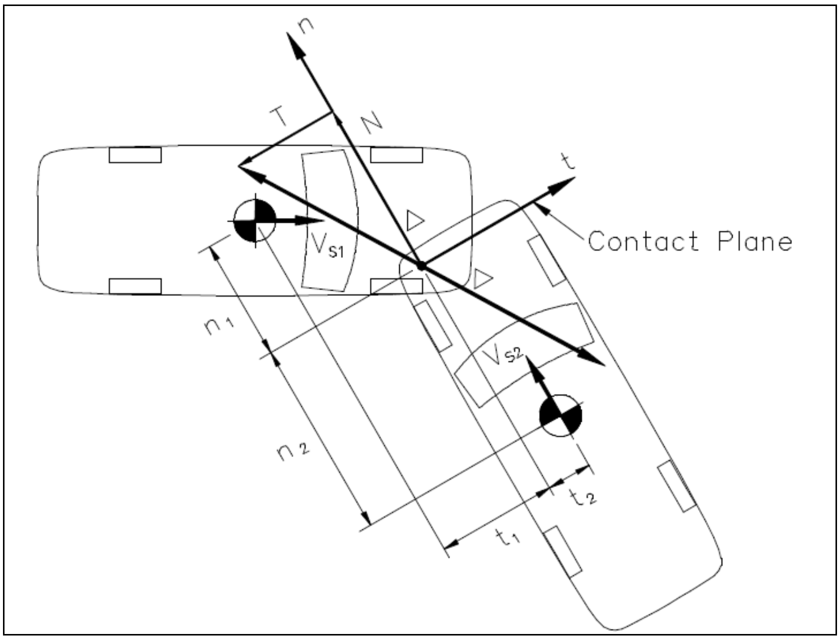
The momentum-based 3 dimensional impact model relies on restitution rather than vehicle crush or stiffness coefficients. This model assumes an exchange of the impact forces within an infinitely small time step at a single point, herein called "impulse point". Instead of resolving the impact forces over time, only the integral of the force-time curve (the impulse) is considered. This model, which was described first by Kudlich [3] and Slibar [4], contains the means to calculate "full impacts" (impacts in which a common velocity is reached by the contacting areas of the two vehicles) and "sliding impacts" (impacts where no common velocity is reached, commonly called sideswipe impacts). The crash model allows the calculation of the post-impact parameters after the definition of the pre-impact phase (speeds and positions).

The post-impact movement depends on following parameters:

- impact speed
- point of impact and orientation of contact plane
- vehicle masses
- coefficient of restitution
- coefficient of friction (in case of a sliding collision)

Figure 7 shows the principal scheme of an impact configuration.

Figure 7 **Collision configuration [1]**



The signals of the kinematical data show a discontinuity because the impact is calculated at a time point. This has to be considered for the evaluation of these signals.

Stiffness based impact model

Another impact model used is the stiffness based model. The influencing parameters on the post-impact are equivalent to the ones of the impact based model with the following modifications:

- The restitution is replaced by the stiffness of the vehicle.
- The impact is calculated over a time interval starting with the first contact of the vehicle's outline and ending with the separation of the vehicle with the impact partner.
- The vehicle is represented by several ellipsoids which are used for contact determination.

With this model it is possible to recieve a continuous characteristic of the dynamical data necessary for the sensor system test (linear and angular accelerations) and no step in these characteristics.

Ramp induced rollovers

For the ramp induced scenario the modelling of the environment focuses on the set up of the ramp object. Therefore the ramp is represented by polygons with different inclinations. The main influencing parameters for this are:

- Geometry of the ramp
- Vehicle parameters (suspension parameters, mass distribution)

It has to be noted that ramp objects appear in different types (end of guard rails, concrete block, ditches, flat hood of a vehicle in case of an under-run, etc.)

Scenarios study

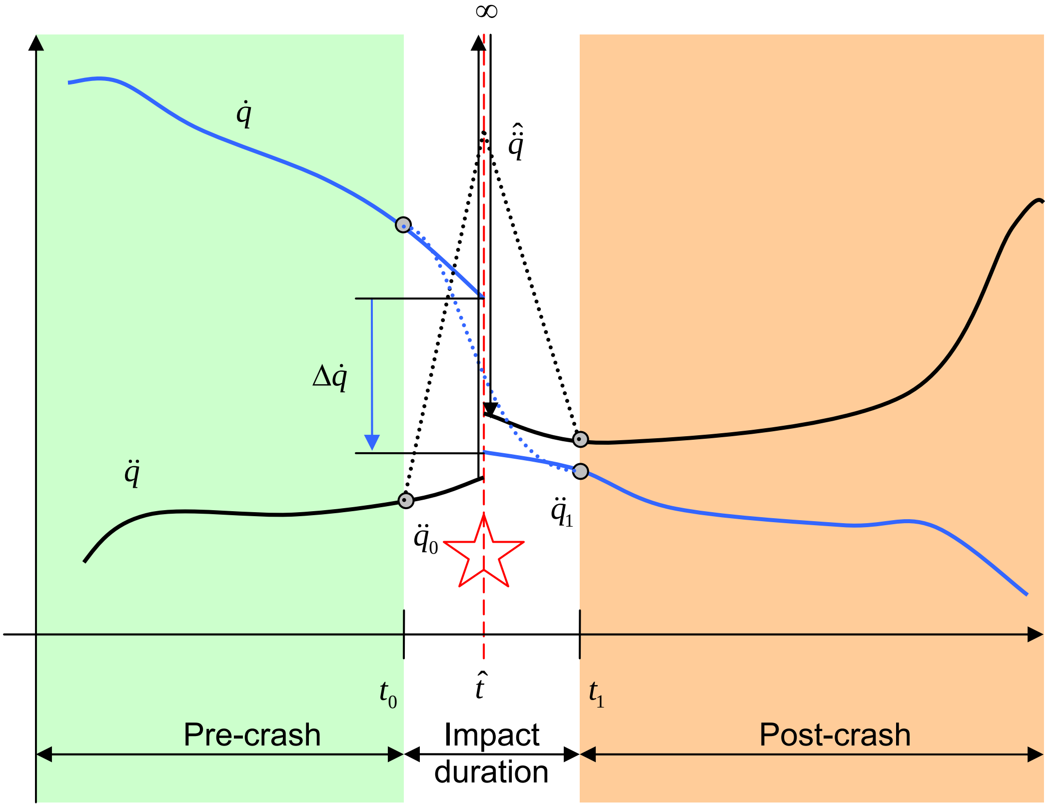
Based on the scenarios in the case library [5] studies on several cases were performed. The reconstructions of the cases were optimised to receive the input for the virtual sensing system evaluation.

Time step	0.001 sec
Kinematical data	linear/angular 3-dimensional accelerations in the centre of gravity (or according to the demands of the sensor system test programme)

The general requirements for the simulation outputs are:

For the impact induced scenario with the momentum-based impact model the change in velocity occurs at one time point. This theoretically leads to infinite accelerations. To avoid this an impact duration has to be introduced (e.g. 60ms) and the accelerations (linear/angular) at the time point of impact have to be modified. With a linear approach for e.g. +/- 30ms on the distribution of the accelerations the velocity at the start of impact has to be continuously transferred to the velocity at the end of impact (see Figure 8).

Figure 8 **Kinematics adaptation for the impact based model (sketch)**



Definition:

$\dot{q}$	general velocity [m/s, rad/s]
$\ddot{q}$	general acceleration [m/s², rad/s²]
$\Delta\dot{q}$	change of general velocity [m/s, rad/s]
$\ddot{q}_0, \ddot{q}_1, \hat{\ddot{q}}$	general acceleration at impact start, impact end, peak [m/s², rad/s²]
$t_0, t_1, \hat{t}$	time at impact start, impact end, change compression–restitution [s]

<u>Evaluation of the rollover sensing</u>

The evaluation of the rollover sensing system is done by predicting the time to fire by simulation methods. In principle the hardware (sensors, microcontrollers, etc.) is modelled including all effects (aging, tolerances, etc.).

The calculated kinematics is then used as input for the rollover sensing evaluation. Several calculations are performed to determine the earliest and latest time to fire. In this stage different algorithm strategies can be tested.

For the evaluation of the system by simulation methods more details can be found in the T4.3 report from Delphi were Matlab/Simulink is used for modelling.

Conclusions

For sensing system simulation in rollover it is necessary to obtain virtual signals for sensors. These signals can be derived from the vehicle kinematics using the linear and angular accelerations. Therefore a vehicle dynamic simulation is used.

PC-Crash offers the possibility to set up a virtual environment for different scenarios. This can be a single vehicle accident or also an impact by another vehicle. The quality of the simulation can be influenced by using a user-defined interface. This allows interrupting the simulation and changing parameters e.g. using values from look-up tables or included specific algorithms such as a stability programme. The results of the simulation are further processed by the hardware and algorithm simulation tools.

The variation of parameters (e.g. speed, geometries etc.) and the use of the dynamic data exchange (DEE) offers the possibility to perform an automatic test programme on a specific scenario.

For the simulation validation tests of the vehicle kinematics experimental driving tests are recommended if the vehicle parameters are not reliable.

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[4] Slibar, A., "Die mechanischen Grundsätze des Stoßvorganges freier und geführter Körper und ihre Anwendung auf den Stoßvorgang von Fahrzeugen", Archiv für Unfallforschung, 2. Jg., H. 1, 1966, 31ff.

[5] Accident case library, Project intern database, European Community – R&TD-Project – 5th Framework-Programme “Growth” – Project “Rollover” G3RD-CT-2002-00802, 2002-2005

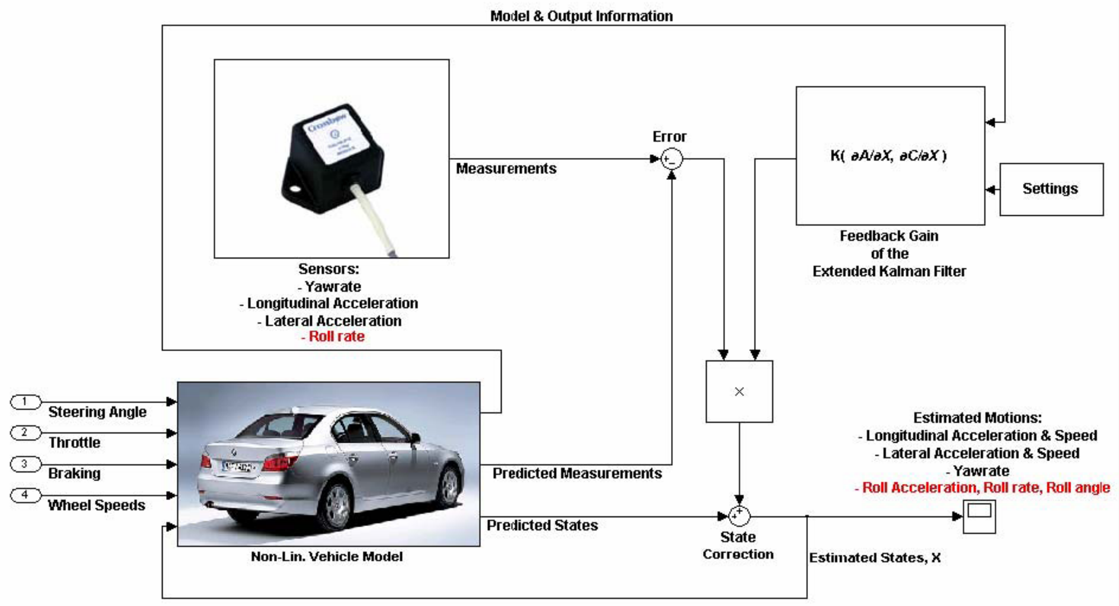
TNO Rollover state estimator

Rollover induced by tire road friction forces is mainly in the domain of Vehicle Dynamics. Detection of this type of rollover occurrence currently requires extensive sensor systems and complex data processing methods. TNO has developed a State Estimator concept for vehicle control applications which is successfully applied for various vehicle control applications, and it uses a limited set of (cheap) sensors. The State Estimator is extended to include roll motions, and an evaluation is done on a rollover incident with an extensively instrumented vehicle. The results show that the State Estimator concept achieves very accurate prediction of the roll motion, and that the lead time in rollover prediction can be expected to be in the order of a few tenths of a second. The conclusion is that TNO’s State Estimator approach has a good potential to be applied in rollover detection systems.

State Estimator concept

The TNO State Estimator concept is developed using the extended Kalman Filter approach. Basically this means that simulation accuracy of non-linear vehicle model is enhanced using a limited set of measured vehicle motion signals. The output of the simulation model provides reliable vehicle motion signals that can be used for control applications and/or safety devices. The simulation model runs real-time, in pace with the measured vehicle motion signals. Reliability of the estimation is strongly related to which sensor signals are used and how the feedback gains are set. In case of Rollover application the roll rate signal is most important. The concept of the TNO State estimator for vehicle control is depicted in the following figure.

Figure 1: State Estimator concept

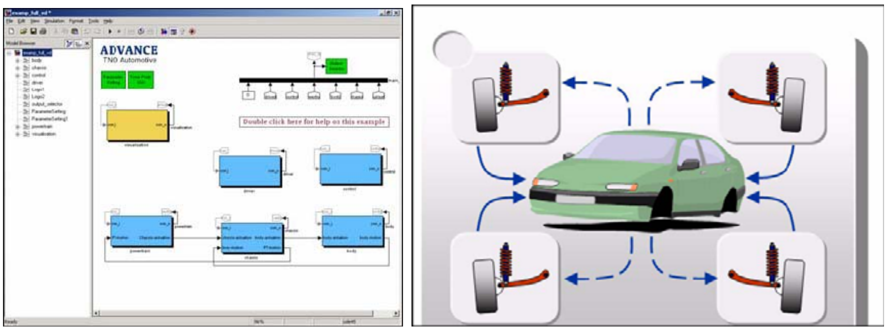


In order to ensure accurate motion prediction under various environmental conditions also some road characteristics are estimated. For the application of rollover recognition, a roll rate sensor is added to the system and the set of estimated motions is extended with roll-related quantities.

Verification with simulation

The roll prediction state estimator is first verified with a three dimensional vehicle model. This vehicle model was created using TNO's Simulink library ADVANCE [1]. The model consists of a rigid chassis to which the front and rear wheel hubs are connected using effective suspension characteristics. This means that instead of modelling all suspension components only kinematics and compliance effects of the whole suspension are defined. The tyres are modelled using TNO's MF-Swift model that includes all important rollover tyre characteristics [2]. Figure 2 shows the model both graphically and as used in Simulink.

Figure 2: Advance Simulation model



The ADVANCE model was used to simulate a high speed reversed steering test that results in vehicle rollover. The simulated motions and driver commands are fed into the State estimator and the Feedback gains of the Extended Kalman Filter are optimised for the roll rate response.

Verification with measurements

UVMV carried out a rollover manoeuvre on their test track with a modified Ford Fiesta. The modification was required in order achieve the rollover condition as the original vehicle was far too stable. The centre of gravity of the vehicle was elevated by modification of the suspension, and alternatively the front stabiliser bar was removed to induce oversteer. During this test the main vehicle motions and steering were applied using a steering robot. The actual roll angle was not measured, but some pictures show the state of the vehicle at different time intervals as indicated in the UVMV test report. The State Estimator that was set up using the simulation model is evaluated using recorded data from the test. The following signals were fed into the State Estimator: - Lateral acceleration - Yaw velocity - Roll rate - Vehicle speed (from one wheel) - Steering angle (command to steering robot). Pictures that were made during the test are shown below, as well as the indication of the corresponding time in the measurement signals.

Figure 4: Vehicle at T = 4.2 s, stationary after steering 33 degrees to the right

Conclusions

The TNO State Estimator has successfully been extended to allow roll angle prediction. The set up of the State Estimator was developed using a simple three dimensional vehicle simulation model, and verification with measurements of a rollover event shows that also for measurement signals the State Estimator approach is promising. The lead time for rollover prediction can be in the order of a few tenths of a second. TNO's State Estimator approach has a good potential to be applied in rollover detection systems.

References

[1] Vis, M.A., van de Venne J.W.C.M., Vink, W., van der Steen, M., Lupker, H.A., "Combining Driveline and Suspension Models for Real-Time Simulations" Aachener Kolloquium Fahrzeug- und Motorentechnik, October 2000

[2] Jansen, S.T.H., Lupker, H.A., Koppenaal, C.J.P., "Tyre Influences on Untripped Rollover Behaviour", Proceedings of AVEC 2002, Hiroshima, Japan

DELPHI Rollover Sensing System Simulation

This document describes numerical methods, i.e. simulation models and tools to develop Rollover Sensing Systems.

Prior to definition of any rollover sensing simulation model it must be decided which sensing algorithm is selected and what components are required to meet the algorithms goals.

Simulation model must consider mathematical/physical calculations as well as all HW (Hardware) components that will be used in the ECU (Electronic Control Unit).

Delphi's Rollover Algorithm, used in EU Rollover Project

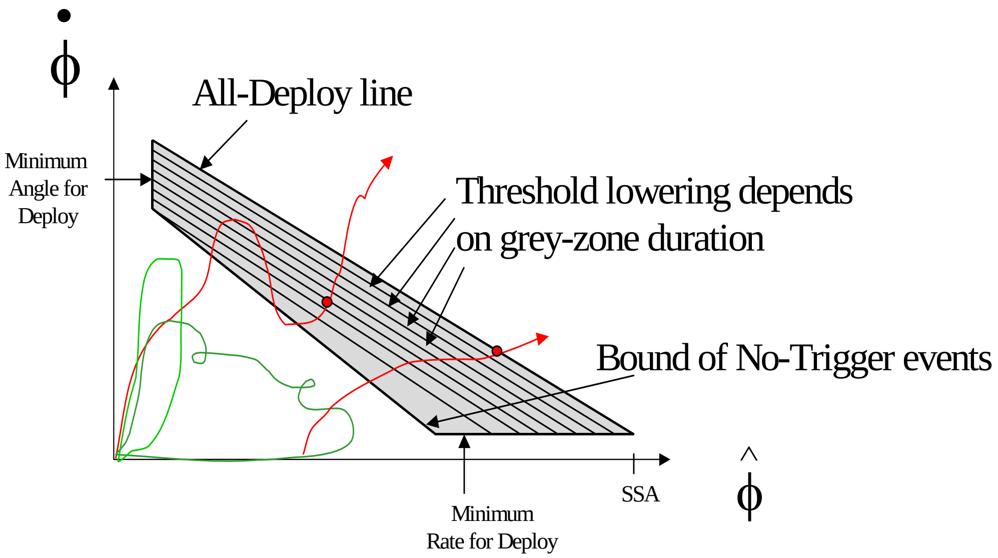
One of Delphi's rollover algorithms that was chosen for this European Rollover Project is called WinGAMR, standing for Windowed Gyroscope Algorithm Measuring Rollover.

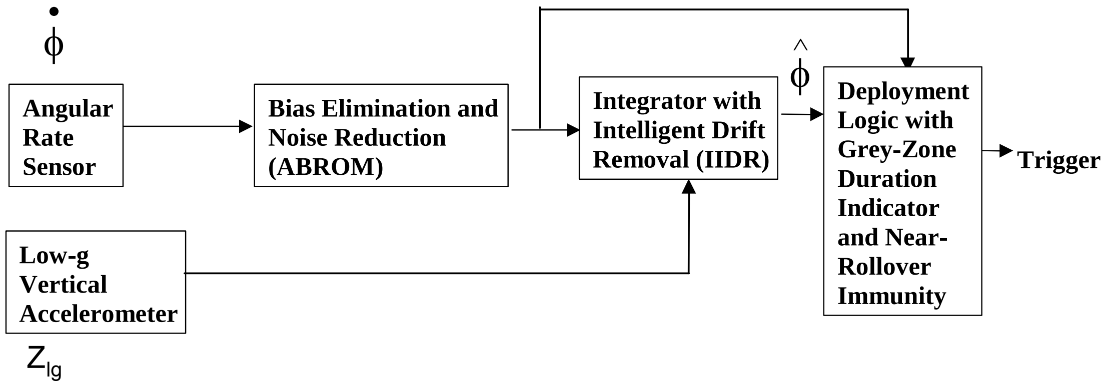
The key measure for this algorithm is angular velocity around the x-axis (roll rate).

