DEVELOPMENT OF A GENERIC ASSESSMENT METHODOLOGY FOR ADVANCED SAFETY SYSTEMS

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Paper Number 09-0286

ABSTRACT

Advanced safety systems which use pre-crash sensing information from the environment and/or the vehicle occupants have an "active response" which improve primary or secondary safety. Many systems are in development which use pre-crash sensing information as a decision input and it is widely predicted that the implementation of such safety systems, together with appropriate actuators and control algorithms, offer significant safety potential.

Existing test methods evaluate the crash performance of a vehicle, but are unsuitable for the assessment of advanced safety systems because additional evaluations of the sensing performance and the effect of autonomous actions on the driver response are required. To meet this need, work package 1.3 of the European Advanced Protection Systems (APROSYS) project developed a generic methodology which was intended to define guidelines for development of a specific test programme. This paper presents the final generic methodology for advanced safety systems and details a 'test case' carried out to demonstrate the application of the methodology.

INTRODUCTION

The European 6th Framework Programme Integrated Project (IP) on Advanced Protection Systems (APROSYS) was focused on developments in the field of vehicle safety. Within work package 1.3 (WP 1.3) "Advanced safety functions", the objective was to develop an evaluation method for the assessment of advanced safety systems that employ pre-crash information from environmental sensor systems. As defined in APROSYS deliverable D1.3.1 [1], these systems were considered to be *primary or secondary safety systems that adapt to different scenarios to reduce accident severity and/or injury risk.* These systems use sensed occupant data and/or pre-crash information obtained from environmental sensors and vehicle data.

This definition covers a broad range of advanced systems, ranging from occupant classification systems for intelligent airbag and restraint deployment, to pre-crash braking or other collision mitigation and avoidance systems.

The methodology developed was intended to be generic in terms of the systems to which it could be applied and also in terms of the application of the assessment. For example, the methodology could be used by OEMs in development, regulators as the basis for type approval compliance, or consumer information organisations to provide information on advanced system performance.

Current Regulatory Compliance

For a vehicle to gain type approval, it must satisfy the requirements of EC Directive 92/53/EEC. Article 8(2) of Directive 92/53/EEC (amending Directive 70/156/EEC), prescribes that if the vehicle is equipped with technologies or concepts incompatible with current directives, the Member State should provide a report containing:

- The reason why the technologies prevent the vehicle or component from complying with the requirements of the relevant(s) Directive(s);
- A description of the areas of safety and environmental protection concerned and the measures taken;
- A description of the tests and their results that demonstrate at least an equivalent level of safety and environmental protection as is provided by the requirements of one or more of the relevant separate Directives;
- Proposals for amendments to the relevant separate Directives or new separate Directive(s) as applicable.

In the case of systems involving pre-crash sensing, a modification of the vehicle behaviour or safety system to improve the level of protection offered is made. Thus, in order to gain regulatory compliance, proof that the sensor and actuator system function as intended is necessary. Tests of the sensor, actuator, and the effect on safety of false triggering are required for most systems employing pre-crash sensing. For example, this is true for pre-crash pedestrian systems. However, in the case of some advanced safety systems, for example reversible occupant systems, it is considered that these could

function in existing regulatory and consumer crash tests.

For autonomous pre-crash braking there is a compliance issue with all current legislative and consumer crash tests because such a system would reduce the impact speed prescribed by regulatory tests. In this case, the pre-crash braking should be deactivated for the regulatory test and further tests to demonstrate the system function and safety carried out to prove that the sensing and activation of the system is appropriate and that the activation of the system only occurs in the unavoidable accident phase.

Systems which take control of the car away from the driver are also in conflict with at least some interpretations of the wording of the 1968 Vienna Convention, which states that the driver must be in control of the vehicle at all times. The content of the relevant sections of this convention may require amendment to reflect the significant technical developments in advanced safety systems, which take control away from the driver, providing that the safety implications of this action can be scientifically justified and assessed using an agreed methodology.

GENERIC ASSESSMENT METHODOLOGY FOR ADVANCED SAFETY SYSTEMS

The generic evaluation methodology developed by APROSYS *is suitable for use by a wide variety of stakeholders, for example, consumer organisations, legal authorities and industry*, all of whom have a need to verify or evaluate the technical performance of pre-crash safety systems.

In case of regulatory approval, the route for advanced safety systems is currently defined by Article 8(2) of EC Directive 92/53/EEC. Advanced safety systems which are incompatible with existing Directives require additional testing, but the evaluation methodology is not defined. *In the future, this generic methodology could be used as a basis for these tests to assure a minimum performance requirement for advanced safety systems.*

Description of the Generic Methodology

The generic evaluation methodology is shown in Figure 1. In the following sections, each the stage of the flowchart is described in greater detail. The following sections should therefore be read and interpreted with reference to Figure 1.

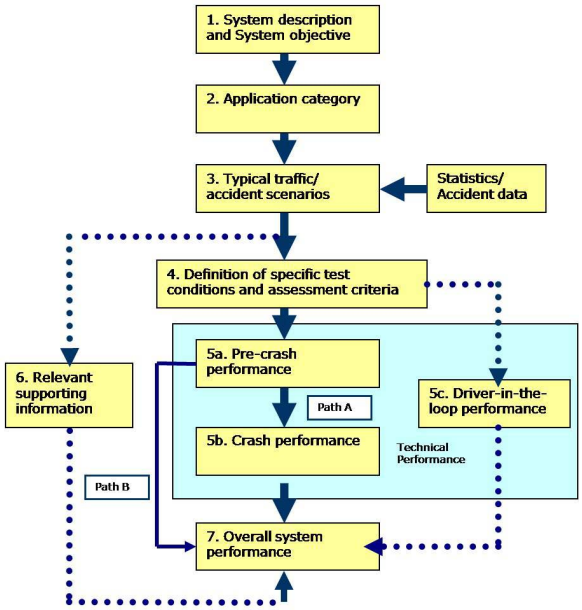


Figure 1. Flow chart for the generic assessment methodology for advanced safety systems.

<u>System Description and System Objective</u> - The system description is a brief description of the product or function to be evaluated. The following key characteristics of the system should be addressed:

- The application name and type;
- The major technologies and application under assessment (especially relevant for integrated systems);
- The functionality or service offered by the system;
- Any technical system limitations in terms of the conditions under which the technology is not designed to function effectively (e.g. in darkness or above/below certain speed thresholds).

The evaluation process should *always be performed for the complete system which offers the stated function.* For example, if sensing systems provide information to multiple systems, the information from the sensing system should be assessed separately for each function.

The objective of the system *will provide the key indicators to determine the parameters which must be assessed in the evaluation of the system*. Therefore, it is necessary to specify the manner in which the system is expected to reduce the injury risk. The description should also include limitations relating to the intended system objective. Further to any technical limitations, the limitations on performance should be noted. For example, the performance of an

emergency braking system would be reduced by a low friction road surface, despite the fact that the sensing system functions appropriately.

Application Category - In the application category, information should be provided regarding *the road-user groups and accident types in which protection is offered*. The categories of road users protected by the safety system are recommended as follows:

- car occupants
- truck and bus occupants
- non-motorised vulnerable road users
- motorcyclists

The broad categories of accident types for which the safety system is considered relevant are listed below. Note that this is not necessarily the direction in which the sensor information is focussed:

- frontal impact
- lateral impact
- rear-end impact
- rollover

In addition, the vehicle category to which the safety system is implemented should be identified and this, along with the application category, used as input for box 3 where the relevant accident types are identified.

Typical Traffic / Accident Scenarios - In box 3, *a set of generic scenarios should be defined based on accident data or real world situations*. These should include relevant accident scenarios and, depending on the type of system and actuator, relevant traffic scenarios that may include situations with a high accident risk, near miss scenarios, and other critical situations.

The definition of relevant scenarios is a critical step in defining appropriate test conditions because these must be representative of the most important situations in the real world for which the system is expected to provide a benefit. Thus, it is recommended that the scenario selection process consider the following general steps:

- Identify an accident data source that is applicable in scope and level of detail which is representative of the region for which the assessment is being made;
- Identify accidents which occurred in general conditions where the system should be functional (i.e. design limitations of the system are excluded);
- Identify accidents involving the user group for which the system is designed to offer a benefit;
- Assess frequency of fatal and/or seriously injured casualties by accident parameters, including, but not limited to: road type, impact speed, impact angle, impact object, road conditions.

In addition, accident and injury causation should be examined. Although this information may not be necessary to define the test scenarios, it is important for estimating the injury benefit of the advanced safety system. It is recommended that the relevant scenarios are identified based on the accident types resulting in the greatest frequency of fatalities, since this criteria is more directly comparable among European countries than other severity levels or national cost benefit values.

Definition of Specific Test Conditions and Assessment Criteria - In the box "definition of specific test conditions and assessment criteria", *the test conditions and the assessment criteria should be defined for the pre-crash tests, crash tests and driver in the loop tests*. In addition to test conditions developed from accident data, test conditions may be developed which are not derived directly from box 3, e.g. to assess environmental conditions that are expected to be more complex for the sensor system and which are not recorded in existing accident data. Details regarding the test conditions should be defined, including possible new test devices which might be necessary, for example new test environments, new barriers for the sensor tests, or new types of impactors or dummies for crash tests.

The assessment criteria used to evaluate the benefit of the advanced safety system should be defined. Standard legislation or consumer crash test criteria could be used for this purpose. However, other criteria may be used to assess the system. Note that the definition of the test conditions and criteria were outside the scope of this work, since this is application and system specific. Therefore, this should be addressed by the party applying the generic methodology. Within WP 1.3, this process was performed for a pedestrian pre-crash system to evaluate the applicability of this methodology.

Technical Performance - The assessment of the technical performance of the safety system is achieved by *the assessment of the pre-crash performance, the crash performance, and the driver in the loop performance*. Within the methodology presented here, evaluation of the driver-in-the-loop

performance was considered a compulsory component if the driver behaviour could influence the performance of the system. In the case that this methodology is being used to obtain compliance with existing or future regulation, "driver in the loop" tests should be performed to ensure that the pre-crash system does not have a negative influence on the driver during trigger events, and that the level of safety is not less than that without the system fitted.

Assessment of Pre-crash Performance - For pre-crash performance, *test scenarios and criteria defined in box 4 will be used in non-destructive tests to assess the pre-crash performance of the system*. A range of scenarios should be assessed ranging from very relevant (but simple) to less relevant (but more complex). The number of test scenarios passed by the system may be used to rate the pre-crash performance. In this way it can be shown that the system works as intended in a defined proportion of real world accident cases, since the test scenarios can be defined as covering a percentage of the real world accident data cases.

For each individual advanced safety system, specific criteria are required to evaluate the pre-crash performance in the defined accident scenarios. One possible convenient assessment criterion which could be applicable for some safety systems is the trigger time. If this time is not available, the 'system-in-function time' might also be used as an assessment criterion. The 'system-in-function time' is defined as the time at which the system offers the designed level of protection. In some cases it may be problematical to obtain this measure, especially as it might be impossible to gain direct access to the system on a signal level. For the Pedestrian GTR (Global Technical Regulation) it was proposed that the manufacturer provides both the head impact time and the sensor time. Based on this information it is decided if the head-to-bonnet impact tests can be performed with the bonnet in its deployed state [2].

For some systems, a minimum system-in-function time might not be an appropriate criterion, because an exact timing of the complete activation of the system could be necessary for optimal system performance. For example, for some type of pedestrian protection airbag systems, the airbag timing is critical to the level of safety offered. Thus for these systems, not only a minimum system-in-function-time, but also a time window of activation must be determined. An appropriate method must be developed for each specific safety system under assessment.

After the pre-crash performance has been assessed, two different paths can be followed to complete the system evaluation:

- Path A should be followed in case the actuator is expected to have an influence on the crash performance, or if the crash performance is not available;
- Path B should be followed in case the actuator will not influence the crash performance and the crash performance without the system is already available, for example a driver warning system.
- For both paths, if the system effectiveness could be influenced by the driver response, then driver in the loop tests should form part of the system evaluation.

Assessment of Crash Performance - If path A is followed, the crash performance must be assessed using the measured pre-crash performance. Using existing test procedures from regulations or consumer tests as a basis, the actuator system will be triggered (by the sensing system or synthetically) according to the results of the pre-crash performance tests. During the test, measurements will be made according to the standard procedures (if they are available) and the results will be compared and rated using the standard crash test as a reference.

For some new safety systems, the existing procedures from regulations or customer tests might not be appropriate to measure the crash performance. For example in some cases the dummy kinematics could be significantly different to those of a real occupant or the dummy injury criteria might not be sensitive enough to accurately represent any injury benefit. In such a case, other additional methods might be considered. This could include using new testing devices as well as numerical simulation (e.g. human body models) to evaluate the benefit of the system.

Assessment of Driver-in-the-Loop Performance - In the driver in the loop tests, the scenarios and criteria defined in box 4 will be used to investigate if and how the system activation influences the safety of the occupants. The influence could be negative (e.g. in terms of distraction in case of a false alarm) or neutral. In addition, driver-in-the-loop tests are important to evaluate the driver reaction, or to generate missing input for scenarios. Driving simulators or subject trials are tools which could be used to evaluate the driver-in-the loop performance.

Relevant Supporting Information - This box provides the manufacturer of the system the opportunity to provide additional larger scale or longer term information to the evaluation. Studies may be retrospective (using accident data) or realistic estimations based upon field studies or numerical simulations. Examples include:

- driving tests with professional drivers;
- field operational trials
- large scale driving simulator tests;
- accident data collection to monitor real world effectiveness

This generic methodology is focussed the assessment of technical performance. However, information supplied by the OEM or tier one suppliers regarding the longer term effects, and the "on the road" system effectiveness are an important part of the assessment of pre-crash systems. This information may be supplied from manufacturer testing carried out in the development phase. Furthermore, it is recommended that for any future regulation, and for systems gaining approval under the current Article 8 (2) route, this information should be mandatory. This evidence will demonstrate the safety of the system in a much greater range of road situations than can be assessed in specific evaluation tests. Future regulation may wish to explicitly specify the requirements for these tests.