The measured roll rate is first filtered by anti aliasing HW filter (Bessel filter) and then by an adaptive high pass SW filter during signal processing.

Based on numerical integration of filtered roll rate signal the corresponding roll angle can be estimated. There are adjustments of the estimated roll angle based on y- and/or z-acceleration measure and over the entire operation time.

The rollover detection is performed by checking the filtered roll rate and estimated roll angle in any calculation cycle. That means both of these measures must exceed an appropriate threshold to facilitate rollover decision. See the grey-zone figure and flow chart below for more detail.





Rollover Simulation Model, based on Delphi's Concept

The simulation model consists of several parts that will be described in more detail below. To be able to compare simulation behaviour with real life behaviour the following points must be covered by the simulation model

- HW must be simulated in all components
- Sensitivity and Resolution

- Measuring range
- Frequency response
- Offset
- Aging effects (bias, etc.)
- tolerances

Simulation Environment should contain „SW filter operations“ to compensate inaccuracy of HW as good as possible

All calculations must be considered as if running in real time applications

Simulations must be able to run several crashes automatically (permanent testing for the entire Crash Library)

Simulation results must be reproducible

There must be a way to distinguish unambiguously among simulation results in respect to their individual calibration settings (check sum for each parameter setting must be available)

SimInput:

•Event Library Path

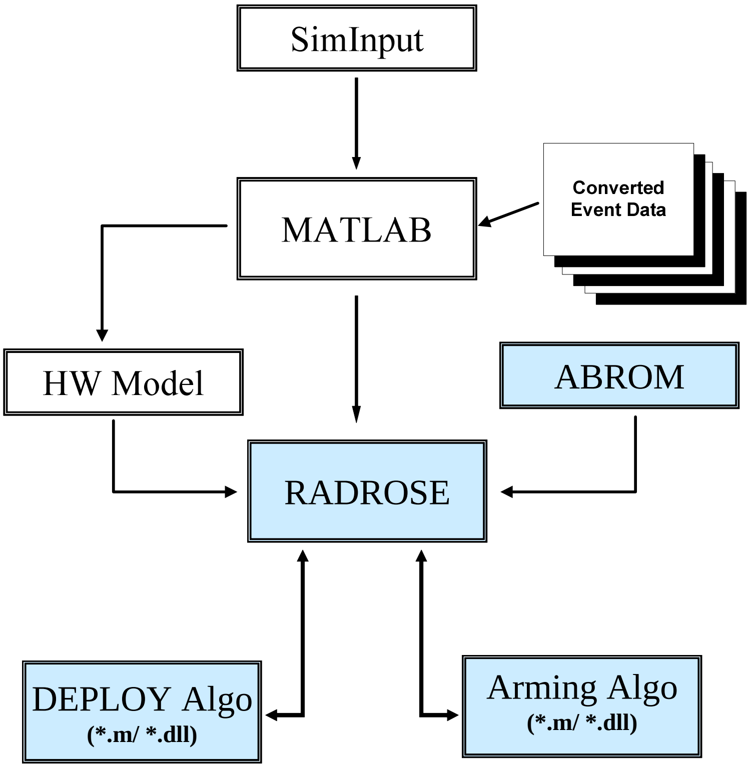
•Control values

•HW Parameters

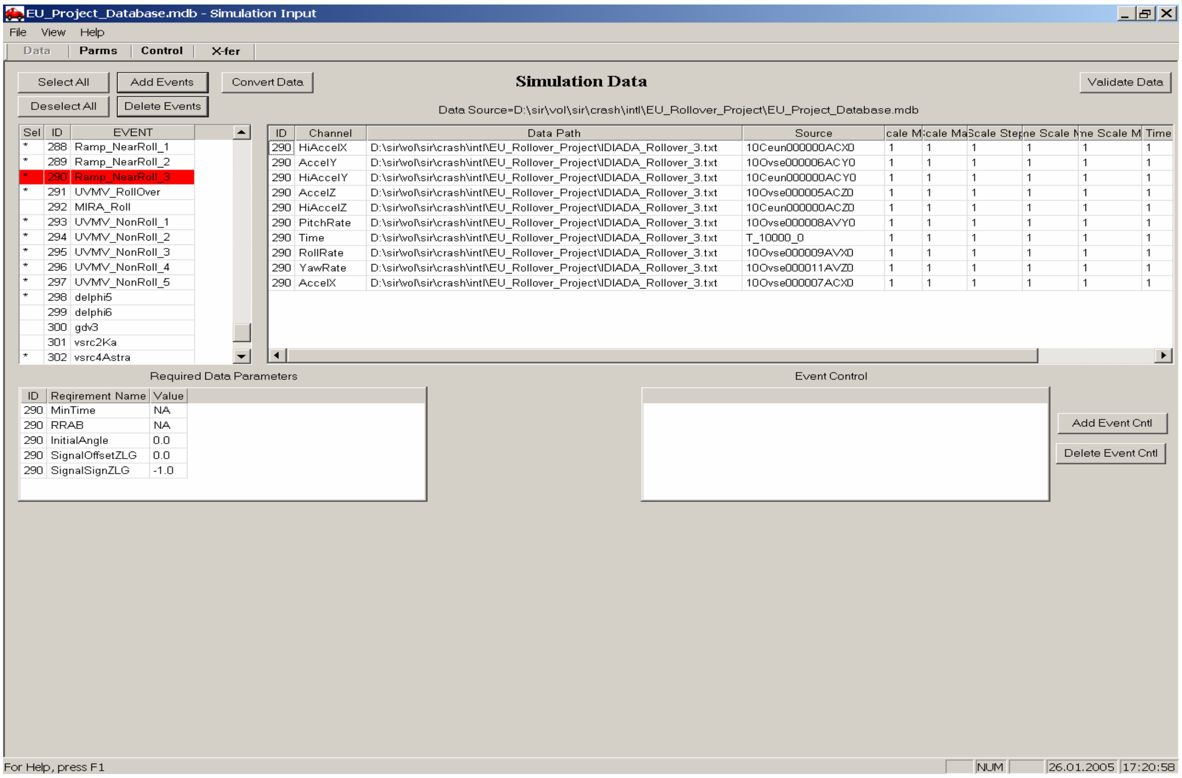
RADROSE

•Invokes Active X server

•Eventcontrol & Run#



Below you can see the structure of the SimInput tool. In this window feature of SimInput you can find the registered event files with their respective channels and addresses.



Simulation Data

Data Source=D:\sir\vol\sir\crash\intl\EU_Rollover_Project\EU_Project_Database.mdb

Sel	ID	EVENT
*	288	Ramp_NearRoll_1
*	289	Ramp_NearRoll_2
*	290	Ramp_NearRoll_3
*	291	UVMV_RollOver
	292	MIRA_Roll
*	293	UVMV_NonRoll_1
*	294	UVMV_NonRoll_2
*	295	UVMV_NonRoll_3
*	296	UVMV_NonRoll_4
*	297	UVMV_NonRoll_5
*	298	delphi5
	299	delphi6
	300	gdv3
	301	vsrc2Ka
*	302	vsrc4Astra

ID	Channel	Data Path	Source	cale M	cale Ma	Scale Ste	ne Scale M	ne Scale M	Time
290	HiAccelX	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ceun000000ACX0	1	1	1	1	1	1
290	AccelY	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ovse000006ACY0	1	1	1	1	1	1
290	HiAccelY	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ceun000000ACY0	1	1	1	1	1	1
290	AccelZ	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ovse000005ACZ0	1	1	1	1	1	1
290	HiAccelZ	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ceun000000ACZ0	1	1	1	1	1	1
290	PitchRate	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ovse000008AVY0	1	1	1	1	1	1
290	Time	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	T_10000_0	1	1	1	1	1	1
290	RollRate	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ovse000009AVX0	1	1	1	1	1	1
290	YawRate	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ovse000011AVZ0	1	1	1	1	1	1
290	AccelX	D:\sir\vol\sir\crash\intl\EU_Rollover_Project\IDIADA_Rollover_3.txt	10Ovse000007ACX0	1	1	1	1	1	1

Required Data Parameters

ID	Reqirement Name	Value
290	MinTime	NA
290	RRAB	NA
290	InitialAngle	0.0
290	SignalOffsetZLG	0.0
290	SignalSignZLG	-1.0

Event Control

Triggering times summary

All results were reported for a dual stage rollover sensing system. Stage1 is defined for near rollover detection with reversible restraints. Stage2 is for detection of most likely rollover scenarios. Results were performed based on a default calibration, as no triggering requirements were declared. Therefore the same parameter setting was used for all 42 available rollover cases in the library. Simulation results show a good immunity against inadvertent deployment on Non-Rollover events.

For some soil trip scenarios earlier deployment may be achieved either by adjusting the parameter settings or considering Delphi’s new rollover sensing algorithm. In this new algorithm the lateral forces are included with a higher weight. In appendix the results for Stage2 can be seen as comparison.

Comparison of initially planned activities and work actually accomplished

By the different sub reports a guideline is developed to give advice for numerical simulation of the rollover sensing system. These parts consist of the major 2 groups:

1. Vehicle dynamic simulation and kinematical data output
2. Simulation of the sensing system (hardware and algorithm) and trigger output

With this guidance the initially planned activities are accomplished.

List of deliverable(s)

The studies performed within this task are

- TUG State of the art report
- TNO Overview of simulation tools
- TUG Rollover sensing with PC-Crash
- TNO Rollover state estimator
- DELPHI Rollover Sensing System Simulation

They are available in sub reports to the deliverable

D4.3 Report on design guidance for numerical models used in the assessment of sensors used for rollover detection and triggering

References

See “Scientific and technical description of the results”

15. Task 5.1: Structural test (IDIADA)

Scientific and technical description of the results

The first step taken in task 5.1 was the development of an effective test methodology. The following is an overview of the relevant steps taken to successfully complete the task.

Defining the test to be used for the physical simulation. This has been completed and was done by researching rollover test methodologies. Through evaluation of these methodologies a test was chosen. The reasoning for the choice is outlined briefly in this document

Refining the test. This essentially is the aim of this document -‘Test Development’. 76 cases were reconstructed in this project; these cases were evaluated with regards to the impact angles and velocity in order to determine a test that represents the majority of the most serious rollover scenarios.

Identification of effective test methodologies:

The main considerations when making an effective test were found to be the following:

Repeatability (1). This means that if the same test is carried out any number of times the results would always be identical, therefore creating a standard for all vehicles, within reason. This is a key factor and of utmost importance when testing vehicle structures for rollover protection. A repeatable test would enable the creation of an accurate model on which to base the development of safer vehicles in a rollover scenario.

Representative (2) of the real life accidents. For obvious reasons, a test that is only remotely representative of what it is supposed to test is no good.

Insensitive to vehicle size (3). This is important when attempting to create a standard which can be applied to all vehicles, within reason. For example, all passenger vehicles, from small cars to Multi Passenger Vehicles and 4X4 vehicles.

Other relative criteria for a rollover test method are that the test should:

- take into account the effects of roll momentum.
- indicate occupant kinematics
- be simple and cost effective

The following section will review the test methodologies in the ‘Rollover Test Methodologies’ document, with respect to these three key factors.(1,2,3 above)

Test Method	Repeatable	Representative	Vehicle Size
FMVSS 208	x	√	x
FMVSS 216 Roof crush	√	x	√
FMVSS 201 Occupant protection in interior impact	√	x	√
The Inverted Drop Test	√	√	√
The Corkscrew Rollover	x	√	x
The High Capacity Centrifuge test	√	x	x
Exponent's Test and Engineering Centre (TEC)			
Lateral roll into a dirt or curb tripped roll	x	√	x
translating and rotating vehicle drop system	x	√	x
Monash University (AUSTRALIA)			
Drop test	√	√	√
Pendulum device	√	√	x
Dropped from a moving vehicle on to roof	x	√	x
Dynamic Rollover Platform (NHTSA)	√	x	x

The table above indicates that there are two test methodologies that incorporate all three factors successfully. These are

- the inverted drop test
- the Monash University (MU) drop test

As they sound, the two tests are very similar. The only difference is that MU takes into consideration the frictional forces of the ground to a greater extent than the other drop test, by including the drop onto an inclined floor.

In the drop test there is essentially only one direction of movement and so the effect of the height of the centre of gravity is minimised. At present the drop test carried out consists of one drop at particular roll, and pitch angles. The reconstructed accident cases will be used to develop more tests at statistically 'important' orientations.

Applus+IDIADA went on to develop the drop test with the aim of creating a series of tests, which will be accurate and representative of the 76 cases in the Accident Library established in WP1 and WP2 of the rollover project.

The cases were analysed in order to identify the most severe impact positions in 3 different ways:

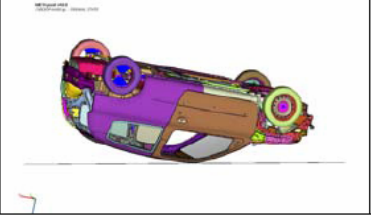
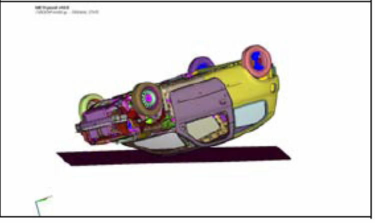
- The first was to indicate the strongest impact position and show the severity of the injury that resulted.
- The second used the same strongest impact position as before; however indicating the damage to the occupant compartment that resulted.
- The third also used the same strongest impact position, this time indicating both injury and damage to occupant compartment levels; they are not always mutually inclusive.

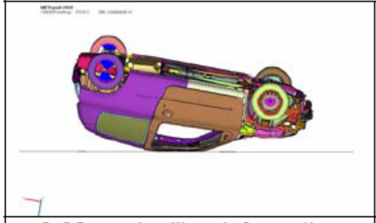
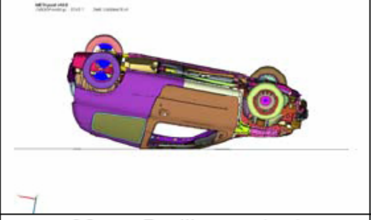
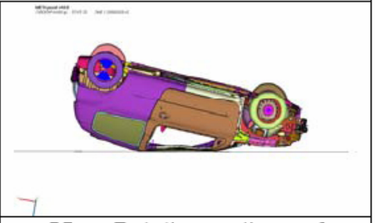
A further stage was carried out to indicate if a seatbelt was being worn during the accident. If a severe injury and a high level of damage resulted from the accident and a seatbelt was worn by the occupant then, the case qualify for a most serious case.

A brief description of each of the 76 cases is included in the report, including photographic and numerical representations of the case and an estimate of the estimated strongest impact position.

Each case was evaluated by means of a resolution of vectors, first in the lateral (x-y) plane and then a review was conducted for all the cases, to include a resolution in the vertical (z) plane. The point of reference was the impact position and corresponding velocity, when the most substantial damage and intrusion of the occupant compartment occurred - therefore attempting to represent the worst case scenario in the test development process. The principle behind the review was that we considered that the most important direction of the loading was the vertical axes and therefore the review of the cases was carried out with the notion that this was the loading plane with the most substantial damage potential.

The result of the review was a set of configurations that was validated for severity using simulation techniques; vertical velocity of 11.3km/h and four (roll; pitch) angle combinations – (130°; +/-10°) and (170°; +/-10°) respectively. The proposed configurations were validated for severity with simulation techniques. Three configurations were simulated with three different Roll angles: 170, 150 and 135 degrees, such as shown below. This task was completed by Renault.

Roll Angle	Pitch angle	Velocity
170°	10°	11,3 km/h
		

Kinematics		
The vehicle turn over the roof		
		
0-30ms: A-pillar deformation	30ms: B-pillar contact	55ms:Rotation on the roof

Tests were carried out for demonstration purposes. We produced the inverted drop test checklist first then carried out the two inverted drop tests and presented the results to all the partners. Renault produced a document detailing the drop test results as shown below.

Figure 1 First Inverted drop test

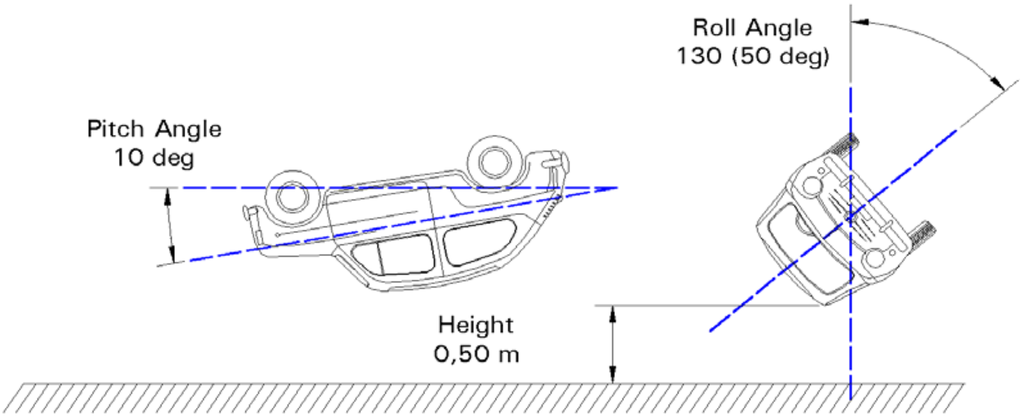
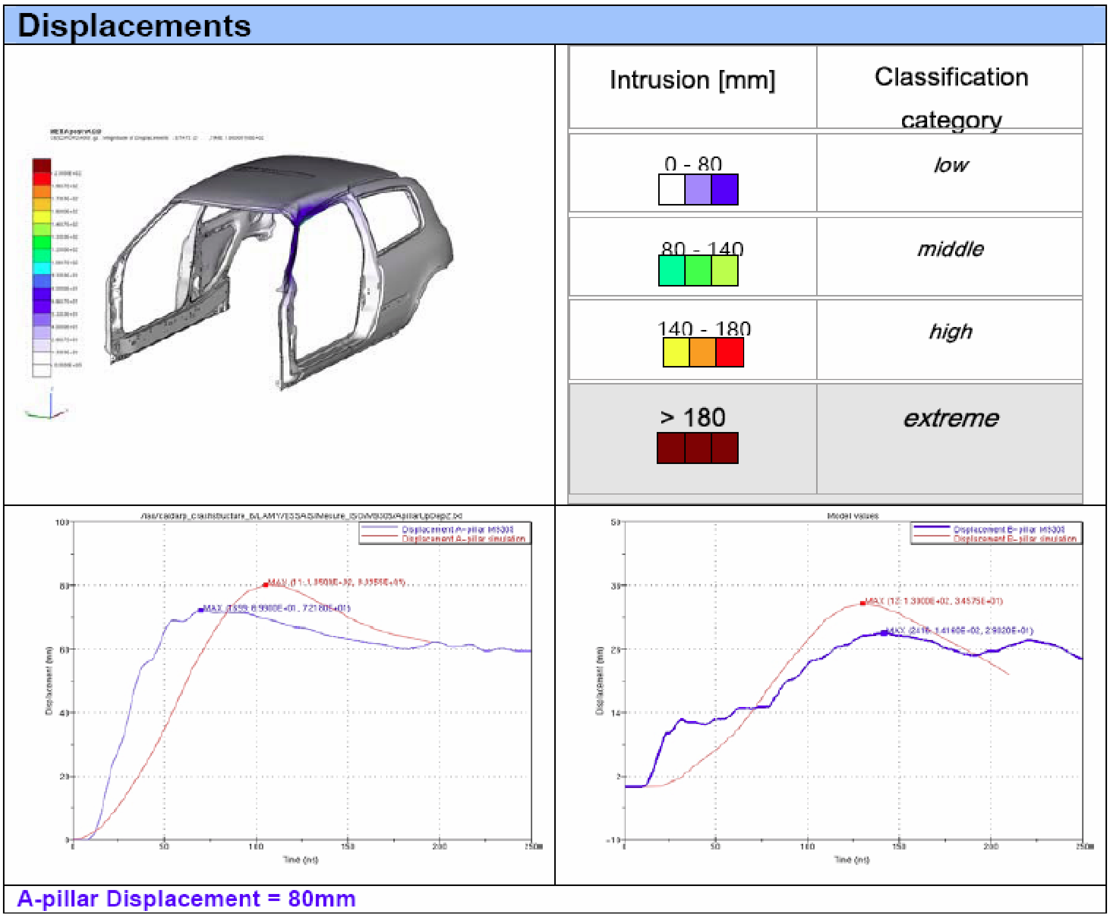


Figure 2 First drop test displacements



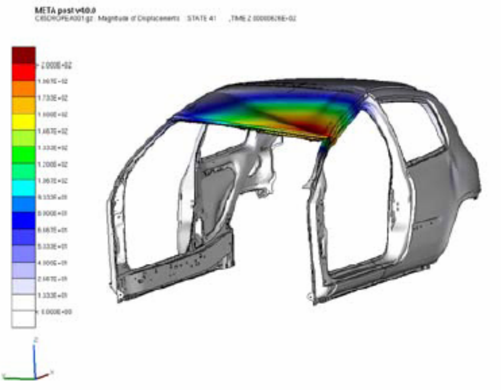
Displacements

Intrusion [mm]	Classification category
0 - 80 ⬜🟪🟪	*low*
80 - 140 🟩🟩🟩	*middle*
140 - 180 🟨🟧🟥	*high*
> 180 🟥🟥🟥	*extreme*

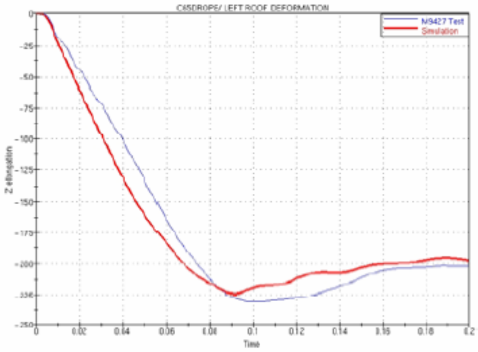
A-pillar Displacement = 80mm

For the first testing procedure, the deformation proved to be less than what was expected in the test predictions, and the configurations of the test were modified. New configurations were proposed after a series of simulations, and comparison with real rollover cases.

Displacements



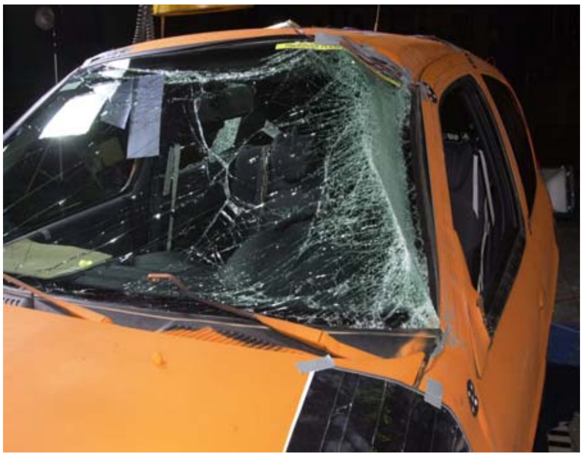
Intrusion [mm]	Classification category
0 - 80 ⬜🟪🟦	*low*
80 - 140 🟩🟩🟩	*middle*
140 - 180 🟨🟧🟥	*high*
> 180 🟥🟥🟥	*extreme*



A-pillar Displacement = 230mm

The second test was more representative of a worst case and the comparison with the simulation and a real case proved the test to be robust.

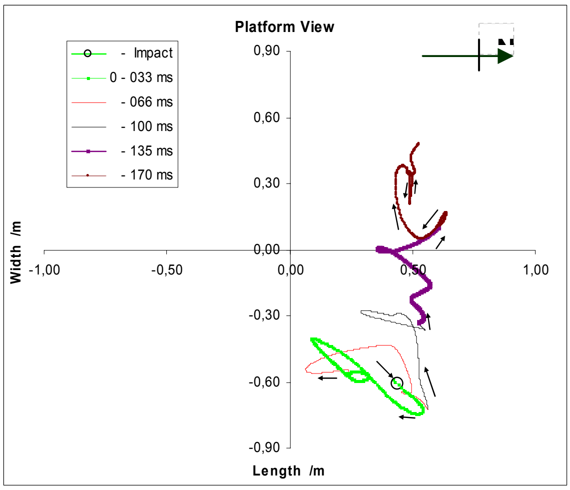
First Drop test

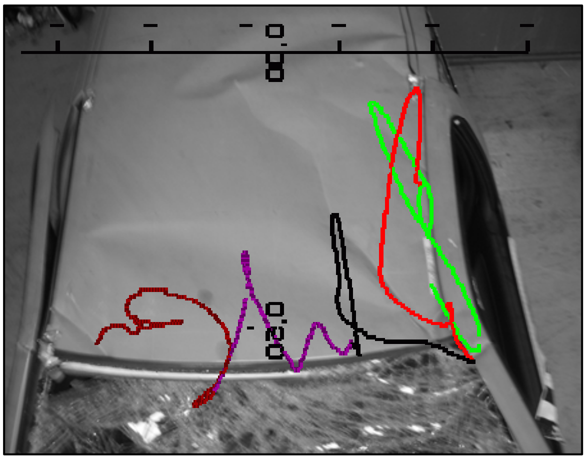


Second Drop test

Second Inverted drop test interior/exterior comparison with real case.

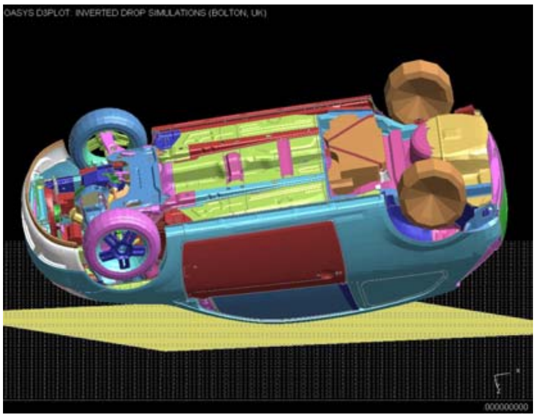
We carried out an analysis of the load distribution during the crash.

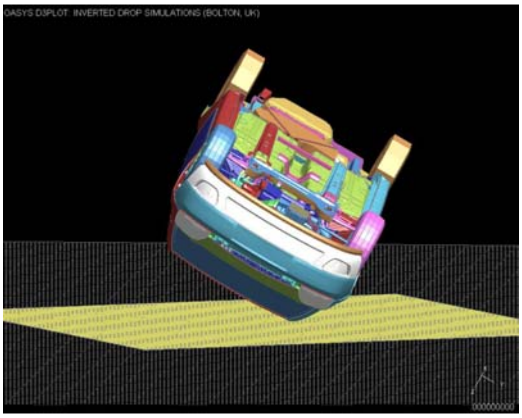




A balance of moments about the centre of the platform shows the dynamic coordinates of the principal force; as measured by the load cells. The second figure shows the load superimposed on the vehicle and the directions of the load during the crash.

The Bolton Institute carried out inverted drop test simulations of a Ford Fiesta in order to gain a deeper insight into the vehicle movements. A finite element analysis was carried out in order to evaluate these movements.





Three Pitch angles were simulated by Bolton, there were 5, 10 and 15 degrees. The critical vehicle orientation at roof impact that causes the highest amount of roof crush is 10º pitch angle & 12.5º roll angle, which is the same that was employed by IDIADA in the experimental test and what Renault deduced from the simulation on a Renault Clio.

For the intention of Work Package 3 and 5, Bolton Institute also carried out tests on the “Quasi-Static Roof Crush and Body-in-White Components Test“. This involved carrying out a roof crush test and evaluating each pillar with a bending test.

List of deliverable

- The main deliverable is Report Task 5.1 – Structural Tests
- A report on the “Inverted Drop Test Simulations of the Ford Fiesta” was completed by the Bolton Institute.
- “Quasi Static Roof Crash Test”, also completed by the Bolton Institute.

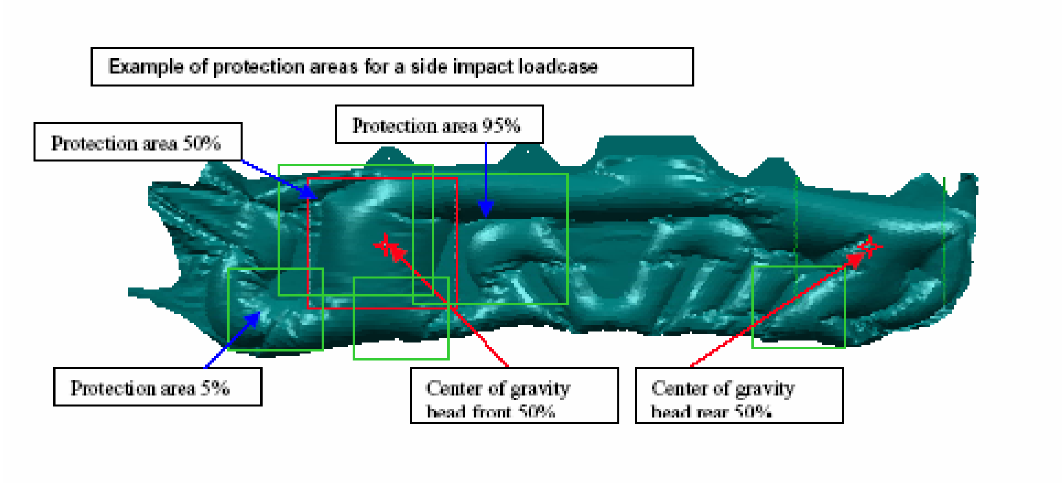
- “Inverted Drop Test Checklist” was prepared by IDIADA.
- “Impact Angle Simulation”, was completed by Renault.
- “Definition of the Acceptance Criteria”, also completed by Renault.
- “Numerical Simulation of Vehicle Structural Design”, completed by Renault.
- Renaults’ final deliverable was the detail of the “Drop Test Results”.

16. Task 5.2: Restraint tests (IDIADA)

Scientific and technical description of the results

We worked in the production of a paper on seat belt methodology. The work in this report was completed as a precursor to the work regarding the roll cage. The information in this paper, details current test methods and practices that are being applied in the automotive industry. Injury suffered in accidents on the roads or in the city come at a very high social and economical cost. An increase in the general use of the safety belt in Spain could produce a substantial drop in the level of injuries of the victims in road accidents. TRW produced a report for the test methodology section covering the use of airbags and Renault completed the section with their review of the tests in practice by vehicle manufacturers.

Lateral Head Airbag



Renaults testing set-up

Despite the R.G.C. (General Road Code) which makes the use of safety belts in urban areas and inter-urban areas obligatory, not all the automobile users observe the code; and what is worse is that a lot of them think the safety belt has more problems than benefits. This document is a review of the principal tests made on safety belts. There are a lot of regulations, standards, directives, procedures, etc… concerning safety belts (seat belts), all with the aim of ensuring a high quality and scope for the safety belts that will be installed and used in automobiles. There are a lot of test procedures that are indirectly related to seat belt safety, but a review with a wider scope than this one would be required in order to include all of them.

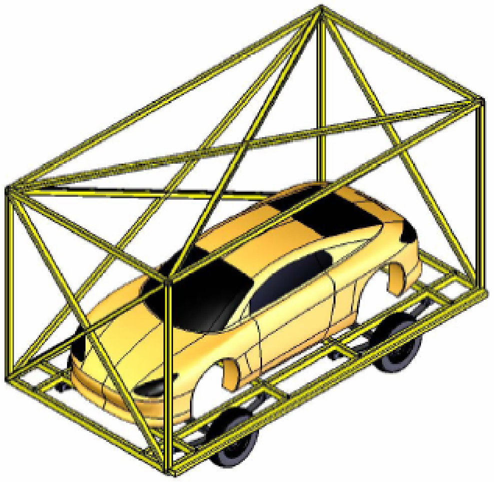
An extensive description of each of the regulated tests that this review covers is included in the regulation review section and a comparison table summarises the differences found between the standards and test practices.

The definition of vehicle movements was completed by TUG and IDIADA, with both performing real-life tests. TUG's contribution was to investigate soil trip rollover accidents and perform a test to evaluate the results.

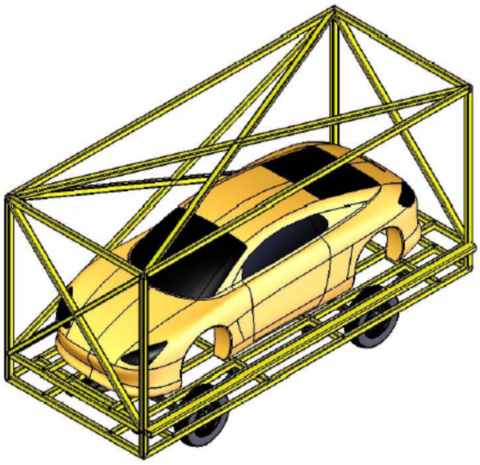
IDIADA carried out 4 non-rollover tests in WP 3.2 and these were used to help determine overall results.

With the result from the tests carried out by IDIADA and TUG, we made a sketch of a sled to simulate a rollover induced by ramp. There were three configurations proposed for the sled.

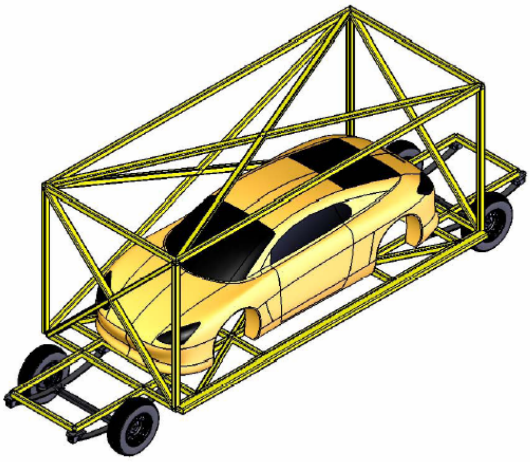
Configuration 1:

-The vehicle wheelbase remains unchanged. - The track width is fixed to a size wider than the real one. -The vehicle's C.O.G height increases slightly but is closer to the real one.	

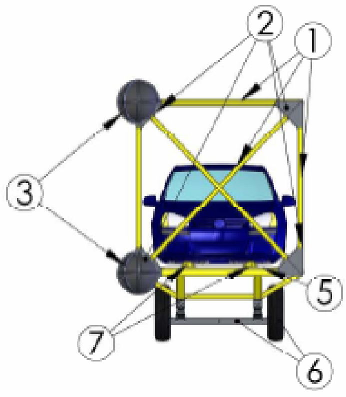
Configuration 2:

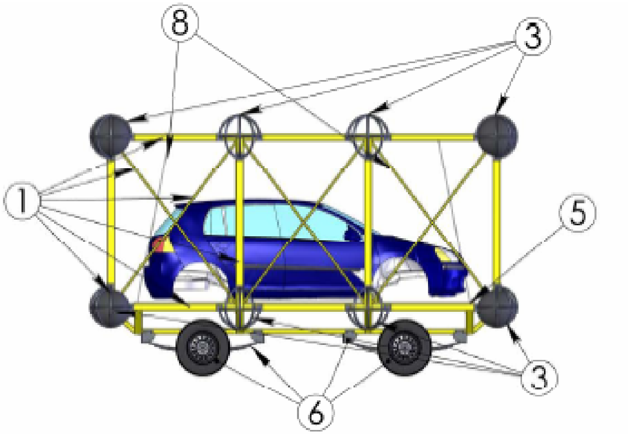
-The vehicle wheelbase remains unchanged. -The track width remains unchanged. -This is the configuration where the C.O.G height increases more.	

Configuration 3:

-The vehicle wheelbase is fixed to a size longer than the real one. -The track width remains unchanged. -The vehicle's C.O.G height increases slightly but is closer to the real one.	

The three test devices were launched against a ramp at 75 km/h and the movement data, angular velocity, (roll angle and roll rate) were obtained. Three different ramps were used, one for each sled configuration. The three configurations were proven in PC-CRASH in order to assess their movements. After that the graphics were compared, and the best was chosen. Some modifications were done on the structure, with the addition of crush absorbers on the ends of the structure. Currently, the model prepared for construction is shown below





The structural model of the roll cage was analysed using PAM-Crash. The Simulation work took longer than had been planned, and resulted in some delays, but the construction and demonstration of the sled is expected soon.,

List of deliverable

- The main deliverable from this work package was Report Task 5.2 – Restraint System Tests has been completed.
- IDIADA contributed towards the seat belt testing methodology with the production of a sub-report.
- “Review of tests in practice by vehicle manufacturers”, produced by Renault.
- “Rollover Test Methodologies”, produced by TRW.
- “Methodology for simulation of near rollover cases”, produced by TNO.
- “Low G Sled Testing Methodology”, was produced by TUG along with the results they obtained form this procedure.
- “Ramp Induced Rollover Test Results at 35kph No.1”, produced by IDIADA.

- “Ramp Induced Rollover Test Results at 35kph No.2”, produced by IDIADA.
- “Ramp Induced Rollover Test Results at 50kph”, Completed by IDIADA.
- “Ramp Induced Rollover Test Results at 65kph”, also produced by IDIADA after the tests had been completed.

17. Task 5.3: Sensor system Tests (UVMV)

What is the objective?

Identify effective test methodologies for the determination of fire/no fire conditions for the development of rollover sensing system technology.

Description of the work

Perform test series to study evaluation methods for vehicle rollover propensity. Perform vehicle misuse testing. Assessment of vehicle angular and linear accelerations with regard to rollover sensor system evaluation and development.

In our opinion, the work on this task should consist of following main parts:

1. Study of the rollover propensity of passenger cars aimed at determination and description of critical driving conditions in terms of rollover risk (including robustness against driver's faulty reaction) and selection of suitable testing methods
2. Investigation of typical values and time histories of vehicle kinematical parameters in order to find key parameters for rollover sensing systems and for correlation with simulations

Add 1)

Set of driving tests should be partially appear from ISO standards with significant dynamic changes of driving conditions – e.g. double lane change, load change or braking in turn etc. Some American (e.g. NHTSA) rollover test procedures should also be investigated. For selection of the test manoeuvres results from WP1 (accident statistics) should be taken into account.

UVMV will primarily use the Renault Scenic from Task 2.2 as a test car. If it will be possible to make some driving tests before the full-scale accident reconstruction with Ford Fiesta (Task 3.2), the Fiesta can also be used for tests. In addition, we would like to include some other types of cars partially into the testing program, namely for comparison purposes; this depends whether or how many cars we manage to loan though.

We assume that the test manoeuvres will be near rollover, but without exceeding the roll stability limits because the test vehicle will not have any special protection means avoiding the full rollover.

Full vehicle kinematics was measured (namely lateral and longitudinal acceleration, roll and yaw angle and/or angular velocities, vehicle speed and slip angle, steering wheel angle). This standard instrumentation could eventually be supplemented by other sensors (e.g. accelerometers).

Add 2)

We suppose to pay interest firstly to quantities describing rolling of the vehicle (roll velocity, roll angular acceleration …) and secondly relationships between rolling and other basic kinematical quantities. The third field of study could be possibilities of indirect measurement of quantities, which may be important in terms of vehicle’s rolling behaviour but it is difficult or expensive to measure them directly. (One possible example of them is the instantaneous wheel load.)

For those purposes, the attention should by paid namely to accelerations, which are most simple and cheap to measure. On the other hand, some future sensing possibilities, which are under development at present (such as built-in sensors in tyres), can also be taken into account.