Overall System Performance - At the system performance stage, the quality of the overall system must be evaluated. Therefore, *the driver-in-the-loop performance, the pre-crash performance and the crash performance will be combined to calculate an overall system performance.* The procedure to determine the overall system performance has yet to be developed since it is dependent on the specific application of the generic methodology. The procedure to assess the overall system performance, including the performance limits, may be different depending on the application of the assessment. The focus in regulatory testing is to guarantee a minimum performance requirement which systems must fulfil to be admitted to the market, whereas the intention of consumer information schemes are to differentiate between the performance of products available on the market.

A casualty benefit estimate could be made by considering the size of the target population; the number of fatal, serious and slight casualties which the system might influence. The results of the testing phases could then be used to estimate the effectiveness of the system in influencing the target population. This would lead to an estimate of the casualty reduction estimate of the system based upon the actual system performance as measured by the test developed using the generic methodology.

APPLICATION OF THE GENERIC METHODOLOGY TO A SPECIFIC SYSTEM

The generic methodology was evaluated by applying it to a specific safety system: a pre-crash pedestrian system. In parallel with this, APROSYS SP6 (titled "Intelligent Safety Systems") developed a pre-crash side impact system which was also evaluated using the generic methodology [4].

Pre-crash Pedestrian System 'Test Case'

Since a complete system was unavailable, the 'test case' pedestrian safety system consisted of separate sensing and actuator systems fitted to two different vehicles, and as such was a "theoretical" pre-crash pedestrian system. The actuator, was provided in a vehicle front-end developed in the German research project INVENT. The sensing system was from the Daimler PRE-SAFE® Brake/ BrakeAssist Plus system, with a modified decision algorithm to allow this dedicated testing within the project; basically this sensing system was not designed for pedestrian detection.

System Description and Objective - The system assessed was a theoretical pre-crash pedestrian protection system installed on a passenger (M1) vehicle, which uses radar sensors to detect pedestrians in front of the vehicle. When an imminent collision is detected, the actuators in the lower spoiler and bumper are activated to adjust the lower spoiler position and bumper stiffness. In addition, a pop-up bonnet is deployed using the same pre-crash information in order to provide head protection. The overall aim of the system is to reduce pedestrian injury.

The major sensor technologies are: 24 GHz forward looking short and 77 GHz long range radar. The field of view and range of the radar sensors are shown in Figure 2.

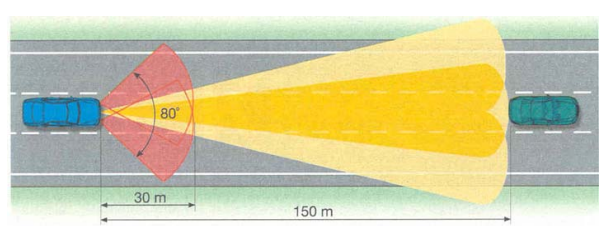


Figure 2. Field of view and range for short range (24 GHz) and long range (77 GHz) radar sensors (Source: Daimler).

The trigger output from the sensing system was displayed using LED indictor lamps fitted to the side of the test vehicle. These included an LED to indicate the trigger signal from the decision algorithm which would be provided to the actuators (had they been fitted on the same vehicle). A second LED was linked to a contact strip on the leading edge of the vehicle's bumper which provided indication of the contact point. These LED indicator lamps are shown in Figure 3.

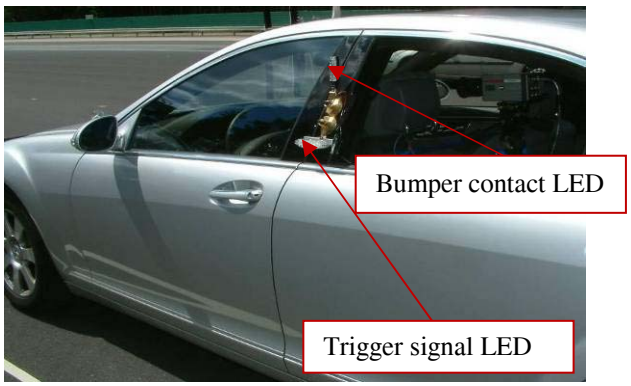


Figure 3. Position of LED indicator lamps for system trigger and bumper contact.

The vehicle front-end consisted of actuators under the bonnet, in the bumper and the lower bumper (Figure 4). The bonnet actuators produced an increase in height at the upper part of the bonnet of about 70 mm. The lower bumper actuator moved the lower bumper 100mm forward and 60 mm downward. The actuator in the bumper can be adjusted in two stages: compliant (0.2 kN) for collisions with pedestrians, and stiff (84 kN) for other impacts. All actuators functioned pneumatically with 12V magnetic valves.

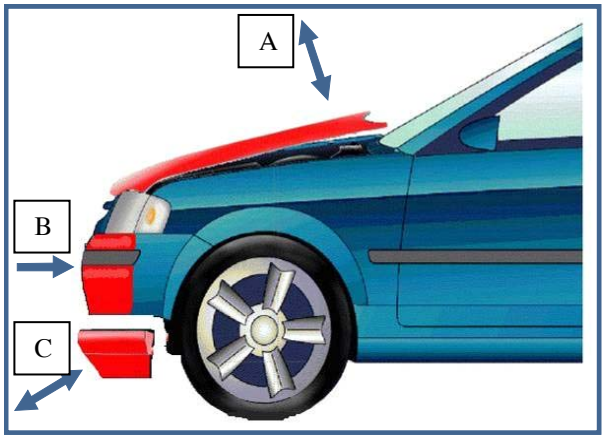


Figure 4. An overview of the actuator systems: pop-up bonnet (A), adjustable bumper stiffness (B), and extendable lower bumper (C) (Source: CSE).

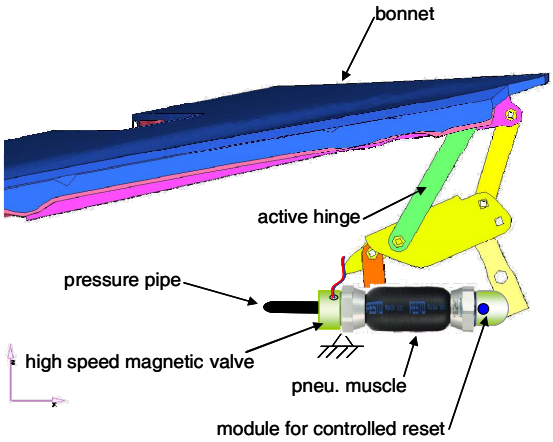


Figure 5: Prototype actuator system for pop-up bonnet (Source: CSE).

Figure 5 shows the basic operation of the actuators in deploying the rear region of the hood.

Application Category - The pre-crash pedestrian system increases the protection offered to pedestrians. It is indented to work in cases where the pedestrian is struck by the front of the vehicle by triggering advanced secondary safety devices on the basis of pre-crash sensing information.

Typical Accident / Traffic Scenarios - Accident scenarios were selected from analysis of the German In-depth Accident Study (GIDAS) database. The data used was not assessed for representativeness of a particular region; the assessment was focussed on the derivation of relevant accident situations.