Some further comments to the test manoeuvre selection:

On the base of experience, literature review and results of reconstructions of accidents, we can state some typical driving conditions, which can conduce to an on-road, untripped rollover. Those can be for example:

- Large sideslip angle, namely at high speed on the road with a high-adhesion surface. Although the subsequent rollover mechanism may also be tripped-type (e.g. after leaving the roadway) primary cause of the rollover is the uncontrolled driving manoeuvre. Nevertheless, prevention of the excessive sideslip angle values is one of the main functions of current ESP systems.
- Quick dynamic changes of roll of direction of yawing, causing roll oscillation of the vehicle.
- Combination of the above-mentioned mechanisms with dynamic changes of load distribution – braking, sudden change of throttle position etc.
- Sudden change of adhesion level while the vehicle is turning or skidding.

We suppose to focus the work namely on the second and the third case. It is to contemplate, whether (and how respectively) should some other types of rollover (*trip over*, *flip over, bounce over*) be included in the analysis.

Partial Goals

- propose and verify suitable test methods for rollover propensity (resistance) testing
- investigate the driving conditions or driver’s reactions critical in terms of rollover
- propose suitable measuring parameters describing the behaviour of the vehicle in terms of rollover risk
- define key parameters for correlation with simulations
- (investigate eventual possibilities of use of easy-measurable quantities – e.g. accelerations – as a substitution of required physical quantities – if needed)

Partners shares – review

- UVMV (4.2mm): task coordination, a series of driving tests
- IDIADA (4 mm): a series of ramp induced tests (TUG12)

- TUG (2mm): development of a low-g sled, a series of low-g sled tests (in conjunction rollover tests results were involved to the DELPHI with T5.2)
- DELPHI (2mm): data analysing, a series of sensor tests
- TNO and MIRA analyses, RENAULT review

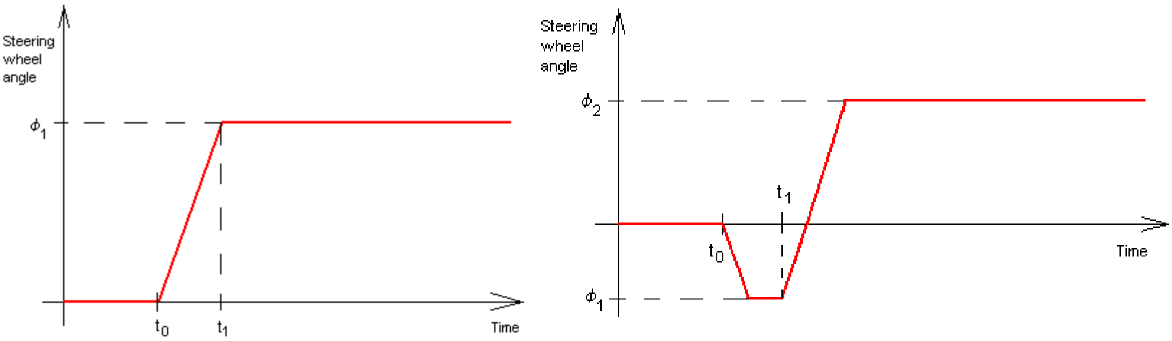
Scientific and technical description of the results

The following section describes in more detail the consensus and the conclusions from the final D52+3 Deliverable report.

UVMV Driving tests

Because of modern cars (including cars as MPVs with higher COG position) have no potential for rollover during steady-state cornering we need more dynamics:

- sudden change of direction of travel
- appropriate timed sequence of travel direction change



All tests were performed in 2 vehicles (Renault Scenic and Ford Fiesta) in 3 different variants, i.e. Ford Fiesta was use as a standard version and a version with modified suspension with COG in higher position.

full kinematics measurements was performed to analyse from all driving tests

- COG longitudinal and lateral accelerations
- yaw and roll angle/rate
- vehicle speed and sideslip angle
- steering wheel angle

Test matrix for vehicle A - Ford Fiesta – standard type (without suspension modifications)

Manoeuvre description	Nominal initial speed	Nominal steering wheel angle
	[km.h-1]	[deg]
J-turn	60,65,70,75,80,85,90	135
	60,65,70,75,80,85,90	180
J-turn with power-off	60,70,80	270
J-turn with pulse braking	60,70,80,90	135
Sequence of 3 consecutive steering wheel pulses	60,80,90	180
to the same direction	75	180
Fishhook, time delay (t1 – t0) approx. 0.3 s	70,75,80,85	135,18
Fishhook, time delay (t1 – t0) approx. 0.6 s	70,8	135,18

Test matrix for vehicle A - Ford Fiesta – version with modified suspension – tyre pressure influence

Manoeuvre description	Tyre pressure	Nominal initial speed	Nominal steering wheel angle
	[kPa]	[km.h-1]	[deg]
J-turn	180 (standard)	50,60,70	150

Fishhook		50,6	150
J-turn 50	140	50,6	150
Fishhook		50	150

Test matrix for vehicle A - Ford Fiesta – version with modified suspension – load conditions

Manoeuvre description	Total load	Nominal initial speed	Nominal steering wheel angle
		[km.h-1]	(φ1;φ2) [deg]
J-turn	unloaded (total vehicle mass 1403 kg)	50,60,70,80,90	180
	unloaded (total vehicle mass 1403 kg)	50,60,70,80,90	270
	loaded (total vehicle mass 1787 kg)	50,6	270
Fishhook	unloaded (total vehicle mass 1403 kg)	50,60,70,80	135; 270
	loaded (total vehicle mass 1787 kg)	50,55,60,70,80	135; 270

Review

- 2 different vehicles (4 modifications and loading states in total)
- near-rollover driving states and situation
- test procedures based on so-called J-turn and fishhook manoeuvres
- full vehicle kinematics measured during all tests
- basic dynamic characteristics measured for computer models validation purposes
- proposed “vehicle misuse” test consisting in driving on the track with lateral slope changing periodically (like long U-ramp) was not carried out due to unavailability of suitable test track. Delphi made this test as hardware-in-the-loop

Conclusion

The prime goal of these tests was to provide data for further analysis for rollover sensor system research and development. The tests itself do not provide any conclusions in this regard. But nevertheless, some conclusions regarding behaviour of the vehicle before rollover and basic mechanism of untripped rollover can be expressed on the base of the test results:

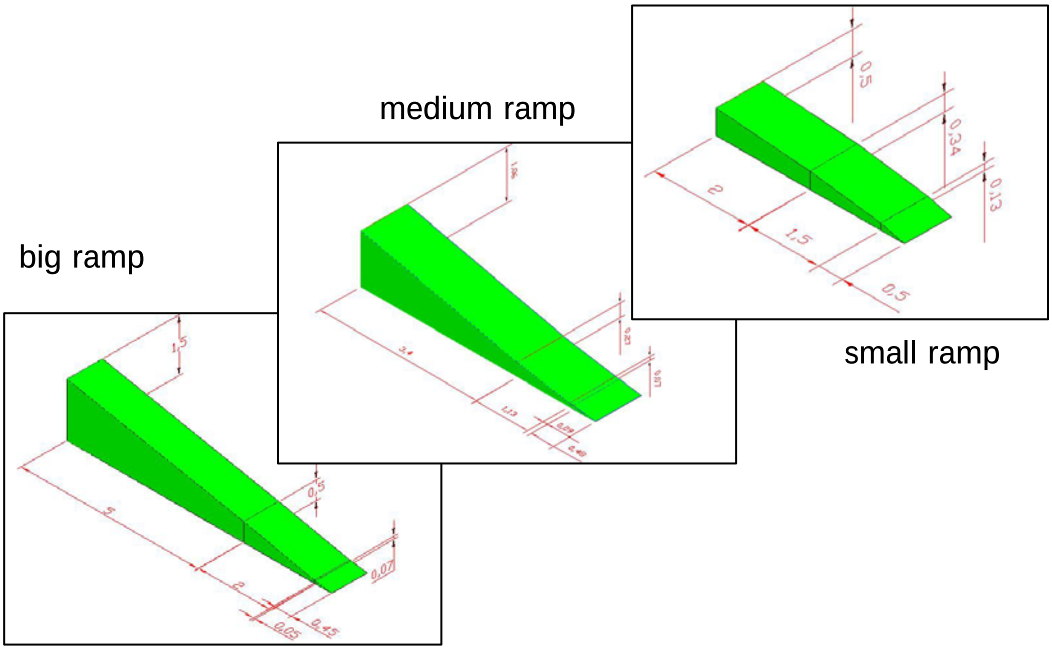
- Standard version of the Ford Fiesta did not tend to rollover even at relatively high initial speed. Increasing the initial speed did not mean a substantially more excessive vehicle response.
- The Fiesta with “crippled” suspension showed the one-wheel lift, higher roll angle and a little more sensitivity on roll motion dynamics (overshooting in the roll angle diagram) and initial speed, but was still sufficiently stable, without trend to rollover.
- Renault Scenic is much more sensitive on the initial speed as well as on the roll motion dynamics (significantly more excessive response at

fishhook when compared to J-turn). The Scenic was tested as fully loaded too; two-wheel lift was achieved in this loading state at fishhook with 80 km/h. Extreme load is applied on the outer front wheel at fishhook and led to damage of the wheel at the highest test speed.

- Lateral accelerations achieved at J-turn and fishhook are higher than maximum values achievable at steady state circular driving test. The maximum acceleration is practically invariable with changing speed and other conditions. This is a proof of “saturation” of the tyres (operating point is on the unstable part of the tyre sideslip-force characteristic.
- One-wheel lift can definitely not be considered as a criterion of rollover propensity. It is usual for some kinds of current passenger cars.
- Oscillatory motions in pitch and roll interconnected one to the other were observed on the Renault Scenic. This apparently put more energy to the oscillation and amplified the response of the vehicle. This phenomenon is probably connected i.a. with the position of the vehicle roll axis.
- Tests showed that rollover propensity of a vehicle is closely connected with the sensitivity of the vehicle roll response on the dynamic changes in lateral acceleration direction and on the initial speed. Both appropriate dependences should be degressive with a horizontal asymptote if the vehicle should not roll over at any initial speed.
- On the both cars tested, influence of longitud. dynamics (braking, pulse braking, poweroff) on the vehicle response in terms of rollover risk was negligible. Vehicle sideslip angle of about 20 deg or more is enough in itself for giving rise to max. roll response of the vehicle at the given test speed and further increase of the sideslip angle by additional actions causing trend to oversteer do not have a large effect.

IDIADA Ramp Induced Rollover Tests

IDIADA carried out a series of non-rollover tests for the development of rollover sensor system technology using the vehicles with 3 variants of ramps:



The test matrix consisted of selected combinations of 3 ramp sizes, 5 different initial velocities and 2 types of vehicle (Ford Fiesta, Renault Clio).

Velocity (km/h)	Small Ramp	Medium Ramp	Big Ramp
25	Ford Fiesta		
35	Renault Clio	Renault Clio	
50	Ford Fiesta	Renault Clio	
65	Renault Clio		
77			Ford Fiesta

The results from the screw rollover tests performed in Work Package 3.2 were also incorporated into the evaluation of the sensor systems in order to provide a greater range of test velocities and ramp sizes.

TNO Methodologies for Simulation of Near Rollover

TNO was responsible for the production of a sub report reviewing the methodologies for simulation of Near Rollover. The specific sections include:

- Introduction – Covering current status and general aim of these test methodologies as well as the importance of rollover tool chain and other approaches.
- Introduction to numerical simulation of near-rollover cases – Including a review of the Repetitive roll case scenario, Simulations tools, Rollover test simulation and Model Description.
- Rollover Sensitivity Study – Such as Rollover Mechanisms, Rollover and non-Rollover examples, Rollover assessment criteria, First sensitivity study and suggestions for extensions of the conceptual dynamic model.
- Rollover Acquaintance Test Procedure & Results - Including Rollover Test Procedures and Rollover Acquaintance Test Results.
- Vehicle Characterisation – To determine Initial Parameter Set, Characterisation of the Vehicle and Numerical Simulation of Near-Rollover.
- Rollover Test Procedure & Results – Presenting the Rollover Test Procedures and Rollover Test Results.
- Validation & Evaluation – Including the Initial Parameter Set and Characterisation of the Vehicle.
- Conclusions & Recommendations.

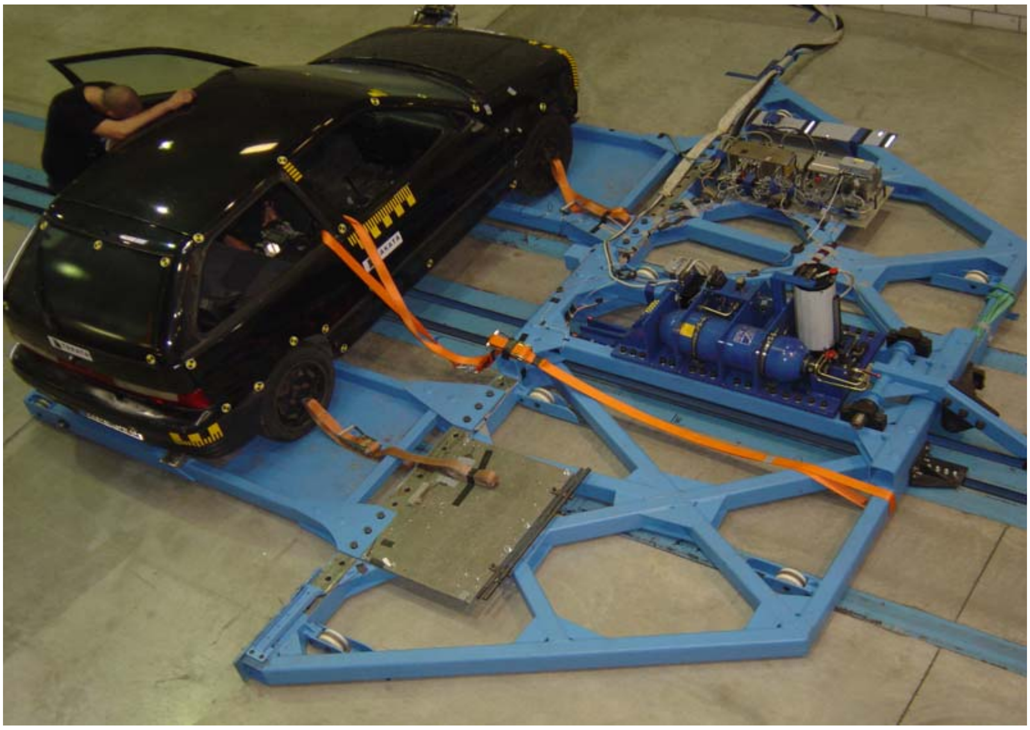
Review of Tests in Practice – Produced by Renault

This report details a series of testing regulations currently employed by vehicle manufacturers testing in the field of rollover and injury prevention in the case of rollover. The regulations explored within the paper include:

- ECE 21 – Occupant protection in interior impact – The purpose of this test is to check specific interior elements conform geometrically and their energy capacity is fully absorbed.
- ECE 44 Overturning – Child Restraint System - The objective of this test is to ensure the approval of a restraint seating device for the restraint of child occupants. The test is ensured following a procedure of rotating the seat around its horizontal axis.
- FMVSS 201 – This test was devised to test the occupant impact protection offered by particular vehicles and interior construction.
- FMVSS 208 – A testing regulation devised to evaluate the restraint systems of a vehicle with the use of anthropomorphic test dummies.
- The Corkscrew Rollover – The Corkscrew Rollover is a testing procedure used to test the structure of the vehicle in a rollover accident.

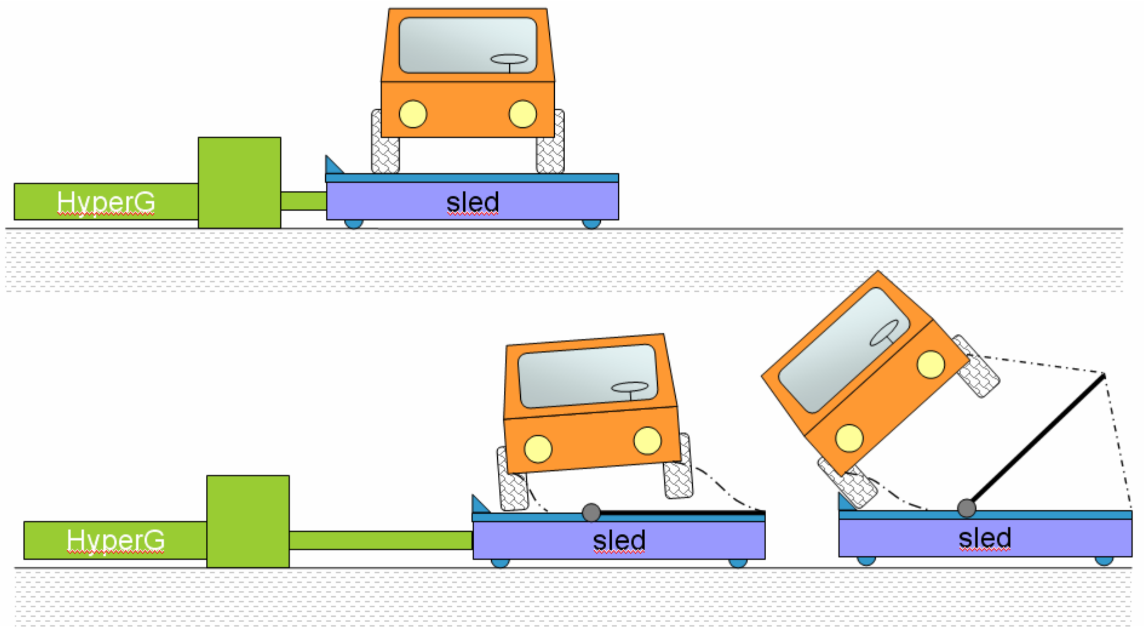
TUG LowG Sled Test Method

TUG developed a closed-loop controlled LowG system as an experimental test method for restraint and rollover testing systems, with specific concentration on the soil trip test. The methodology is proven with a full scale LowG sled test.



The specific sections explored are:

- Analysis of Real World Accidents - For experimental testing it is important that the test method represents real world conditions in a repeatable way. Because real world testing is not yet repeatable a test methodology has to represent the main factors of the real world accident. Looking at the kinematics of real world rollover accidents the two main groups can be described:
- High lateral movement of the vehicle with high friction (tripping) leading to the rollover (soil trip, curb trip). The longitudinal component of the velocity is small.
- Objects acting like a ramp for the car (screw rollover). In this case the rollover is induced by the geometry of an object. The main factor for this type of rollover is the roll rate – time dependency. The longitudinal velocity can be on different levels but there is only a minor change in the velocity and therefore a low longitudinal acceleration. The lateral movement is low.



Soil trip

The rollover scenario explored in this report is the “skidding & yawing – trip induced”. This scenario covers rollover accidents in which a vehicle is out of control and due to the increasing lateral forces on the tires starts to roll. The lateral forces increase due to the digging of the tires into soft soil, increased friction on a road surface and other effects. The characteristic of these rollover scenarios is that the roll rate increases moderately versus the roll angle.

Generating Reference Pulses

The low-g sled is able to represent a 2-d movement of a vehicle. There are two degrees of freedom to be analysed:

- Lateral linear acceleration
- Roll rate

The LowG sled is capable of controlling its deceleration by a specific braking pulse. Therefore the analyses for the generation of reference brake-pulses have to consider this limitation and focus on the lateral acceleration of the vehicle in a world reference system (sled system).

When we look at real world soil trip events, the vehicle tilts over the tyres in the tyre contact points during the first phase of rollover. The analysis focuses on the behaviour of the roll axis through the tire contact points.

Pre-simulation was completed before the physical tests were carried out.

Experimental tests TUG (in co-operation with IDIADA) performed 5 soil trip experimental tests with the LowG sled facility and studies the behaviour of the curb and different belts (standard belt w/o pretensioners, H-belt). – The test configurations were as follows:

- Validation test 1.4g (no. 207)
- Validation test 1.8g (no. 208)
- Validation test 1.8g (no. 209), with soil curb
- Validation test 1.8g (no. 210), with soil curb and first stage triggering
- Full test 1.8g (no. 211), with soil curb, standard trigger and H-belt

Conclusion

The LowG test methodology is an effective and repeatable way to test the sensor and restraint system for a first phase of rollover in a simplified 2-d scenario. Soil trip events as well as curb trip events can be tested. Some modification to enlarge the roll angle should be done to see more effects of the restraint system.

During low-g events the dummy only represents the behaviour of a human roughly because of the absence of muscle activity. To evaluate the difference a series with volunteers should be performed.

A critical cause of injury is the contact of the head with the roof or side structure during the intrusion. Even if the intrusion is minor the compression on the neck is critical. This means that the high intrusion velocity combined with the pre-contact of the head with the structure in this test is the cause of injuries and not the impact of the head with the structure.

Improvements with padding of the critical structure, better restraining of the occupants, limiting the lateral movement of the occupants by improved seat design and enlarging the head room will have positive effects on the reduction of compression injuries to the neck.

All the test data were transmitted to Delphi for further evaluation. Those data and data from rollover full scale reconstructions (T3.2) were analysed and used for verification of the „Rollover sensing module“ in terms of functionality and robustness under „misuse“ conditions.

Delphi

Delphi received 25 real Rollover test data and 17 generated Rollover data created with PC-Crash from project partners. These two generated pulses are “sine” shaped roll rate signals with different amplitudes. Based on calculations the “NO_GO” signal is created as non-trigger event. The “GO” signal has higher amplitude and is determined as trigger event.

For all of these scenarios (44 events) PC simulated triggering times have been acquired.

All of these signals were injected into the Rollover Detection Sensor Box and triggering times have been detected (bench test). The triggering times between PC-simulation and bench test showed a good correlation. Based on these results the Sensor System Performance can be evaluated as robust. These results are summarised in respective tables for comparison purposes below.

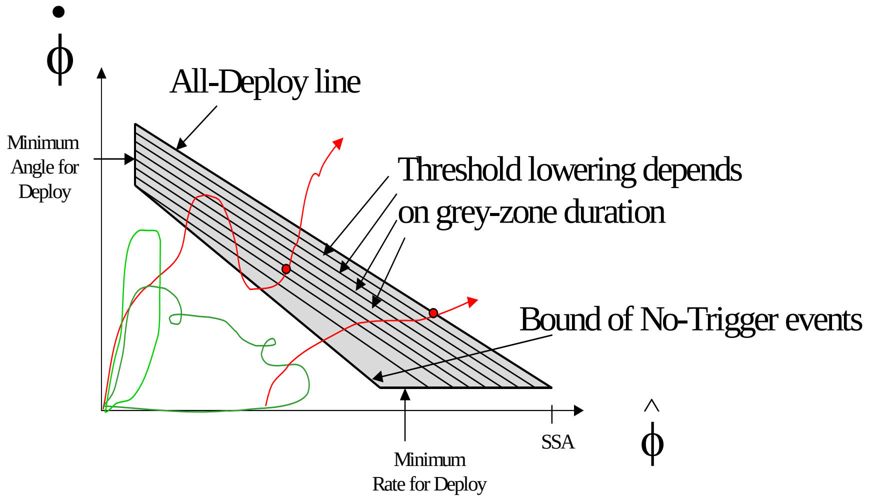
Delphi analysing philosophy was based on following items:

- Simulation Tools
- Simulation Environment
- Simulation Model
- Sensing Algorithm
- Simulation Results

The simulations were performed on higher and lower sensor specifications (MSH, MSL). Deployment times for MSH and MSL mean the latest and fastest deployment time that may be expected for each event.

Delphi‘s HW model was considered for signal- processing and filtering

Calculation cycles of 10ms were chosen to report detection times.



<u>Conclusion of calibration results</u>

- Simulation results show a good immunity against inadvertent detection on All Non-Rollover events

- Results were performed based on a Default Calibration, as no Triggering Requirements were present
- Analysis to be done by project partners, if Deployment Times are early enough to prevent occupant‘s injury
- Based on these results the Sensor System Performance can be evaluated as robust.

Mira – impact induced tests

- Vehicle was placed backwards on a sled
- Sled speed: 70 km/h
- Initial Roll Angle ~18.5°, Initial Pitch Angle ~13.7°

Results of this test were used by Delphi for further analysis

Comparison of initially planned activities and work actually accomplished

Most of experimental work planed for Task 5.3 was finished within the Y3 period. Near-rollover driving tests of two cars (Ford Fiesta and Renault Scenic) were carried out at UVMV. Test report was issued at May 12, 2005. IDIADA carried out a series of non-rollover tests for the development of rollover sensor system technology using the vehicles with ramp. The test matrix consisted of selected combinations of 3 ramp sizes, 5 different initial velocities and 2 types of vehicle (Ford Fiesta, Renault Clio).

TUG planned to develop the closed-loop controlled low-G sled system for rollover simulations. The system was fully functional and several tests were carried out using this system. All the test data were transmitted to Delphi for further evaluation. Those data and data from rollover full scale reconstructions (T3.2) were analysed and used for verification of the „Rollover sensing module“ in terms of functionality and robustness under „misuse“ conditions.

In Y3 and Y4 period IDIADA and TUG performed a series of soil trip tests with the LowG sled facility and study the behaviour of the curb and different belts (standard belt w/o pretensioner, H-belt). 5 Tests including finally one full rollover were planned with a Renault Clio. The plan was to finish these tests in the first part of Aug 2005. The expected term of reporting is the end of Aug 2005. UVMV supposed to collect all partner reports until the end of Aug 2005. Then the final report as a conclusion of the whole task T5.3 will be generated until the end of September 2006.

The LowG test methodology was evaluated as an effective and repeatable way to test the sensor and restraint system for a first phase of rollover in a simplified 2-d scenario. Soil trip events as well as curb trip events can be tested. Some modification to enlarge the roll angle should be done to see more effects of the restraint system.

Delphi planned to collect a group of signals from various testing methods. Finally Delphi finished analysing of 25 real Rollover test data and 17 generated Rollover data created with PC-Crash from project partners as well as 2 generated “sine” shaped pulses as roll rate signals with different amplitudes. Based on calculations the “NO_GO” signal was created as non-trigger event. The “GO” signal with higher amplitude was determined as trigger event. For all of these scenarios (44 events) PC simulated triggering times were acquired. All of these signals were injected into the Rollover Detection Sensor Box and triggering times were detected (bench test). The triggering times between PC-simulation and bench test showed a good correlation. Based on these results the Sensor System Performance was evaluated as robust. These results were summarised in respective tables for comparison purpose.

List of deliverable(s)

Partial reports of all partners:

- The main deliverable from this work package was Report D52+3 – Restraint and Sensor System Tests. The main deliverable was finally compiled by IDIADA in the only deliverable summary report combined from tasks T5.2 and T5.3
- “Review of tests in practice by vehicle manufacturers”, produced by Renault.
- “Rollover Test Methodologies”, produced by TRW.
- “Methodology for simulation of near rollover cases”, produced by TNO.
- “Low G Sled Testing Methodology”, was produced by TUG along with the results they obtained form this procedure.
- “Ramp Induced Rollover Test Results at 35kph No.1”, produced by IDIADA.
- “Ramp Induced Rollover Test Results at 35kph No.2”, produced by IDIADA.
- “Ramp Induced Rollover Test Results at 50kph”, Completed by IDIADA.
- “Ramp Induced Rollover Test Results at 65kph”, also produced by IDIADA after the tests had been completed.
- TNO Methodologies for Simulation of Near Rollover
- „Sensor System Tests“, produced by Delphi as a summary of sensor test analysing and the algorithm development

18. Task 5.4: Trim and interior fittings tests (Concept)

Scientific and technical description of the results

The aim of this task was to identify test methodologies of interior trim and fittings to provide enhanced rollover protection.

Therefore the available data from existing interior impact methods were analysed. Then different test configurations were developed and tested. And finally the test results were analysed and the test methodology was assessed.

Analyse of available data from existing interior impact test methods

IDIADA prepared a report on this topic, which give an overview of the current test methodologies for interior. These are:

- FMVSS 201u
- FMVSS 201p
- FMVSS 214 - Static
- FMVSS 214 – Dynamic
- FMVSS 216
- Test proposed by EEVC WG13:
    - Free Motion Headform test method
    - Pole Test
- Inflatable curtain test
- High speed pendulum test
- Featureless headform model

Because of the complexity of an interior impact it was the goal in this task group to find at first an existing test methodology which is most suitable for interior testing concerning rollover. Secondly and if possible, this method should be modified in a way that it takes into account the aspects that are relevant for rollover protection.

If no such method can be found a totally new method has to be developed.

The most important standard for interior testing is the FMVSS201-Occupant protection in interior impact. This test is also the most suitable concerning rollover. Discussions in the working group lead to the key statement that the FMVSS201 can be used for a basis to develop a test methodology for interior concerning rollover.

Definition of different test configurations

Two proposals for a test setup for concerning a rollover situation in interior impact were prepared concerning this topic. The first came from IDIADA and its key statements are:

- several testing areas with certain level of significance for head-impact are defined with “Rolland”-manikin
- injury criterion is the HIC(d) (Head-Impact criterion)
- Impactor is the 6,8kg headform of the ECE-R21
- Testing speed is 24,1km/h or 19,3km/h in areas with which cover an uninflated airbag

The second proposal was developed by CONCEPT:

- Test setup is based on the FMVSS201
- The WG17-pedestrian protection head impactor is used instead of the free motion headform from the FMVSS201
- Flight direction is defined by the target point and the Heads-COG of the 50% male
- injury criterion is the HIC(d) (Head-Impact criterion) and should not be above 1000

Calculation of the HIC(d)

An extract from the Legislation in FMVSS201:

The HIC(d) should not exceed 1000, when calculated according to the following formula:

HIC(d) = 0.75446 (Free Motion Headform HIC) + 166.4

The Free Motion Headform HIC is calculated with the following formula:

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} adt \right]^{2,5} \cdot (t_2 - t_1)$$

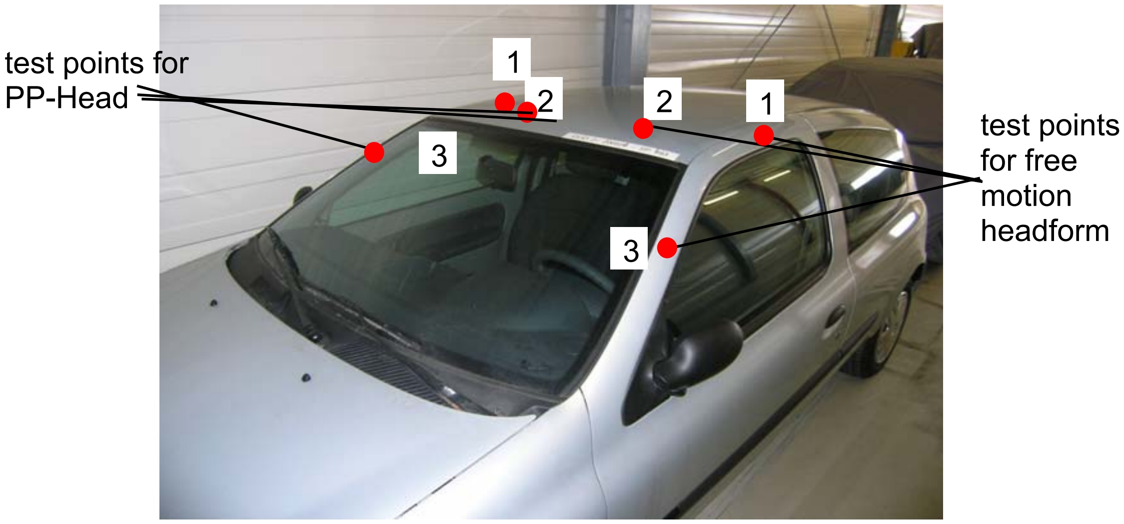
In doing so, $A_R = [A_x{}^2 + A_y{}^2 + A_z{}^2]^{\frac{1}{2}}$ describes the resulting acceleration in the centre, the CG, of the Free Motion Headform.

t_1 and t_2 are two undefined points in time during the impact, separated by no more than 36 ms.

Therefore a pre-test at CONCEPT was performed to evaluate the difference between using a pedestrian protection head and a free motion headform for interior testing.

Three representative testing points for each head on each side of the car were chosen. (Figure 9)

Figure 9: Test points for pedestrian protection head and free motion headform



The impact speed of the PP-Head was adjusted in a way, that the kinetic energy is equivalent the free motion headforms (Table 3).

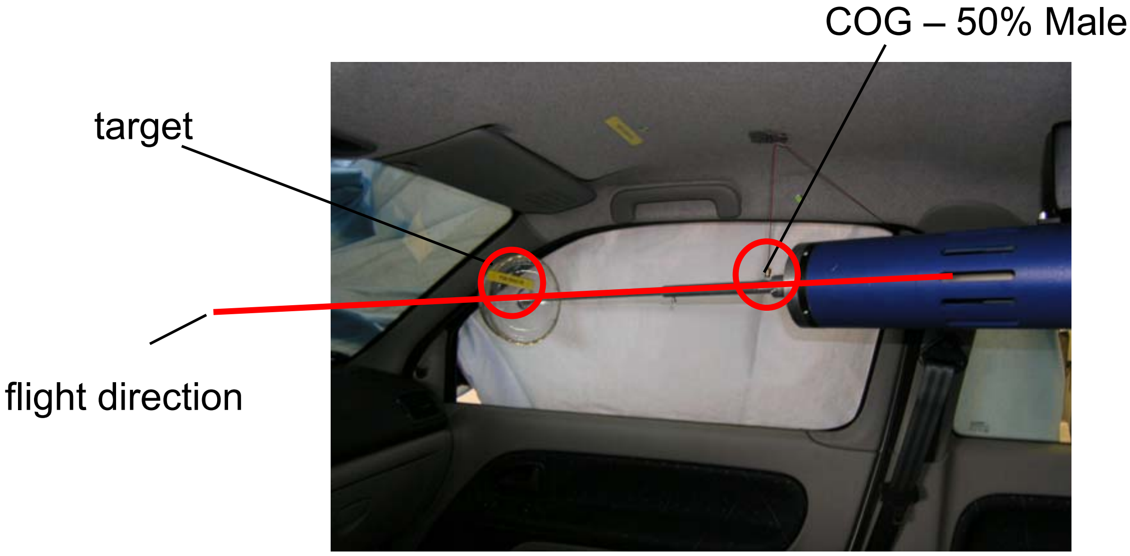
Table 3: Test parameters of pedestrian protection head and free motion headform

	PP-HEAD	FMH-HEAD
mass [kg]	4,8	4,45
initial velocity [km/h]	23.1	24.0
Energy [J]	197,6	197,6

The flight direction for the PP-head was defined by the line between the COG of the 50%-Male and the target. (Figure 10).

The flight direction for the free motion headform test points FMH-01 and FMH-02 were determined according the guidelines in FMVSS201. The flight direction for the FMH-03-point was set equivalent to the direction determined in PP-03

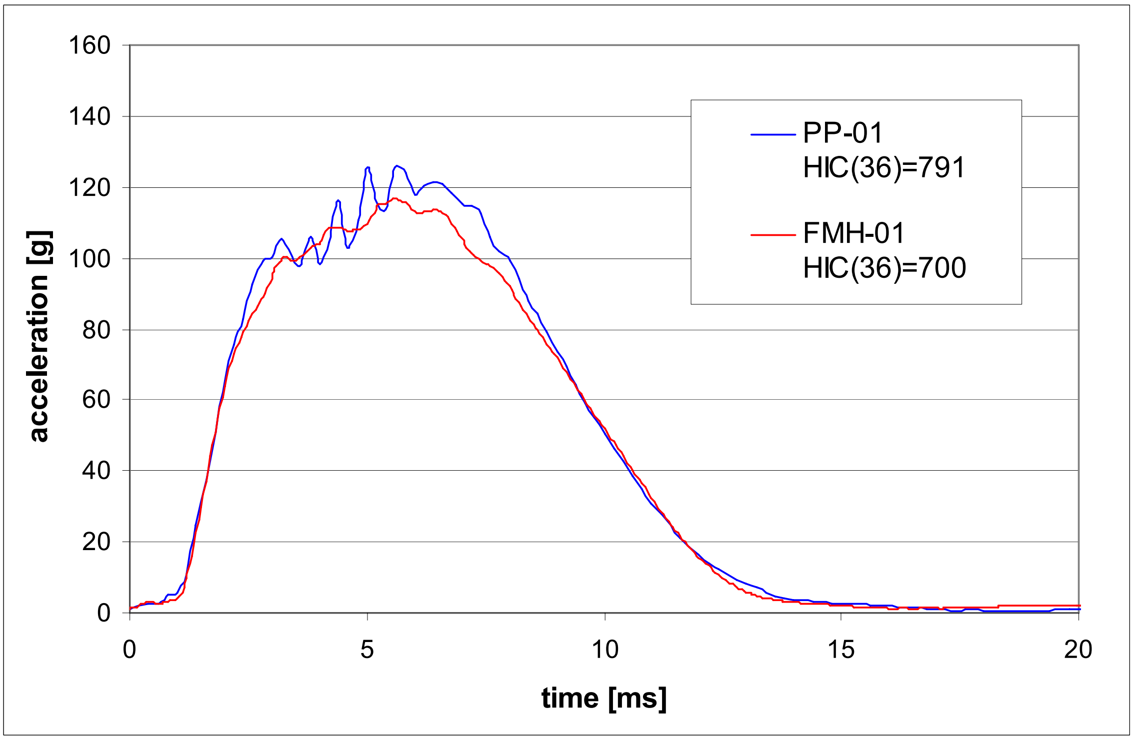
Figure 10: Determination of flight direction for the PP-head



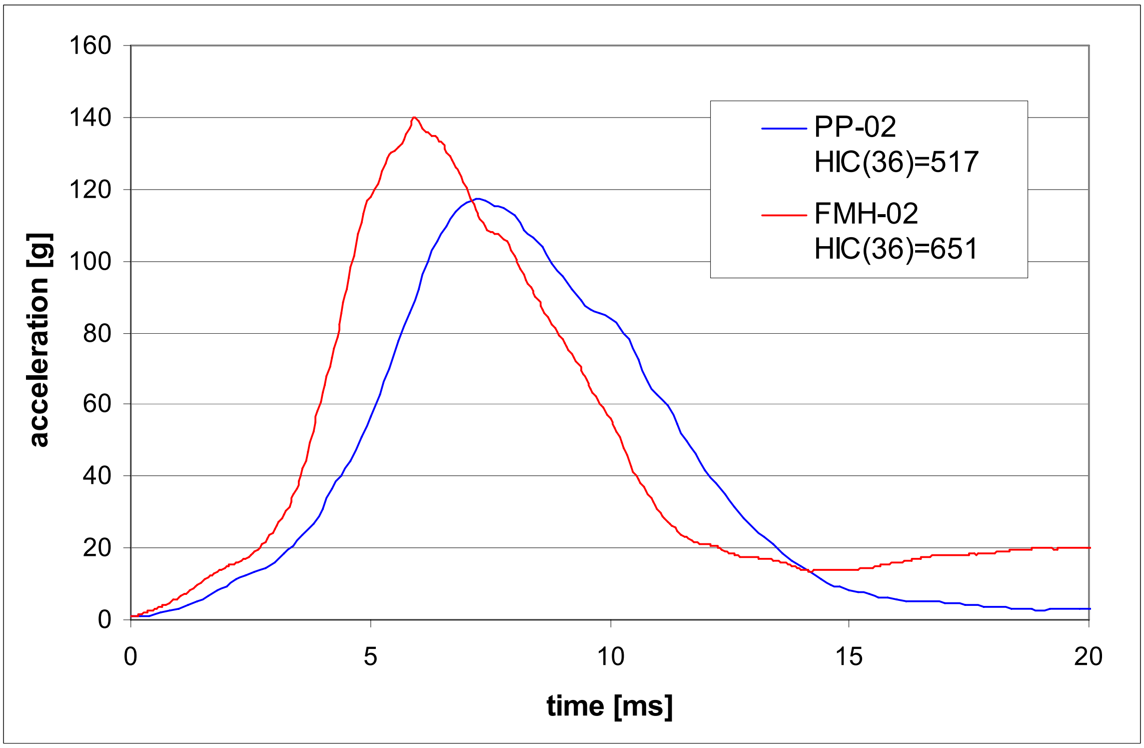
Results:

As results the acceleration-displacement curves and the HIC are given in the following graphs.