Within the GIDAS database, selections were made for pedestrian accidents with passenger cars and MPVs. From 1,924 accidents, cases were selected in which the Maximum Abbreviated Injury Scale [3], (MAIS) injury of the pedestrian was AIS 2 or greater. This resulted in 896 accidents, of which 649 accidents related to frontal collisions. This group of accidents were taken as basis for further analysis and were classified into different pedestrian accident types as shown in Figure 6.

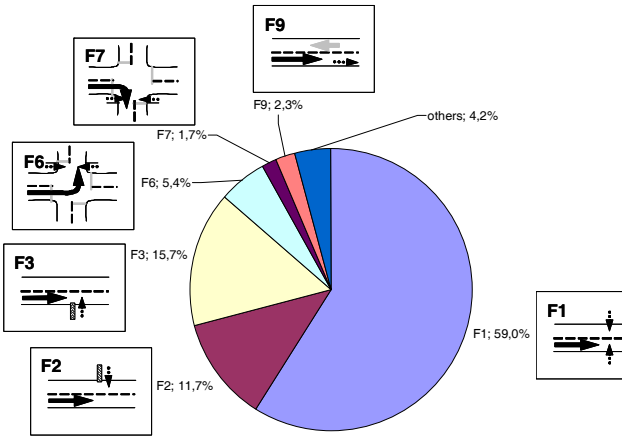
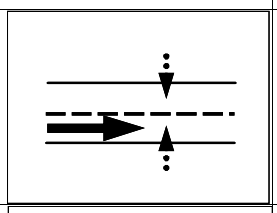
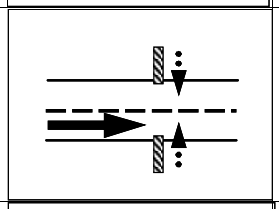
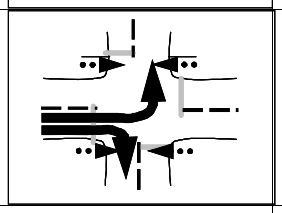


Figure 6. Frontal pedestrian accidents with MAIS 2+ by accident type (GIDAS data).

Using the scenarios illustrated in Figure 6, four main types of pedestrian accident were identified based on the relevance with respect to MAIS 2+ injury. These groups can be seen in Table 1.

Table 1. Scenario groups and their relevance in the GIDAS data

Pedestrian accident type description	Schematic view of pedestrian accident type	Relevance (% of MAIS 2+ pedestrian accidents)
Pedestrian crossing on straight road		59 %
Pedestrian crossing on straight road with occlusion		27.4 %
Pedestrian crossing road shortly after vehicle turning at junction		7.1 %
Others	-	6.5 %

A more detailed analysis was performed on the GIDAS data to derive the ranges of the relevant parameters to be used in the definition of the specific test conditions. The parameters considered are presented in Table 2.

Table 2.
Relevant parameters

Parameter	Description
$V_{vehicle\ initial}$	Vehicle initial velocity
$V_{vehicle\ impact}$	Vehicle impact velocity
$V_{pedestrian}$	Pedestrian velocity
$D_{pedestrian}$	Direction of the pedestrian movement relative to the vehicle (angle)
$X_{vehicle-pedestrian}$	Initial distance between the vehicle and the pedestrian
$Y_{vehicle-pedestrian}$	Initial lateral distance (offset) between the vehicle and the pedestrian
$H_{pedestrian}$	Standing height of pedestrian
D_{object}	Direction of object movement relative to the vehicle (angle)
$X_{object-pedestrian}$	Initial distance between the pedestrian and the object
T_{object}	Type of object obscuring view
$R_{vehicle}$	Turning radius of the vehicle
Light	Light conditions
Weather	Weather conditions
Road	Road condition
Objects	Other surrounding objects

The accident data was analysed to derive relevant ranges for each of the parameters listed in each accident type. The three generic scenarios can be seen in Figure 7 and the ranges for each of the parameters can be found in Table 3.

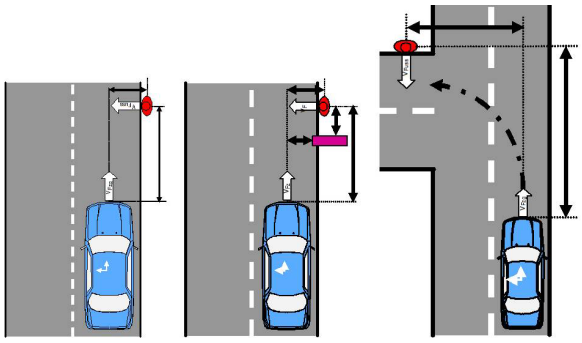


Figure 7. Pre-crash pedestrian test scenarios.

Table 3. Parameters for the pre-crash test scenarios

Parameter	Scenario 1	Scenario 2	Scenario 3
$V_{vehicle\ initial}$ [km/h]	50 ±20	45 ±25	20 ±10
$V_{vehicle\ impact}$ [km/h]	35^{+20}_{-10}	35 ±20	20^{+10}_{-15}
$V_{pedestrian}$ [km/h]	$5.4^{+10.8}_{-3.6}$	$5.4^{+10.8}_{-3.6}$	$5.4_{-3.6}$
$D_{pedestrian}$ [°]	±90	±90	±90
$X_{vehicle-pedestrian}$ [m][1)]	> 20	> 20	> 20
$Y_{vehicle-pedestrian}$ [m][2)]	To be calculated (see note)	To be calculated (see note)	8
$T_{vehicle}$ [-]	Passenger car	Passenger car	Passenger car
$H_{pedestrian}$ [m]	1.7 ± 0.2	1.7 ± 0.2	1.7 ± 0.2
D_{object} [°]	-	Fixed	-
$X_{object-pedestrian}$ [m]	-	0.5	-
T_{object} [-]	-	Parked car / van	-
$R_{vehicle}$ [m]	-	-	6
Environment related parameters			
Light	Day, night	Day	Day, night
Weather	Dry	Dry	Dry
Road	Dry asphalt	Dry asphalt	Dry asphalt
Objects	n/a	n/a	n/a

[1)] Pedestrian initially outside sensor field of view.
[2)] Impact point should be mid-front of the vehicle. The initial offset needed should be derived from the initial distance between the vehicle and the pedestrian and their velocities.

The parallel work conducted by APROSYS SP6 identified that some expert knowledge was necessary to define 'typical' traffic environments relevant for the performance of the sensor system. Consequently, in the APROSYS SP6 evaluation, additional scenarios were defined which were a greater challenge for the sensor system and decision algorithm than those derived from accident data.

Definition of Specific Test Conditions and Assessment Criteria

Pre-crash Performance Tests - Pre-crash tests are required to assess the performance of the sensing system and decision algorithm. These tests are derived from the scenarios defined in box 3, The tests are required to be non-destructive, because performance characterisation of sensor systems is based on statistical performance measures. A series of test scenarios were defined based on the ranges of the parameters listed in Table 3, which involved varying vehicle and pedestrian velocities, test objects travelling from the left and right, and with and without vehicle braking. Each test was repeated up to four times. Other assessments might consider a greater number of tests depending on the statistical significance required.