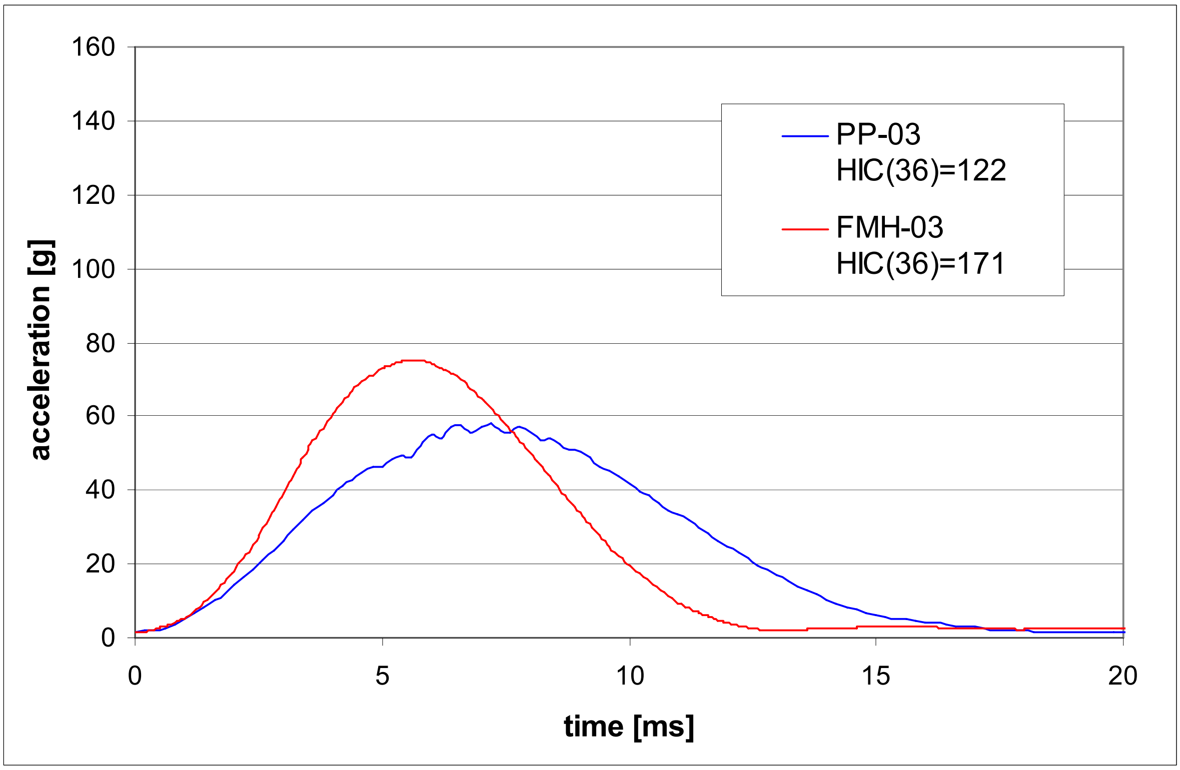
Graph 10: Comparison of acceleration curves of the PP-head and the FMH for test point 1



Graph 11: Comparison of acceleration curves of the PP-head and the FMH for test point 2



Graph 12: Comparison of acceleration curves of the PP-head and the FMH for test point 3



The pedestrian protection head shows similar results as the free motion headform, especially at higher levels of impact.

The definition of the flight direction using the COG is clearly defined. But in some cases it is not very practicable, because especially in smaller cars the needed space for targeting certain points in the car is not available.

Moreover a discussion in the whole project group brought the conclusion, that the interior of the car is mostly not hit from the direction of the COG. Instead of that during the roll phase the head is moving in the passenger compartment around and when the car hits the ground the head moves from its actual position directly towards the interior.

This fact leads to the conclusion that the flight direction for interior testing should be perpendicular to the tangential plane in the target point.

Final Proposal of test methodology for interior testing

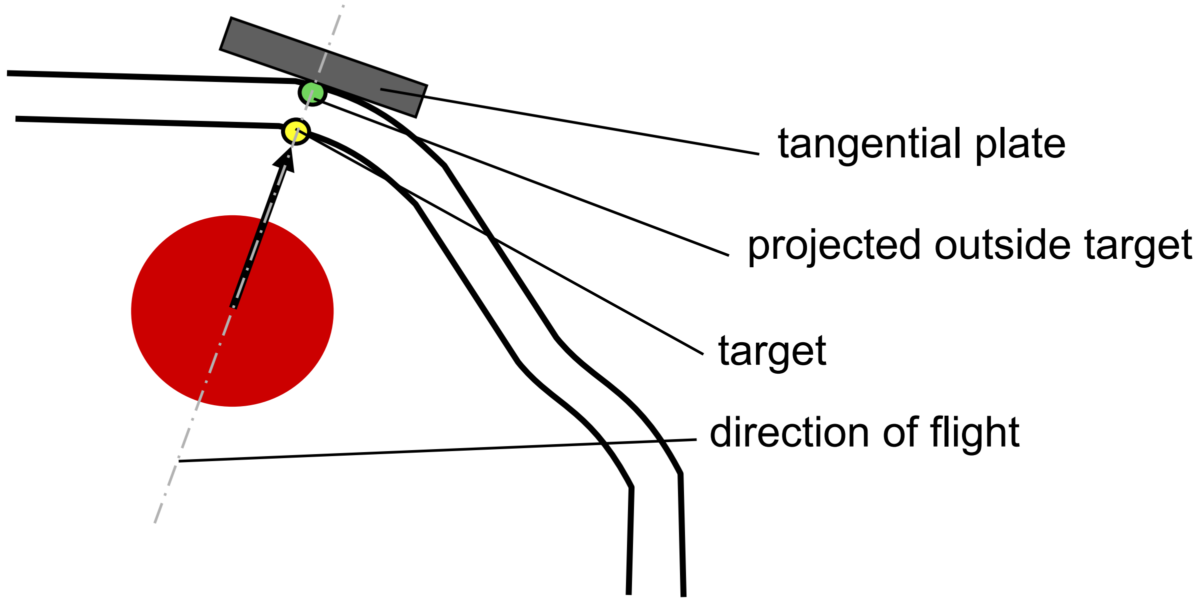
This final proposal is the outcome of thoroughly discussions in the whole project team about the two proposals from IDIADA and CONCEPT. The test methodology for interior testing concerning rollover is based on the FMVSS201 with several modifications.

Modifications of general test setup:

The targets on the inside are projected onto the outer surface of the vehicle in the direction of the flight.

The outside target is fixed with a tangential plate and the maximum deflection of the outside target must not be bigger than 3mm. This blocking of the outer structure should simulate a “car is lying on the roof”-scenario.

Figure 11: Draft of test configuration with fixing outer structure of vehicle



Modifications in use of impactor:

Instead of the free motion headform, which is used in the FMVSS201 the WG17 pedestrian protection head impactor, with a total weight of 4,8kg is used.

The non-spherical geometry of the free motion headform leads always to a certain amount of rotational energy which makes precise and reproducible test results very challenging. The use of the spherical pedestrian protection head would be a great advantage concerning this issue.

Modifications of flight direction:

As already mention above the flight direction shall be perpendicular to the tangential plane in the target point. There is no limit in vertical flight direction as in the FMVSS201; the preliminary tests showed that even a vertical flight angle of 90° is no problem for the impactor. Also concerns of a falling impactor damaging the firing device were not confirmed during these tests.

Modification of the impact speed

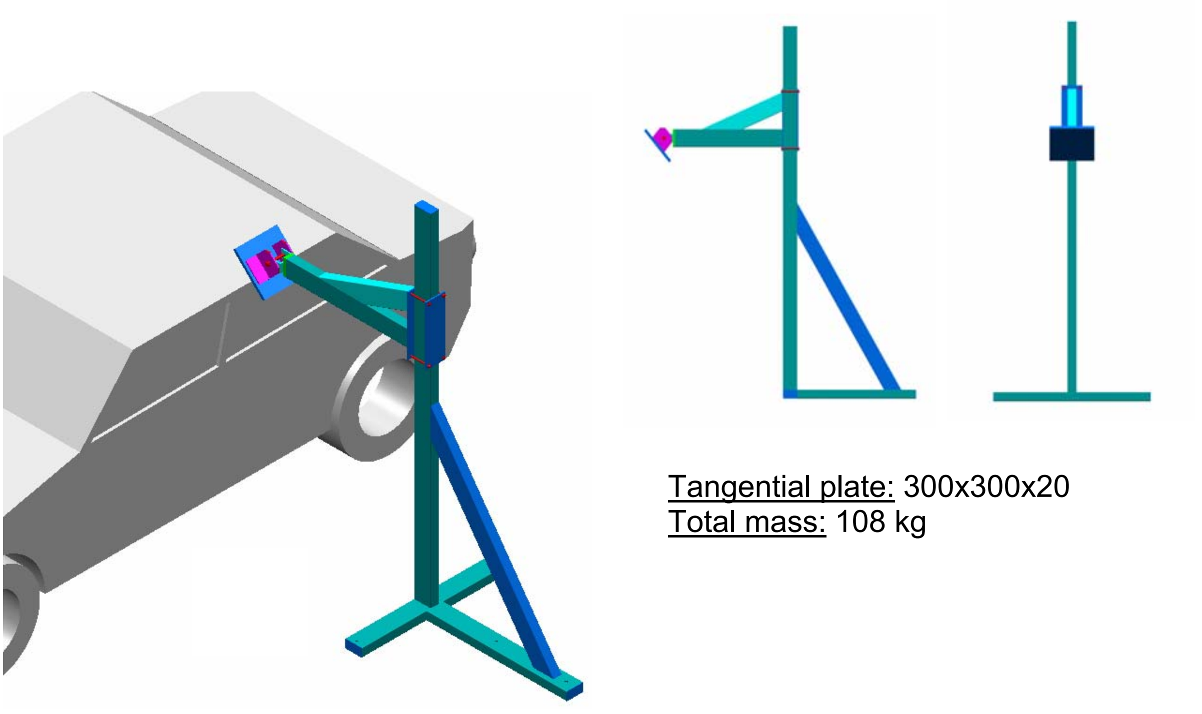
Due to the fixing of the outer surface the impact speed is reduced to 19km/h. This test speed is comparable to the reduced test speed of the FMVSS201u requirement for areas with stowed inflatable restraint systems.

Conducted test series

The test series were performed according the final proposal described in 0.

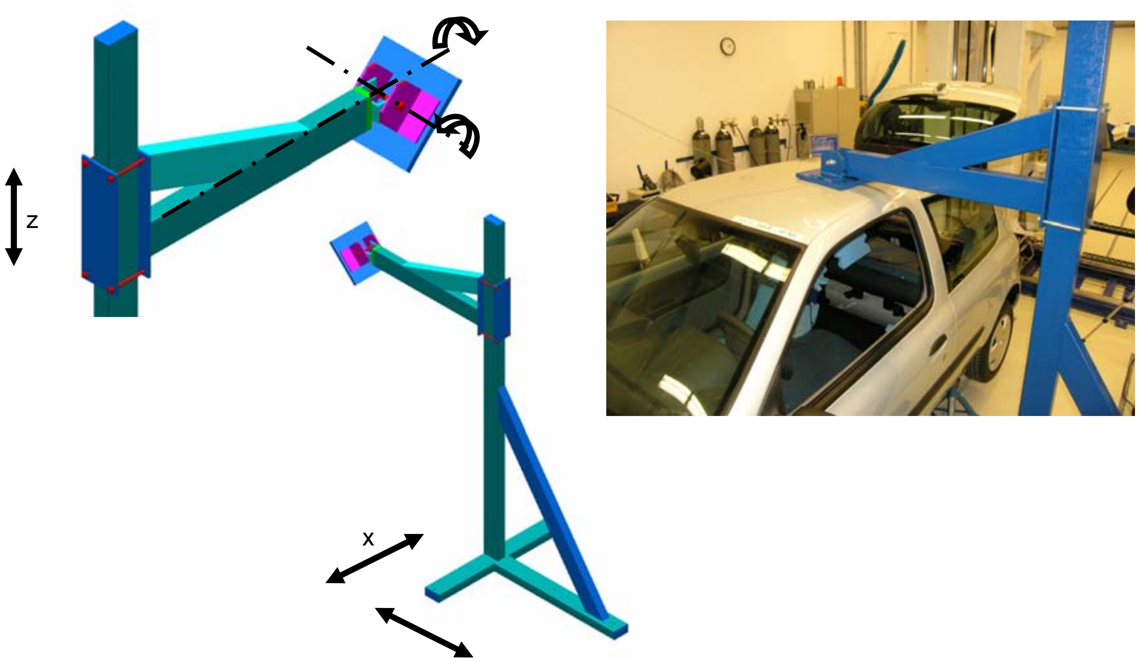
The tests were performed with a Renault Clio 1, 2 16V. For fixing of the outer surface of the vehicle a simple designed element of steel was used. (Figure 12, Figure 13)

Figure 12: Supporting device for fixing outer surface of vehicle



Tangential plate: 300x300x20
Total mass: 108 kg

Figure 13: Positioning of the tangential plate



10 points in the car were chosen for testing. (Figure 14, Table 4)

Figure 14: Testing points in vehicle

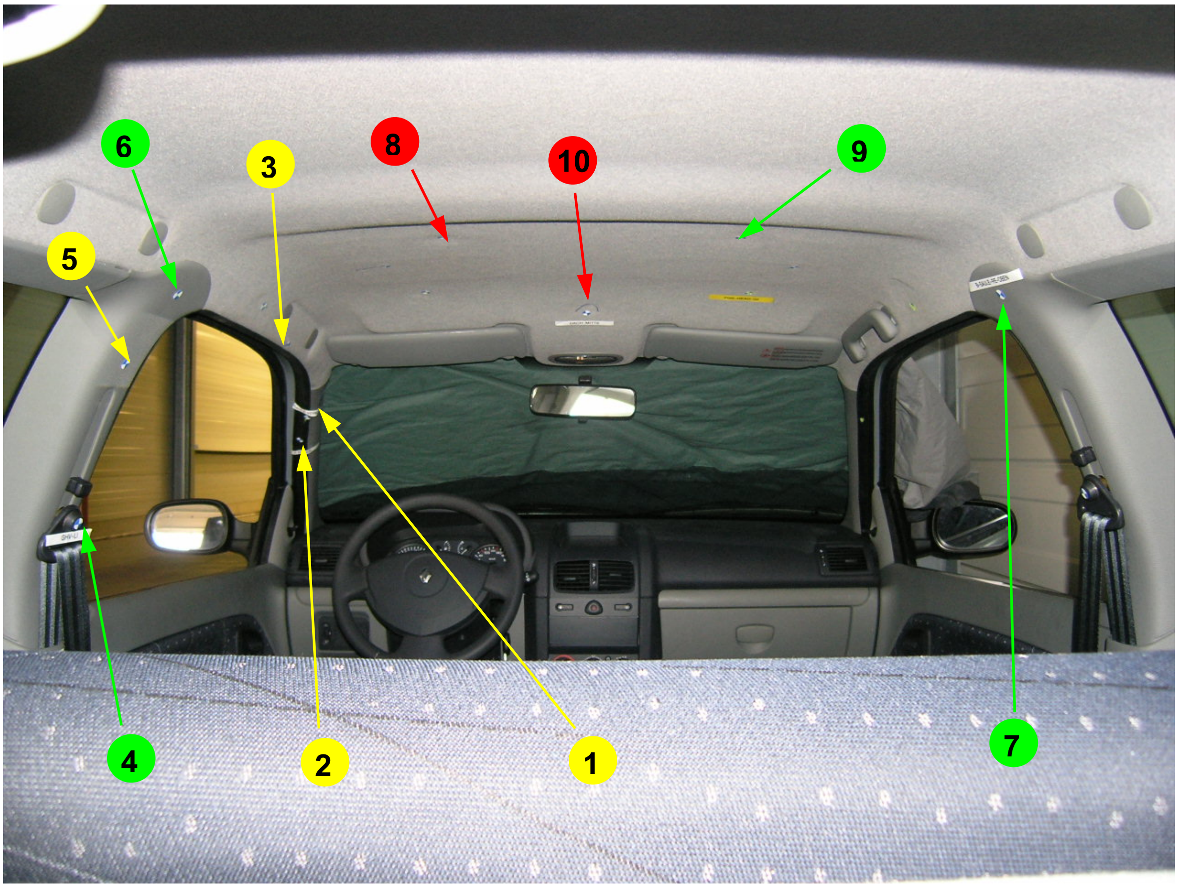


Table 4: Overview of testing points

Test point	Location	Supporting device	Test point	Location	Supporting device
1	A-Pillar trim	yes	6	B-Pillar-left-top	yes
2	A-Pillar weather strip	yes	7	B-Pillar-right-top	no
3	Side-Rail	yes	8	Roof-left-90	yes
4	Height adjuster strap left	yes	9	Roof-right-90	no
5	B-Pillar-left-middle	yes	10	Roof-middle	yes

Seven points (1, 2, 3, 4, 5, 6, and 8) where tested on the left side, one (10) in the middle and two points (7, 9) on the right side of the vehicle.

For the tests on the points 7 and 9 the supporting device was not used. These points on the right side of the car are mirrored from points 6 and 8 and should show the influence of the supporting device.

Results

An overview of the test results is given here. For detailed information please refer to the test report “Rollover Head Interior Tests with FGS Head and a support device” which is appended at the end of this report

Table 5: Overview of test results

Test Point		HIC(d)	Max. Acceleration [g]	supporting device	plate deflection
1	1 -A-Pillar Trim	816	154,7	yes	1,3
2	A-Pillar-weather strip	900	164,3	yes	2,5
3	Side Rail-1	901	149,9	yes	1,66
4	Height adjuster strap –Left	763	152,0	yes	2,4
5	B-Pillar-Left-middle	856	162,4	yes	2,8
6	B-Pillar-left-top	704	135,8	yes	0,6
7	B-Pillar-right-top	608	123,5	no	-
8	Roof-left-90	2049	370,7	yes	8,2
9	Roof-right-90	603	115,2	no	-
10	Roof-middle	1584	347,0	yes	8,1

In all regions with “thicker” structure the results are positive. At the two test-points 8 and 10 at the roof the HIC(d) is above 1000, which indicates very clearly the too thin deformation structure in these areas. In comparison the HIC(d) at the point 9, also on the roof but without the supporting structure gets a very good result with a HIC(d) of 603. This shows the significantly increase of injury risk in a “car is lying on the roof”-scenario, where the roof cannot deform.

The B-Pillar got mainly better results than the A-Pillar, but all these results are below the assessed HIC(d)-criterion of 1000.

The difference of the HIC(d) between the supported test point 6 on the top left side and the unsupported point 7 on the right side is only 100. This indicates as expected, that in these regions where enough space between the trim and the body shell is available the influence of the fixed outer surface is significantly lower than in thinner regions like the roof.

The supporting device fulfilled twice not the defined criteria of 3mm as maximum deflection on the outside target. In these two cases (test point 8 and 10 – the points on the roof) the acceleration and the HIC(d) was also significantly higher than in the other cases. This shows once again the high occurring forces in the thinner regions. The supporting device has to be designed stiffer to fulfil the requirement of the maximum deflection not to be bigger than 3mm. This would not change the results in a significant way. The HIC(d)-value would get even worse in those two points where less deformation is possible.

Assessment of test methodology

The performed tests showed that the chosen test methodology is applicable for the needs of interior testing concerning rollover.

- no problems with the use of pedestrian protection impactor instead of the free motion headform occurred
- the abolition of a vertical flight limit for test points on the roof lead not to problems concerning accuracy in impact speed and maybe damaging the firing device when the impactor is falling down
- the fixing of the outside target with the tangential plane can be easily performed
- the exceeding of the deflection limit in two points is no general problem, the supporting device used for the tests has just to be designed stiffer
- the definition of the flight direction perpendicular to the tangential plane in the target point was also easy to set up in practise
- the use of the impact speed of 19km/h is a good choice for reaching comparable HIC(d)-results as in the normal FMVSS201 below 1000 for regions where enough deformation space is available

Together with the whole project team the previously described test setup described was assessed for interior trim and fitting testing to provide enhanced rollover protection.

Proposal of assessment criteria and key parameters for correlation with simulation technique

The free motion headform impact in car interior according to the FMVSS201 can be done with adequate accuracy in simulation.

Moreover the modifications in the assessed test setup can be easily implemented in simulation.

Conclusions

The performed tests with this test setup showed, that the modifications of the test setup did not trouble the test handling in comparison to the FMVSS201 in any way.

Regions with thin deformation structure between the trim and the body shell at the roof get very bad results using this testing method.

Calculations with HIC(d)-design tools showed that in this load case and with a minimum package for absorber materials of 20-25mm HIC(d)-values below 1000 can be expected.

This would lead to a considerable, but feasible redesign in these thinner regions.

List of deliverable(s)

D5.4: Report on developed test method for interior impacts concerning rollover

19. Task 6.1: Performance criteria (MSF)

Scientific and technical description of the results

The following section describes in more detail the consensus and the conclusions from the final D6.1 Deliverable report.

Remark: Finally FORD wished to be disassociated with the results of task 6.1.

Consensus

Performance Criteria for Structural Design

The proposed test method for structural behaviour in Rollover can be summarised:

Test method

- Inverted drop test
- Pitch angle 10°
- Roll angle 170° (10°)
- Impact speed: 11.3 km/h corresponding to 0.5 drop height

Criteria:

- 200mm maximum static negative headroom for all seating positions
- Measurement Device for negative headroom: FMVSS201 lolly or "Rolland" measuring device
- During the test no door and tailgate may open.
- During the test no locking of the locking systems of the front doors may occur.
- After the impact, it must be possible to open at least one door per row of seats.without the use of tools. In cases where there is no such door it must be possible to move the seats or tilt their backrests as necessary to allow the evacuation of all the occupants; this is, however, only applicable to vehicles having a roof of rigid construction;
- No separation between the windscreen and the windshield opening frame greater than 10 %. This means that no more than 10% is allowed to come loose to assure the holding of the windscreen

Performance Criteria for Occupant

Summarising the input in Task 6.1b the following criteria are proposed:

- No specific test with current dummies is recommended
- Head impact test, HIC<1000, test setup according to Task 5.4

- Ejection: free motion headform test
- Additional general criteria:
    - Recommendation for belt routing to avoid slipping out of the belt
    - Triggering of belt pretensioning system is recommended, evaluation of such systems should be done by the “EEVC pretensioner group”
    - Triggering of inflatable head protection under certain circumstances

Performance Criteria for Sensor System

Rollover sensing systems should activate protection systems within sufficient time. Protection systems must pose minimal risk of injury to occupants due to their activation.

The sensing system should be able to detect different stages of the rollover for triggering the relevant protection system.

Related to the stage when protection systems have to be activated, several tests should be performed. Due to the complexity of rollover events, it is recommended to use at least 20 typical load cases for rollover/near rollover and approx. 20 misuse cases.

For a first tuning of the algorithms, rollover load cases and trigger times for airbag firing of the TNO stochastic study [19] for different scenarios are recommended.

For some scenarios, simplified methods were developed that can be tested with cost-effective sled-test methods.

In case of head-bag systems, it is additionally recommended to add an occupant sensing system to locate the exact position of the head. Due to the complexity of rollover events and the lack of anthropometrical test devices with active muscle features, the position of the occupant’s head cannot be accurately identified and predicted during the deployment stage.

To achieve affordable system development costs for rollover sensor systems it is recommended for future research topics to investigate CAE tools which allow the development of sensor systems on a virtual basis with a minimum number of physical testing.

Conclusions

According to the objectives of annex 1 of the Rollover contract (Task 6.1), performance criteria have been defined. These performance criteria include investigations on structural stiffness, interior design, restraint systems and triggering.

Criteria were divided into:

- Performance criteria for **structural design** – a requirement for the stiffness of the vehicle structure was defined, recommending minimum requirements on the integrity of the passenger compartment.

- Performance criteria for the **occupants** – focus is on the reduction of risk for complete and partial ejection as well as for limiting the impact severity of the head on interior components. Therefore ejection requirements and a modified head impact test were proposed.
- Performance criteria for the **sensor system** – Recommendations for triggering protective devices have been given. The triggering of these devices should be done in several stages, according to the type of the protective device and the potential of the triggering system.

Based upon these investigations, design instructions were derived in task 6.2. These design instructions will lead to additional features or protection devices for rollover protection. The benefit will be demonstrated in task 6.3 and 6.4.

A detailed cost/benefit analysis was done in task 6.5 revealing which of these systems is able to improve occupant safety during rollover within reasonable costs.

List of deliverable(s)

- D6.1: Report on summary of rollover performance criteria for structural stiffness, interior design, restraint systems and triggering.

References

[1] GRD2-2001-50086 Rollover, Annex 1 Description of work

[2] Eichberger (2005): WP6_planned_work_AE_20050201.ppt

[3] Barrios J.M. (2004): T51 IDIADA Inverted drop test development. Report for EC project rollover

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[24] NHTSA (2003) Initiatives to Address the Mitigation of Vehicle Rollover. NHTSA, June 2003

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[34] Duffy, Stephen: Test Procedures for Evaluating Ejection Mitigation Systems. http://www-nrd.nhtsa.dot.gov/pdf/nrd-01/SAE/SAE2002/SDuffy_SAE2K2.pdf

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20. Task 6.2: Design instructions (MSF)

Scientific and technical description of the results

The following section describes the conclusions of task 6.2, according to the final deliverable report.

Remark: Finally FORD wished to be disassociated with the results of task 6.2.

Conclusions

Design instructions coming out of this project are based on countermeasures against ejection, intrusion of the roof and occupant impact against interior parts, taken into account the timing of activation of protecting systems.

To show the benefit of these design instructions the virtual demonstrator (investigated in task 6.3/6.4) includes the following countermeasures:

Counter Measure	*Investigated by:*
Seat Belt reminder	Recommendation
Reversible electrical pretensioner that might be activated early in scenarios (first stage)	virtual demonstrator
Standard pretensioner	virtual demonstrator
Belt location including seat integrated belt	virtual demonstrator
Laminated glass in side window/sunroof	Recommendation/investigation Task 6.5
Closing of side windows	Recommendation
integrity of passenger compartment	Recommendation/virtual demonstrator
Roof Padding	recommendation
Curtain airbag, including 7 sec of minimum inflated time	Recommendation/TNO stochastic study
Seat design: side wings/inflated side wings	Virtual demonstrator
Occupant position monitoring	Recommendation
Innovations: roof airbag AUTOLIV rollover belt TAKATA rollover headbag Cross belt/H-belt	Not considered
Sensor system incl. multi stage triggering	recommendation

These countermeasures were also the basis for the cost-benefit analysis in task 6.5

List of deliverable(s)

D6.2: Report on summary of rollover design instructions for structural stiffness, interior design, restraint systems and triggering

References

[1] GRD2-2001-50086 Rollover, Annex 1 Description of work

[2] Eichberger (2005): WP6_planned_work_AE_20050201.ppt

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21. Task 6.3: Demonstration model and Task 6.4: Verification of improvements (Renault)

The two tasks were combined to its high interrelation.

The following chapters are excerpts from the latest reports compiled by the coordinator due to missing input from the task leader.

Scientific and technical description of the results

Introduction

According to the study accident research realized, it seems that to protect the occupants in rollovers, it is necessary to work on 2 main axes:

- Avoid the ejection (90 % earning of the fatalities)
- Protect the occupants towards the structure

The design instructions defined in task 6.2 [1] are proposed to reduce both the risk and severity of serious injuries in rollover crashes.

The demonstrator investigated in tasks 6.3/6.4 must show and verify the benefit of these design instructions.

Methodology

The design instructions defined in task 6.2 are based on countermeasures against ejection, intrusion of the roof and occupant impact against interior parts in rollover scenarios:

- Protection against ejection: Seat belt reminder, Belt location, Belt pretensioning, Glazing
- Protection towards the structure: Occupant compartment integrity, Curtain Airbag, Padding

The demonstrator, foreseen in task 6.3 to verify certain number of these recommendations, is decomposed into 2 parts:

- Virtual demonstrator:

  Based on Madymo Model with Human Body Occupants, several simulations are realized to validate:

  - the influence of the belt location on the occupant

  - the contribution of the pretension
  - the influence of the seat design

- Hardware demonstrator:

Several tests were realized to verify the other criteria:

  - The Rolland anthropometric validate the survival space
  - A static rollover test with and without pretension to validate the reduction of the movement of the occupant with pretensioner during the rollover
  - Ejection tests with and without laminated glasses to validate the no ejection of the occupant by side windows
  - Ejection tests with curtain Airbag to validate the not ejection of the occupants and the absorption of energy

Results

The demonstrator is divided in two parts: virtual demonstrator (simulations) and hardware demonstrator (physical tests) to validate the design instructions defined in task 6.2.

Virtual Demonstrator (TUG)

The analysis and results of the virtual demonstration can be found in the sub report “Virtual Demonstrator”.

The following improvements are analyzed:

- Buckle pretensioner
- Seat integrated belt
- Electro mechanical tensioning of the belt (eSpooler)
- Seat design (side wings)

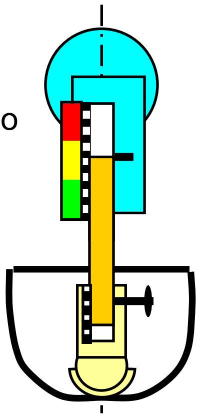
It can be concluded that looking to the occupant movement the most sufficient improvement is the seat design. This avoids belt excursion as well as keeps the occupant out of the curtain deployment zone. Positive effects on restraining the occupant in lateral and roll movement is observed for the other instruments. A combination of all improvements gives the best restraining of the occupant.

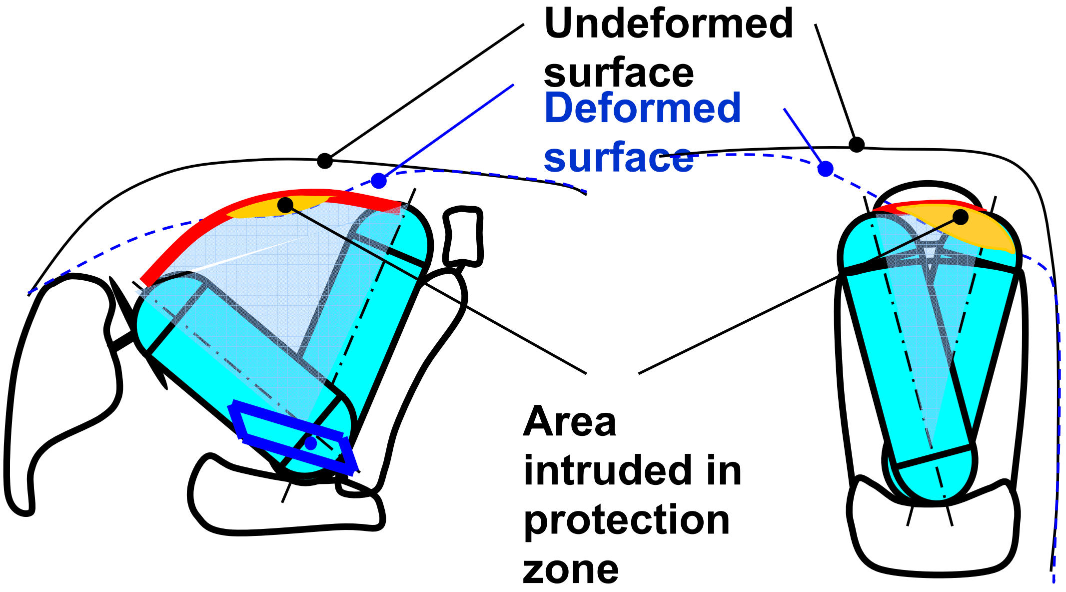
Effects of these systems to other accident scenarios have not been analyzed. It is assumed that the some improvements (wings) give positive influence in other scenarios (e.g. side impact). For the belt location it could be that in frontal crashes the load are negative influenced. In that case the belt location could be driven by intelligent systems to get an optimum location for different scenarios.

Hardware demonstrator

Rolland anthropometric (MSF)

The Rolland is a prototype built by MSF to measure and to validate the protection area and the negative headroom.



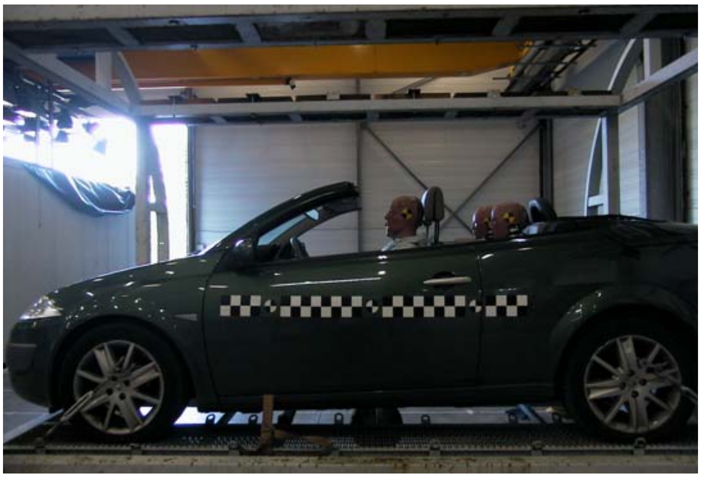


Influence of the pretension (Renault)

The pretension couples occupants to the vehicle and limits their movement in the passenger compartment.

To estimate the earning of a pretension in rollover, a rollover static test was realized on a cabriolet.

Test configuration:



2 HII 50 % Man in front places without belt gap

2 HIII 50 % Man in rear places without belt gap

Driver: triggering the Pyrotechnic Pretensioner of Buckle (PPB)

Front passenger: no triggering

Left Rear passenger: triggering the pyrotechnic belt retractor

Right Rear passenger: no triggering

The vehicle is fixed to the plate of a "squirrel cage". The pretension is activated by trigger box firing before the rollover. The rollover of half a tour of the vehicle is manually realized thanks to hand levers (quasi-static rollover).

Test results:

The analysis of the photos before and after the test allowed measuring the displacement of the occupants.

Occupant	Pretension	Occupant Displacement

Driver	PPB	26mm
Front Passenger	No pretension	75mm
Left Rear Passenger	Pyro belt Retractor	35mm
Right Rear Passenger	No pretension	70mm

Pretension	**Earning (mm)**	**Earning (%)**
Pyrotechnic Pretensioner of Buckle	49	65%
Pyrotechnic belt Retractor	35	50%

The different position of the high lateral anchorage/ occupant in front and rear place doesn't allow to compare the earnings with pretensioner / and pyrotechnic belt retractor.

In conclusion, the triggering of the pretension decreases considerably the occupant displacement in rollover and reduces the risks of head impacts.

The triggering of the pyrotechnic pretensioner of buckle allows an earning of 65 % of the occupant displacement. The triggering of the pyrotechnic belt retractor allows a 50 % earning.

Laminated glasses (Renault)

To avoid the total or partial ejection by the sunroof or the lateral windows it is necessary to use a laminated glazing.
The purpose of the tests below is to verify the not ejection of the occupant in the case of use of laminated glasses, as well as the injury criteria of the occupant.

Test configuration:

Ejection is considered by testing the side window with an impactor test.

The first tested configuration is the FMVSS201 configuration: mass of the head 4.5kgs and velocity 24.1km/h.

The second tested configuration is the most severe proposition proposed by the NHTSA which corresponds to the energy of a mass of the head 18kgs and a velocity 24.1km/h.

The proposed Criteria for this test are biomechanical limits for the head
The ejection Criteria is: The head must be restrained by the side window

Matrix of the tests:

test	Configuration	glass	Impact Position	Remarks
C8413-1	FMVSS201	standard	1	-
C8413-2	FMVSS201	laminated	1	-
C8413-3	FMVSS201	laminated	1	With retention bracket of the window in the frame of door
C8413-4	FMVSS201	laminated	2	With retention bracket
C8413-5	FMVSS201	laminated	3	With retention bracket
C8413-6	Ejection	laminated	3	With retention bracket and adhesive tape around the window
C8413-7	Ejection	laminated	3	With retention bracket and high pillar of door strengthened but without adhesive tape
C8413-8	Ejection	laminated	3	With retention bracket and adhesive tape around the window and high pillar of door strengthened
C8413-9	Ejection	standard	3	With retention bracket and adhesive tape around the window and high pillar of door strengthened

22. Task 6.5: Cost/Benefit analyses (LMU)

Scientific and technical description of the results

This section is the main part of the report and comprises different technical chapters covering the research approach and the work performed under the project and highlighting the main results achieved. Tables, figures or charts should be used where appropriate.

Material and Methods

For the Cost-Benefit Analysis at first it is necessary to know the amount of personal damage that occurs in the EU in one year due to accidents with an element of rollover. Then the preventable portion of fatalities and severely injured occupants due to specific countermeasures has to be calculated.

The preventable portion of personal damage displays the benefit that can be expected by the mentioned passive safety measures, if they had been implemented in the EU vehicle fleet. The benefit is expressed as costs in € for one year in the EU25.

Further the costs of the passive safety measures per car and the portion of cars that have to be improved has to be known to calculate the costs for the European vehicle fleet. As the implementation will take place only gradually the annual costs and the costs per expected life saved will be documented.

The costs per vehicle are taken as prices for the manufacturers, in the end the consumer and thus the public itself will have to defray the costs. The benefits will be gained by the society as well. Of course, the full effect and benefit will be gained only after implementation in all vehicles, which will take more than 10 years to complete. Besides some of the passive safety measures will show benefits in other than rollover situations, but this effect is not implied in the following calculations.

Results of the other tasks within the Rollover Project and results drawn from additional literature review or official data are taken as a basis for the following calculations, assumptions and estimations.

From the UNECE the data for population, number of accidents involving personal injury, road vehicle fleet and derived measures are taken (data of 2003). Assumptions and extrapolation for missing values are made to recieve numbers for the whole EU25. Especially the number of killed occupants due to accidents with a rollover element is essential for the consecutive calculations.