The pre-crash tests were performed both on a test track (see Figure 8) and in laboratory (see Figure 9).

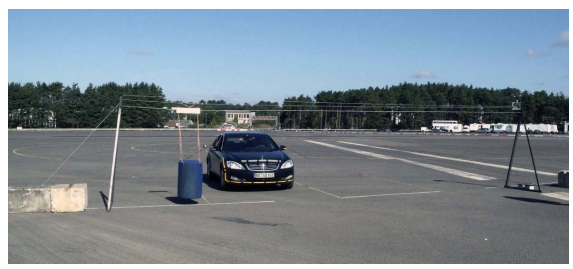


Figure 8. Example track test set up.

Figure 9. Example laboratory test set up.

In order to conduct the track tests, a mechanism was developed so that the test object (a foam cylinder) could be presented into the path of the vehicle at the required velocity and time. A pulley system enabled a small carriage to be driven by a motor calibrated to drive the carriage at the required test speeds. The test object was linked to the carriage via four guide ropes and these were attached with Velcro so that they would detach on impact. The test object was attached so that the bottom edge of the target was in line with the lower spoiler of the test vehicle. The test object was initially positioned off the carriageway marked for the test vehicle. The motion of the test object was triggered by positioning contact sensors on the test

vehicle's approach. These were positioned according to the speed of the test run and whether or not the test configuration involved vehicle braking.

The test results for the track and laboratory tests were analysed by reviewing the high-speed video of each test and determining the time between the trigger signal and first bumper contact. Information on the contact point of the target with the vehicle, assessed by examining the test video was also recorded.

The testing was performed both on a test track (TRL and CSE) and in a laboratory facility (TNO). It was found that both test strategies had strengths and weaknesses; track testing was very flexible and allowed all test configurations to be performed, but controlling all experimental variables proved difficult. Testing in a laboratory environment resulted in excellent control of experimental variables (test velocity and impact site). However, not all of the test scenarios were within the capabilities of the facility, meaning only one test scenario could be assessed.

Crash Performance Tests - Part 1 of EC Directive 2003/102 was chosen to assess the performance of the actuator system. Three head form to bonnet impactor tests: above each actuator and in the middle of the bonnet and two legform impactor tests; mid-vehicle and offset to one side by 427 mm were performed (see Figure 10). Three non-impact deployments were also recorded.

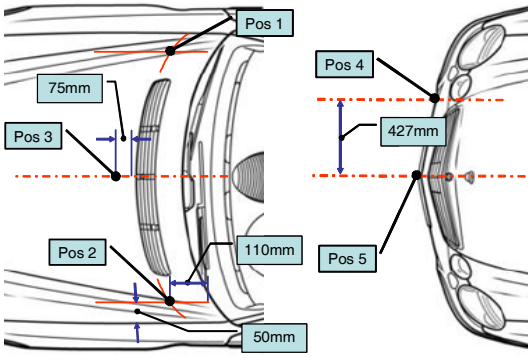


Figure 10. Test sites for headform and legform impacts.

Since the actuator component of the system under assessment was not linked to the sensing and decision algorithm, a synthetic trigger was provided to the vehicle front end 160 ms before impactor contact. The intention of these tests was that the actuators should be 'in function' directly before the impact of lower-leg or head-impactor. In a 'real' assessment, the information on the measured sensing performance would be used as an input to these tests; however, in this test case, the sensing systems was assumed to work as intended and provide a trigger signal to the actuators 160ms prior to impact.

Figure 11. Example actuator tests

Testing was performed by both TRL and CSE; this demonstrated successful pre-triggering of the actuators of a pre-crash pedestrian system to co-ordinate with existing headform and legform test.

Driver-in-the-Loop Performance Tests - In order to investigate the actuator systems whose activation in either the pre-crash or false triggering events might influence safety, "driver in the loop" tests were devised. These were carried out in the Daimler driving simulator and aimed to assess reaction of the driver and the effect on safety during "crash" or "no-crash" conditions.

In the test case, driver reactions to a pre-crash pedestrian protection system (pop-up hood) were investigated and evaluated for various driving circumstances and hazard situations. The main focus was to compare behaviour in a pedestrian impact event ("true") with that of a false activation ("false") and a "reference event"; a realistic event with which to compare the effect on the driving task. These events assessed are shown in Figure 12.

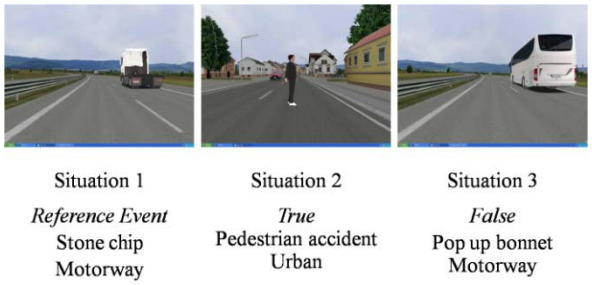


Figure 12. Scenarios defined and tested for "driver in the loop" testing of a pop-up bonnet.

The tests were carried out in the Daimler AG dynamic driving simulator using a total of 44 test subjects. Changes in the lateral dynamics (steering angle) and longitudinal dynamics (speed) during each event were recorded. Small, oscillating steering or "control" movements made by the driver (steering entropy), were used as a measure of the level of mental stress, since this has been proposed as a suitable measure for this parameter [5]. The results are shown in Figure 13.

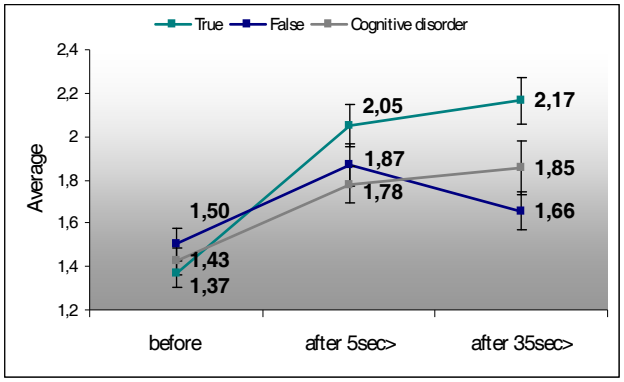


Figure 13. Steering entropy before and after each event.

In all events, the steering entropy increased noticeably after each event, indicating increased driver stress. The increase was greatest and longer-lasting for the pedestrian impact event ("true"). The false trigger event ("false") was similar to the reference event in terms of the effect on mental stress. Ultimately, and in relation to these parameters, no increased risk in managing the task of driving was observed in the driving scenarios chosen here. Subjective evaluation via subject interviews confirmed the objective data and allowed the false activation event to be compared to both a pedestrian impact and a reference event.

Relevant Supporting Information - No relevant supporting information was produced as part of the test case assessment for the pedestrian pre-crash system. However, APROSYS SP6 developed an advanced side impact protection system which used pre-crash radar and video sensing to detect side collisions. SP6 devised a field test to measure sensor performance under normal driving conditions. A route of about 3,000km was selected, comprising different road types, driving conditions and traffic. It was found to be a successful method to collect data on the numbers of false activations in normal traffic.

DISCUSSION

The generic methodology has been developed as a framework which can be applied to a range of advanced systems, and used by a range of stakeholders. For example, it is intended that the guidelines may be used by industry, regulators, or by consumer testing organisations. These stakeholders will apply the methodology with different end goals. For example, the methodology might be used as a basis for regulatory tests to ensure a minimum level of performance and to ensure that risks are adequately controlled. If this is the case, then information supplied via box 6 by OEMs or suppliers might be considered a requirement to demonstrate the performance of the system in a wider range of conditions than can be tested in box 5.

Related to the application of the methodology is whether the tests developed under this framework are in addition to the existing secondary safety requirements, or if the performance assessment could replace existing requirements. For example, if a system includes an automatic braking function and the sensing system can be shown to work as intended, this will result in a reduced impact speed. The generic methodology developed here assesses the performance of the system and the crash evaluation is carried out in line with the pre-crash performance (i.e. conducted at a reduced impact speed). Indeed, this is essential to fully assess the performance at the system and to allow the casualty benefit of the system to be estimated. However, this approach is not incompatible with the current regulatory or consumer testing regimes, as the tests developed from this methodology can be viewed as additional to existing requirements.

For some integrated systems, there may be actuators which utilise the same sensors but react to different trigger signals from the decision-making algorithm. Should a vehicle be equipped with systems which address more than one application category, this results in the derivation of different relevant test conditions (and target populations) being defined. This may result in more than one test suite (pre-crash, crash, driver in the loop) being performed since the generic methodology is system-focussed.

The accident data used to define the relevant accident scenarios is a critical component to ensure that the tests derived are representative of the appropriate accident conditions. The scope of the data required is to some extent dependent on the purpose of the application of the methodology. Furthermore, it seems unlikely that a European data source

containing information at the required level of detail will be available. Therefore, the accident data used as an input to the methodology is likely to remain a combination of representative national data and more detailed in-depth information. The generic methodology provides guidance regarding how the accident data should be used.

The generic methodology does not specify the number of test scenarios or the number of repeats of each test. It is not possible to specify these, since the methodology is generic, and therefore the range of relevant accident scenarios for each system depends on the system. However, the number of repeats should be such that adequate representation of the pre-crash and crash performance can be achieved. Since sensing system for different systems might be set at different levels of sensitivity, depending how "safety critical" the activation is, the number of repeat tests required to characterise the performance is also system dependent. However, the number of tests should be such that as close to 100% of the target population as possible is considered. Furthermore, the number of repeat tests for each test scenario may also depend on how the methodology is being used, but should be such that the performance of the sensor is appropriately accounted for. Ultimately, the required level of confidence required in the results is dependent on the stakeholder and the type of evaluation being undertaken.

The final methodology does not provide detailed specifications for the "driver in the loop" study. However, the pedestrian pre-crash system test case devised a series of simulator events designed to evaluate driver response between true (pre-crash), false (false triggering) and a reference event (realistic driving hazard). This approach was successful in comparing the response of the driver in these situations. Assessment of the effect of the system on the driver was successfully assessed in a driving simulator and this was shown to be an appropriate tool for this purpose.

The principle of measuring the long-term effects of advanced safety systems is important, and may be applied by stakeholders depending on the scope of the assessment. Specifications for field operational tests exist [6] and these may be used to provide requirements for the information supplied via this step of the methodology.

The overall assessment is dependent on the application of the methodology and also on the specific system being assessed. It is envisaged that the results from the technical performance could be integrated to formulate an overall rating scheme, similar to the system used by EuroNCAP. The methodology is also capable of being used to provide an estimate of the casualty-saving potential of the system. This would be achieved by considering the proportion of all casualties accounted for by the accident types derived from step 3 (real world accident data). The performance of the system in the tested accident types would provide performance information to estimate the effect of the system on this group of casualties. The type of overall assessment made is dependent on the stakeholder carrying out the evaluation and the purpose of the evaluation.

CONCLUSIONS

This paper presents the final APROSYS generic methodology for active safety systems. This methodology is intended to be applicable to a wide range of advanced safety systems and describes the different steps that should be taken in the development of a performance evaluation protocol for a specific advanced safety system. The flowchart providing an overview of the methodology is shown in Figure 1. The generic methodology is also designed to be flexible such that it can be used by a wide variety of stakeholders, from consumer organisations, legal authorities and industry, all of whom have a need to evaluate the technical performance of pre-crash safety systems. The main conclusions can be summarised as follows:

- The application of the methodology within the APROSYS project showed that relevant accident scenarios could be identified and transferred to appropriate test conditions. The test procedures developed from the methodology allowed the systems to be evaluated in terms of the pre-crash, crash and driver-in-the-loop performance.

- The generic methodology focuses on developing testing for a specific system to evaluate the system performance. This testing can be applied in addition to existing regulatory and assessment procedures.

- Stakeholders should ensure that the tests as accurately as possible represent the target population (those accidents influenced by the system) and that a sufficient number of repeat tests are performed to characterise system performance; what constitutes this threshold depends on the application of the methodology. A specific test programme

should define requirements for valid tests and suitable means of monitoring the key parameters (such as vehicle speed) to ensure that any testing is repeatable.

- The test conditions developed during the APROSYS testing were highly simplified with relation to the road environment as seen by the sensing system. This indicates that, depending on the specific system under assessment and the purpose of the assessment, relevant supporting information on the "real world" performance of the sensing system may be important. This would assess the pre-crash performance in a wider range of situations than defined in any assessment tests.
- Expert knowledge has been permitted by the methodology to supplement situations derived from accident data, in order to represent typical environmental conditions which cannot be defined from existing data.
- Pre-crash tests were carried out using track and laboratory facilities; both these approaches had strengths and weaknesses. The pre-crash testing carried out on a test track was found to be very adaptable in that all of the relevant test types could be successfully represented on the test track. However, although flexible in terms of the types of test configurations, it was found that achieving a "valid test" – one in which the vehicle struck the test object correctly at the correct speed was affected by small variations in vehicle or target velocity and/or braking level. In contrast, testing in laboratory facilities proved to be very repeatable; however, only one test scenario could be tested in this facility. This suggests a need for a "virtual laboratory" approach, comprising several facility types.
- The overall assessment should be developed by the stakeholder, depending on the purpose of the assessment and the system being assessed. The assessment can be made in terms of the performance of the system within those accident types assessed and/or in terms of the estimated casualty reduction potential of the system.

ACKNOWLEDGEMENTS

The author acknowledges the contribution of the members of the APROSYS 1.3 consortium to this paper:

- BASt, Germany
- Continental, Germany
- Daimler AG, Germany
- TNO, Netherlands
- TRL, UK
- Volkswagen, Germany

The close co-operation with APROSYS SP6 partners is also acknowledged. For more information on the APROSYS project and project deliverables, please refer to www.aprosys.com.

The consortium is grateful for the support of: the European Commission DG-TREN, UK Department for Transport, German Ministry of Transport and Housing, and the Dutch Ministry of Transport for funding this work.