For the outcome distribution of occupants in rollover crashes the following probabilities presented in table 1 are needed. They are derived from databases used in the rollover project:

Table 1: rollover occupants' outcome distribution in percentages for different countries

	Stats19, 2003	GIDAS, Hannover 2000	France 2002	LAB	Spain, 2003	Catalan, 2003	***Estimation for Europe***
p(killed|rollover)	0.024	0.024	0.071	0.06	0.048	0.049	***0.035***
P(serious injured|rollover)	0.164	0.258	0.118	0.65	0.25	0.300	***0.20***
p(slightly injured|rollover)	0.812	0.668	0.811		0.700	0.652	***0.665***
P(uninjured|rollover)	/	0.05	/	0.21	/	/	***0.10***
	100%	100%	100%	100%	100%	100%	***100%***

With these assumed percentages following outcome distribution numbers for the EU can be calculated:

Table 2: rollover occupants' outcome distribution in numbers for EU25

n(killed and rollover)	**5305**	for Belgium and Italy, Slovenia, Malta, Latvia, Cyprus extrapolated figures
n(serious injured and rollover)	**30314**	for Belgium and Italy, Slovenia, Malta, Latvia, Cyprus extrapolated figures
n(slightly injured and rollover)	**100795**	for Belgium and Italy, Slovenia, Malta, Latvia, Cyprus extrapolated figures
n(uninjured and rollover)	**15157**	for Belgium and Italy, Slovenia, Malta, Latvia, Cyprus extrapolated figures
n(occupants in rollover)	**151571**	for Belgium and Italy, Slovenia, Malta, Latvia, Cyprus extrapolated figures

Note: based on 5305 rollover fatalities equal to 3.5% of all occupants in rollovers or 15% of all fatalities in vehicle accidents in Europe (see above)

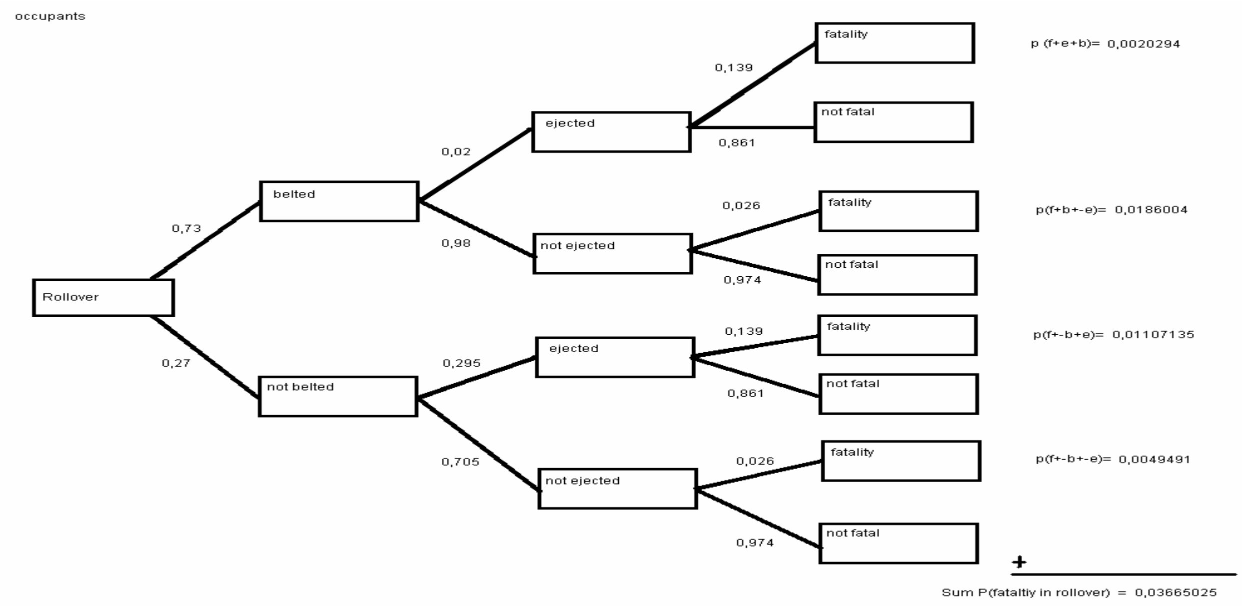
Based on data (ETSC, Rollover Project, European databases, Literature review), assumptions and estimations, the seat belt wearing rate for EU25 is set to 73%, the ejection rate in accidents with a rollover element to 8%. The probability to be killed in a rollover accident if ejected is derived at 13.9% and at 2.6% if not ejected. The probability to be severely injured in a rollover accident if ejected is derived at 27.7% and at 19.3% if not ejected. The ejection rate if the occupant is belted is 2% and 29.5% if not belted.

In the following table 3 the probabilities that reflect the current situation are listed. These values are to be influenced by countermeasures in terms of passive safety systems.

Table 3: probabilities used for benefit analysis

P(belted)	**0.73**	based on: seat belt wearing rate for all occupants
P(nonbelted)	**0.27**	based on: seat belt wearing rate for all occupants
P(ejected|belted)	**0.02**	C S Parenteau, M Shah: Driver Injuries in Single-Event Rollovers. SAE 2001-01-0633, March 2001 and GIDAS
P(notejected|belted)	**0.98**	C S Parenteau, M Shah: Driver Injuries in Single-Event Rollovers. SAE 2001-01-0633, March 2001 and GIDAS
P(ejected|notbelted)	**0.295**	C S Parenteau, M Shah: Driver Injuries in Single-Event Rollovers. SAE 2001-01-0633, March 2001, GIDAS
P(notejected|not belted)	**0.705**	C S Parenteau, M Shah: Driver Injuries in Single-Event Rollovers. SAE 2001-01-0633, March 2001, GIDAS
P(fatality|ejected)	**0.139**	fatality OR (E/-E)=6; FARS between 1975 and 1985, p(k)=0.035, p(ejected)=0.08
P(non-fatal|ejected)	**0.861**	fatality OR (E/-E)=6; FARS between 1975 and 1985, p(k)=0.035, p(ejected)=0.08
P(fatality|notejected)	**0.026**	fatality OR (E/-E)=6; FARS between 1975 and 1985, p(k)=0.035, p(ejected)=0.08
P(non-fatal|notejected)	**0.974**	fatality OR (E/-E)=6; FARS between 1975 and 1985, p(k)=0.035, p(ejected)=0.08
P(severeinjuries|ejected)	**0.277**	p(ejected)=0.08, P(ejected|severeinjuries)=0.111(GIDAS)
P(nosi|ejected)	**0.723**	p(ejected)=0.08, P(ejected|severeinjuries)=0.111(GIDAS)
P(severeinjuries|notejected)	**0.193**	p(ejected)=0.08, P(ejected|severeinjuries)=0.111(GIDAS)
P(nosi|notejected)	**0.807**	p(ejected)=0.08, P(ejected|severeinjuries)=0.111(GIDAS)
In general P(ejection in rollover)	**0.08**	assumption
In general P(killed in rollover)	**0.035**	assumption

Figure 1: Illustration of conditional probabilities



Control of the fatality rate of 3.5% assumed seems acceptable with these data illustrated above by calculation of fatality risk summing up at 3.7%:

Current costs due to personal damage in rollover accidents:

Fatality costs range between 600.000 and 1 million € just for economic costs and the comprehensive costs are about 1.4 to 3 million €. These numbers are calculated by different authors on the data bases of the USA and the UK. For comparison reasons the numbers from the UK are taken, that provide a classification of comprehensive costs for fatal, serious and slight injuries. Table 4 presents the costs due to personal damage calculated and assumed for the situation of EU25 in 2003.

Table 4: amount of costs due to personal damage for rollover crashes in Europe

		Casualty Severity	*Costs per Casualty (€)*	*sum*	*in Mio €*
n(killed and rollover)	5305	Fatal	1,774,163	9411934715	9411.9
n(serious injured and rollover)	30314	Serious	199,353	6043243800	6043.2
n(light injury and rollover)	100795	Slight	15,376	1549823920	1549.8
n(uninjured and rollover)	15157				
n (occupants in rollover)	151571			Sum:	17005.0

With the given data and all assumptions and estimations presented for the European Union yearly costs of 17 Billion € due to rollover casualties (personal damage in accidents with a rollover element) are calculated .

Measures and Effects

Measures suggested by the partners and their expected direct effects are presented in table 5.

Table 5: passive safety measures and their expected effect in rollover crashes

measures	*Direct effects*
seat belt reminder	increase in seatbelt wearing rate
roof crush resistance	reduction of roof intrusion and less head and neck injury
glazing of side windows	less ejection/partial ejection
padding of interior structures (roof, pillars)	injury severity reduction to head
seat design, side padding	increase in-position during impact and less ejection/partial ejection
seat design, active inflatable structures	increase in-position during impact and less ejection/partial ejection
head airbag developed for	less ejection/partial ejection, less severe head

rollover	impact
reversible pretentioner	increase in-position during impact less ejection and less head and neck injury

With the given data the probabilities that can be influenced are pictured in Table 6.

Table 6: Risks that can be influenced by passive safety systems in rollover situations

P(belted)	0,73	Increase by seat belt reminder
P(ejected|belted)	0,02	Decrease by glazing of windows, seat design, reversible pretentioner
P(ejected|notbelted)	0,295	Decrease by glazing of windows, seat design
P(fatality|notejected)	0,026	Decrease by Roof crush resistance, padding of interior structures, seat design, reversible pretentioner, head airbag
P(severe injuries|notejected)	0,193	Decrease by Roof crush resistance, padding of interior structures, seat design, pretentioner, head airbag

The following table 7 presents the estimated effects of the countermeasures; they are derived by calculations and estimations:

Table 7: Amount of suggested preventive potential for passive safety systems in rollover

Assumptions and estimations in bold letters	*NOW*	*seat belt reminder**	*glazing of side windows ***	*seat design, side padding*	*seat design active inflatable structures/ airbags*	*padding of interior structures (roof, pillars)*	*roof crush resistance ****	*head airbag*	*reversible pretentioner*	*reversible pretentioner + seatbelt reminder*	*reversible pretentioner + seatbelt reminder + seat design: side padding*
P(belted)	**0,73**	**0,8**	*0,73*	0,73	0,73	0,73	*0,73*	0,73	0,73	**0,8**	**0,8**
P(nonbelted)	**0,27**	**0,2**	*0,27*	0,27	0,27	0,27	*0,27*	0,27	0,27	**0,2**	**0,2**
P(ejected|belted)	**0,02**	0,02	*0,02*	**0,015**	**0,01**	0,02	*0,02*	**0,01**	**0,005**	**0,005**	**0,004**
P(notejected|belted)	**0,98**	0,98	*0,98*	**0,975**	**0,99**	0,98	*0,98*	**0,99**	**0,995**	**0,995**	**0,996**
P(ejected|notbelted)	**0,295**	0,295	*0,295*	**0,250**	**0,200**	0,295	*0,295*	**0,22**	0,295	0,295	**0,250**
P(notejected|not belted)	**0,705**	0,705	*0,705*	**0,750**	**0,800**	0,705	*0,705*	**0,78**	0,705	0,705	**0,750**
P(fatality|ejected)	**0,139**	0,139	*0,139*	0,139	0,139	0,139	*0,139*	0,139	0,139	0,139	0,139
P(fatality|notejected)	**0,026**	0,026	*0,026*	**0,020**	**0,020**	**0,020**	***0,020***	**0,020**	**0,022**	**0,022**	**0,017**
P(severeinjuries|ejected)	**0,277**	0,277	*0,277*	0,277	0,277	0,277	*0,277*	0,277	0,277	0,277	0,277
P(severeinjuries|notejected)	**0,193**	0,193	*0,193*	**0,148**	**0,148**	**0,148**	***0,020***	**0,148**	**0,163**	**0,163**	**0,126**
p(ejected)°	***0,08***		***0,06***								
p(notejected)°	***0,92***		***0,94***								

* based on Williams 2002

** based on Summers 1995 and CCIS data

*** The assumptions for the roof crush resistance effect are based on the comparison with the estimated effect for the padding of interior structures. This is to be seen critical, as the further calculations imply the estimation derived from NHTSA (NHTSA, 2005) that about 32% of cars at all need an improved roof structure. NHTSA calculations lead to an overall Relative Risk (RR) for fatality of 99.5% and a RR for Severe Injury of 97.9%; out of 9942 fatalities only 44 could have been prevented by an improved roof structure in their study. In the following the results of both ways of calculations are presented.
° used only for the calculations done by Summers, 1995, documented for comparison reasons

Costs

Costs for measures are calculated per car. The seating positions equipped with safety systems include driver and front seat passenger. Roof improvement is calculated for the whole car, the costs for the glazing of side windows refers to all, on average four, side windows.

The percentage of cars already equipped with the suggested countermeasures lies at around 10% for the seat belt reminder. Only around 32% of the current fleet would need a stiffened roof structure (according to NHTSA 2005). All other measures' percentages lie far beneath 0.1% or, like in the case of the head-airbag, are designed for other collision situations.

The number of new licensed vehicles per year in Europe is calculated on the basis of UNECE data to be around 7.2%.

The costs for the single measures per car was discussed by the rollover partners.

The cost characteristics are presented in table 8:

Table 8: Cost figures for passive safety systems and their implementation to the European vehicle fleet

	cost per car	*Rollover sensor + occupant classification system per car*	*rate of already equipped cars*	*no of cars that have to be improved*	***Costs in Mio €***	*yearly costs in Mio € (7,3% new licenced cars in EU25)*
1. seat belt reminder:	15 €		0,1	182470772	2737	198 €
2. roof crush resistance:	12 €		0.68	70960856	**852**	61.56 €
3. glazing of side windows:	125 €		0	202745302	**25343**	1,832.06 €
4. padding of interior structures	30 €		0	202745302	**6082**	439.69 €
5.a seat design: side padding:	20 €		0	202745302	**4055**	293.13 €

	cost per car	*Rollover sensor + occupant classification system per car*	*rate of already equipped cars*	*no of cars that have to be improved*	***Costs in Mio €***	*yearly costs in Mio € (7,3% new licenced cars in EU25)*
5.b seat design: Active inflatable seat	50 €	20 €	0	202745302	**14192**	1,026 €
6. reversible pretentioner	20 €	40 €	0	202745302	**12165**	879 €
7. head airbag developed for rollover	60 €	20 €	0*	202745302	**16220**	1,173 €

* the up till now used head airbags do not keep inflated long enough for the rollover situation

Benefits

The probability changes due to the passive safety systems (Table 7) and the calculation presented beneath Figure 1 is used for the assessment of the reduced fatality risk and reduced risk of severe injury, respectively. The benefit expressed in € is calculated with the new numbers for the casualties as presented in table 7. The costs in terms of personal damage before and after implementation (hypothetically) to the European vehicle fleet are subtracted and presented as benefit. Table 9 presents the benefits in numbers and percentage of fatalities that could have been prevented in 2003 if the specific passive safety system had been implemented in all cars. Further, the number of occupants that could have been prevented from severe injury is presented and finally the comprehensive cost difference before and after implementation in € as benefit is shown.

Table 9: Benefit characteristics of specific passive safety measures in rollover crashes

	Number of lives saved	Percentage of lives saved	number of severely injured occupants prevented	effective reduction of severely injured occupants *	percentage of effective severely injured occupants prevented	**Yearly benefit in Mio €**
1. seat belt reminder:	315	5.9%	244	-71	-0,2%	**571.7**
2. roof crush resistance:	*251*	*4.9%*	*1948*	*1697*	*6%*	***764.7***
effect of NHTSA assumptions:	*23*	*0.4%*	*634*	*611*	*2%*	***169.2***
3. glazing of side windows:	394	7.4%	294	-100	-0,3%	**690.2**

4. padding of interior structures	787	14.8%	6087	5300	17%	**2389.6**
5.a seat design: side padding:	1080	20.4%	6557	5477	18%	**2937.9**
5.b seat design: Active inflatable seat	1354	25.5%	6726	5372	18%	**3400.9**
6. reversible pretentioner	710	13.4%	4246	3536	12%	**1930.0**
7. head airbag developed for rollover	1261	23.8%	6621	5360	18%	**3235.2**
seat belt reminder plus reversible pretentioner	1054	19.9%	4594	3540	12%	**2535.4**
seat belt reminder plus reversible pretentioner + side padding of seat	1919	36.2%	10150	8231	27%	**4920.3**

* prevented fatalities are classified as severely injured, thus the effective number of reduced severities is the difference of the prevented severities and the prevented fatalities; a negative reduction represents an increase

Cost Benefit Analysis

It can be seen that the costs out-perform the benefits in a range between 1.4 to 6.3, with the glazing of the side windows that even reaches a factor of 37 being an outlier. Table 10 presents the difference between the costs for the whole European fleet that needs to be improved and the benefits per year that can be expected by the implementation into all cars. Further, these values are used to show the ratio between costs and benefits. In addition the calculated lives saved and the costs per prevented fatality are documented.

Table 10: Cost-benefit Measures for Passive Safety Systems in Rollover crashes

	cost - benefit in Mio €	***Cost benefit ratio***	*lives saved per year*	*costs per life saved in Mio €*
1. seat belt reminder:	**2165**	**4.9**	315	6.8
2. roof crush resistance	**87**	**1.1**	251	0.3
effect of NHTSA assumptions	**682**	**5.0**	23	29,7
3. glazing of side windows:	**24653**	**36.7**	394	62.6
4. padding of interior structures	**3693**	**2.5**	787	4.7
5.a seat design: side padding:	**1117**	**1.4**	1080	1.0
5.b seat design: Active inflatable seat	**10791**	**4.2**	1354	8.0

6. reversible pretentioner	**10235**	**6.3**	710	14.4
7. head airbag developed for rollover	**12984**	**5.0**	1261	10.3
seat belt reminder plus reversible pretentioner	**11272**	**5.4**	1054	10.7
seat belt reminder plus reversible pretentioner + side padding of seat	**12942**	**3.6**	1919	6.7

The most favourable passive safety systems from this cost/benefit point of view seem to be an improved seat design, seat belt reminder, and padding of interior structures. A combination of measures seems to increase the benefits more than the costs will rise.

Discussion

The most critically identified points in this study are the assumptions and estimations the calculations are based on. More research is necessary to be able to estimate the actual prevention potential of the countermeasures properly, as well as the frequency and characteristics of the crash circumstances in which these systems would be of an advantage. A conservative view was used to be cautious and not to raise hopes that the benefits might not be so high. For example there is another cost-benefit analysis from ETSC 2003 (Mackay et al. 2003), assuming a seat-belt wearing rate rise from 76% to 97% if all cars had audible seat belt reminders. With their implying a discount rate of 5%, a percentage of 10% for new licensed cars and taking into account the actual costs for the consumers by implementing seat-belt reminders only for the two front seats, they end up with a positive benefit compared to the costs. With these assumptions they calculate a cost benefit ratio of 1:6, not specified for rollover but for all collision situations. This reflects that the calculations performed here are at the lower limit in benefit expectation and of course limited to rollover situations only. Further, a yearly rise in benefit is not performed here as there is not enough information provided how the implementation of ESP or the percentage of minivans or SUVs will develop in future years. These figures seem to be relevant factors in the occurrence of rollover crashes in the first place. Secondly, the reason for remaining on the conservative side for the assumptions is the knowledge that a certain amount of injuries and fatalities in rollover crashes do not occur due to the pure rollover movement but due to preceding or following impacts.

Recommendations

In contrast to Henderson and Payne (1998) and Rechnitzer and Lane (1994) the side window integrity does not seem to be of primary interest by the findings of the cost-benefit analysis. But the importance of an ejection reduction is seen here as well. Further agreement can be reached for compartment integrity and roof crush resistance even if the findings here are not satisfactory. Further padding of interior structures seems to be an easy task (as no sensor system is necessary) to reduce injuries. Further accordance of this study lies in the improvement of the seat design, either static or by inflatable structures to prevent and reduce the occupant excursion. A combination of measures seems to provide higher benefit than cost increases which is favourable.

Outlook

Further passive safety research in rollover should focus on prevention of occupant excursion during the roll phase, which can be improved by seat belt reminders and reversible pretensioners, seat design and head airbag developed for rollover. The latter might also keep the occupant from being ejected independently of the occupants' belting status. Furthermore for the not ejected occupants the injury severity would be reduced by trying to soften the impacts within the vehicle's interior by padding, airbags and structural improvements. There are further suggestions like a better belt geometry (Lamy, 2005) and a so-called roofbag (Heudorfer, 2005) which were not evaluated in this study.

For the public health impact in terms of costs and benefits due to personal damage surely better data are necessary as well as a uniform way of collecting collision related data in Europe.

Only by help of a reliable monitoring system quality information can be provided by evaluation of interventions like the implication of passive safety measures or rollover crash tests.

Comparison of initially planned activities and work actually accomplished

Especially the estimations presented in Table 7 should have been based on more precise data. These were not able to be delivered by the partners. These epidemiological "risk reduction potential"-figures are not available neither from literature nor from simulations.

List of deliverable(s)

D6.5 Report on Cost/Benefit analysis

References from the Report : see below

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