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DEMONSTRATOR FOR VIRTUAL TESTING PROCEDURE. APPLICATION TO PEDESTRIAN ADULT HEAD IMPACTS

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Paper Number 09-0393

ABSTRACT

The research activities presented in this paper were carried out within Sub-Project 7 of APROSYS (Advanced PROtection SYStems), a European Integrated Project implemented within the 6th Framework Programme which main objective is the development and introduction of critical technologies that improve passive safety for all European road users in all relevant accident types and accident severities. Furthermore, this IP aims to increase the level of competitiveness of the European industry by developing new safety technologies (safety is a proven selling point) and by developing design tools and evaluation methods that will increase the efficiency of the development process of the involved industries.

SP7 (Virtual Testing) deals with the development of knowledge and tools to facilitate the design and evaluation of advanced crash protection systems by virtual testing (numerical simulation). Within SP7 a Virtual Testing (VT) demonstrator based on a combination of simulations and physical tests for pedestrian protection (head impact) was delivered. Where VT has proven to be predictive and where benefits in terms of increasing safety are expected.

In a first approach, experimental adult head form impacts against bonnet structures were performed. Besides, a series of virtual tests with standard adult head form numerical model and numerical model of the test rig were performed. VT was performed with limited data (only initial conditions) from physical test and no validation results were provided to adjust the nominal simulation model. Finally, a study of experimental testing variation using stochastic models was performed. The effects of these variations were quantified using stochastic analysis.

INTRODUCTION

Pedestrian protection has been identified as one of the fields with greatest potential for improvement. It can be asserted that numerical simulation is meanwhile highly predictive for pedestrian protection testing. Moreover, studies carried out in current EC projects such as APROSYS [1][2] conclude also that the implementation of virtual testing in homologation/regulation with regards to pedestrian protection directives, could lead to tangible benefits in terms of injury reduction and cost reduction in vehicle design. Pedestrian regulation has a medium degree of complexity in comparison with a full scale crash, as impactors are used for the assessment, and only the front part of the vehicle is significantly affected. Nevertheless, unfortunately not a high number of cars reach the maximum level on pedestrian protection. Thus, the potential impact of improving pedestrian protection will be very worthy since the number of pedestrian fatalities is still high like mentioned above.

Within APROSYS SP7 a Virtual Testing (VT) demonstrator based on a combination of simulations and physical tests for pedestrian protection (head impact) was delivered. The goal of these activities is to show the feasibility of the simulation models as well as the accuracy of the virtual and physical tests.

In a first approach, experimental adult head form impacts against bonnet structures were performed. The test matrix was defined covering following characteristics:

- Extended instrumentation (additional instrumentation to measure 3D deformation contours)
- Sensitivity analysis testing (level of results variation due to slight variations in testing configuration)
- Repeatability ranges (level of repeatability for same testing configuration).

Besides, a series of virtual tests with standard adult head form numerical model and numerical model of the test rig were performed. VT was performed with limited data (only initial conditions) from physical test and no validation results were provided to adjust the nominal simulation model. Finally, a study of experimental testing variation using stochastic models was performed. The effects of these variations were quantified using stochastic analysis.

ADULT HEAD IMPACT TESTS

Test bench

A bonnet test bench was built (Figure 1). The design of the test bench is adaptive so it can be

used for testing different kinds of bonnets by only performing minor modifications. The bonnet is mounted on rigid crossbeams placed in correspondence of its hinges, front lock and rubber mountings/grommets. Furthermore, a plate for representation of the motor block was placed.

Figure 1. Bonnet test bench.

The adult head form as specified in Directive 2003/102/EC, phase II [3] was used to record head accelerations caused by contact with the bonnet top. Additionally, a system for measuring three-dimensional deformations has been employed in order to provide additional data about the mechanical behaviour of the bonnet and the positioning and kinematics of the head form. The base of this system is software that computes the deformations of a surface based on the stereoscopic analysis of pictures registered with two high speed video cameras [5]. These results allow to achieve a more complete validation of the results of the numerical simulations, as well as to check the correct positioning of the head form at the contact time.

Test conditions

Four different impact locations were investigated (Figure 2). These locations were selected to represent the most frequent occurred impact points:

1. close to the front lock
2. close to the hinges
3. close to the rubber mountings
4. close to the motor block highest point

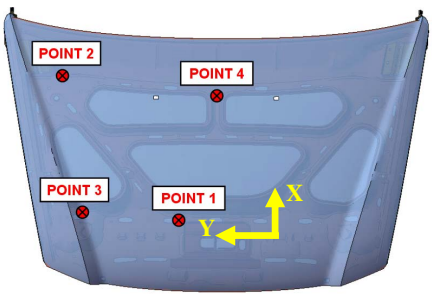

Figure 2. Impact locations.

The objectives of performing these tests were to analyse the level of results variations due to slight variation in testing configuration (sensitivity analysis testing) as well as the level of repeatability for same testing configuration. According to these objectives the test matrix was define.

Initially four reference tests were performed (one in each point). These tests were launched according to the Directive 2003/102/EC [3], phase II. Test conditions for the adult head form impactor are as following:

- Angle of impact: 65º±2º to the ground reference level
- The point of first contact: within ±10mm of tolerance to the selected impact location
- Impact velocity: 11.1±0.2m/s

Then, variations of the impact variables were taken into account. These variations were carried out only in points 1, 2 and 3 whereas point 4 was used to perform the repeatability analysis. Thus, three tests were performed at this point with the same impact conditions (reference boundary conditions according to the standard). At points 2 and 3 the reference test was also repeated so repeatability could be checked also in different points of impact. The test matrix is shown in the next table:

Table 1. Tests matrix.

Point 1 (front lock)			Point 2 (hinge)		
v [m/s]	Ang. [º]	Pos. [mm]	v [m/s]	Ang. [º]	Pos. [mm]
11.1	65	0	11.1	65	0
10.6	65	0	11.1	65	0
11.6	65	0	10.6	65	0
12.1	65	0	11.6	65	0
11.1	60	0	11.1	60	0
11.1	70	0	11.1	70	0
11.1	65	y-10	11.1	65	y-10
11.1	65	y+10	11.1	65	y+10
Point 3 (supports)			**Point 4 (motor highest point)**		
v [m/s]	Ang. [º]	Pos. [mm]	v [m/s]	Ang. [º]	Pos. [mm]
11.1	65	0	11.1	65	0
11.1	65	0	11.1	65	0
10.6	65	0	11.1	65	0
11.6	65	0			
11.1	65	y-10			
11.1	65	y+10			
11.1	65	x-10			
11.1	65	x+10			

BLIND VALIDATION

Series of virtual tests with standard adult head form numerical model and numerical model of the test rig were performed. VT was performed with limited data from physical test. The FE model was built starting from the CAD, material data

properties, description of the connections among the different parts of the bonnet (adhesives, spot-welds…) and test conditions (test set-up) but no validation results were provided to adjust the nominal simulation model.

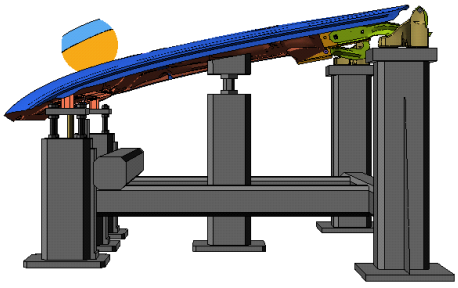

Figure 3. Numerical model.

In order to check the accuracy of the simulation model, a comparison between the simulation results and the test results were performed. This model was not tuned once the comparison with the test results was done.

First of all the four reference tests were considered. The curves obtained are depicted in the following images:

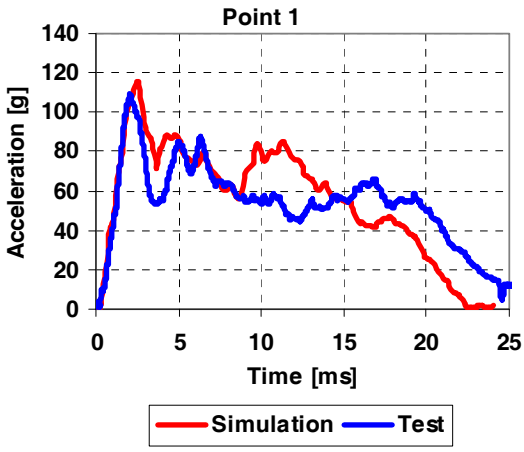

Figure 4. Acceleration pulses (point1).

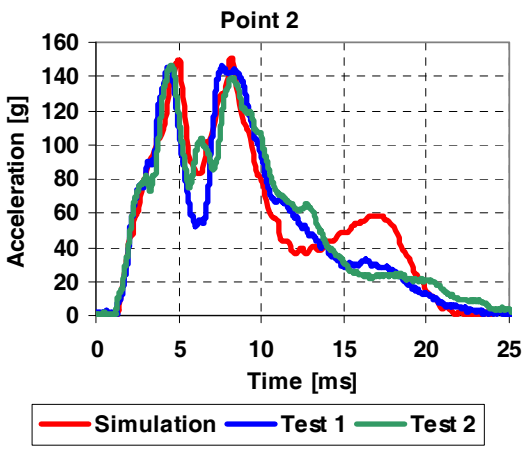

Figure 5. Acceleration pulses (point2).

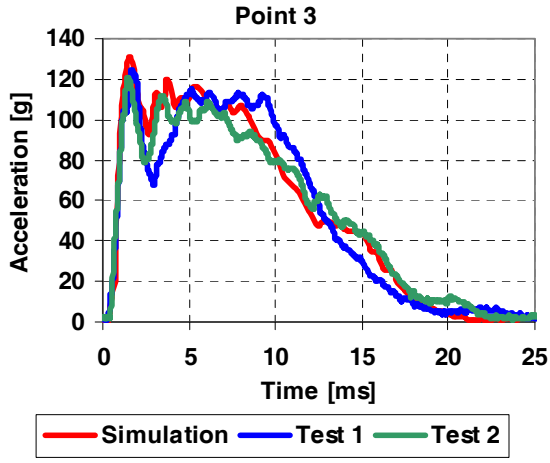

Figure 6. Acceleration pulses (point3).

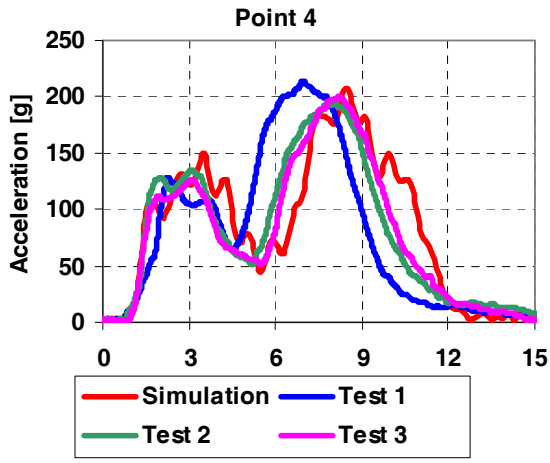

Figure 7. Acceleration pulses (point4).

In the case of the first point there is not repetition of the test, so only one test result is available. Nevertheless, the results presented in all cases show a good correspondence between the output signals of both, simulation model and tests, in shape as well as in absolute peak values.

As it was explained above, a system for measuring three-dimensional deformations has been employed in order to provide additional data about the mechanical behaviour of the bonnet and the positioning and kinematics of the head form impactor.

This system allows measuring of displacements and three-dimensional deformations by two cameras simultaneously recording. A previous calibration process is required. This process consists on taking series of images of several points from a panel which exact distances are known. Then, the program is provided with information about the specific spatial position of the cameras and then it is able to interpret correctly the images obtained

during the tests. On the other hand, the test's object (bonnet and headform impactor in this case) has to be painted with a random mottled (see Figure 8) which provide reference points in order to work out deformations in consecutive images.

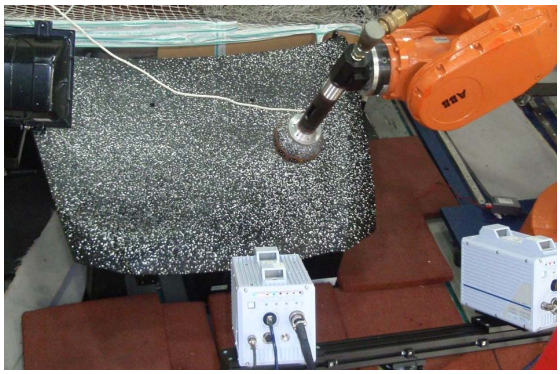

Figure 8. Cameras location and random mottle of the bonnet and headform impactor.

As far as the behaviour of the bonnet is concerned, the kinematics observed in the simulations correlate well with the one registered with the stereoscopic analysis of the high speed images. Some examples can be seen in the next figures. In the upper images (in a white background) the simulation contour is depicted whereas in the lower ones (in a grey background) the contour obtained from the stereoscopic analysis is shown.

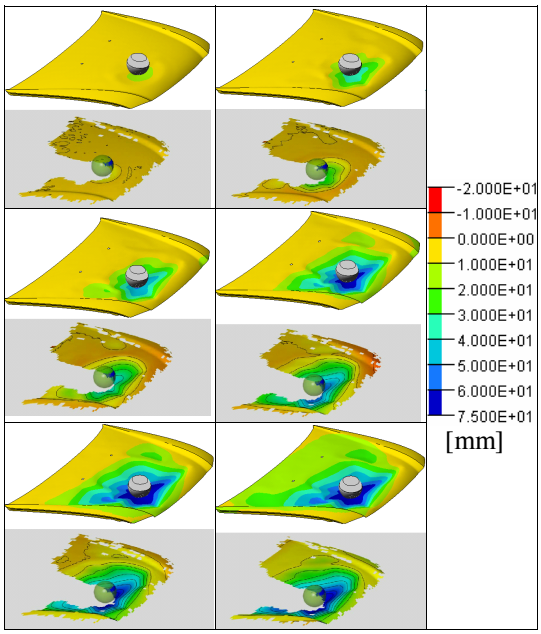

Figure 9. Displacement contours (point1).

Displacement contours of the bonnet as well as the absolute displacement values are very close in all cases for both, virtual tests and real tests (stereoscopic analysis of the high speed images).

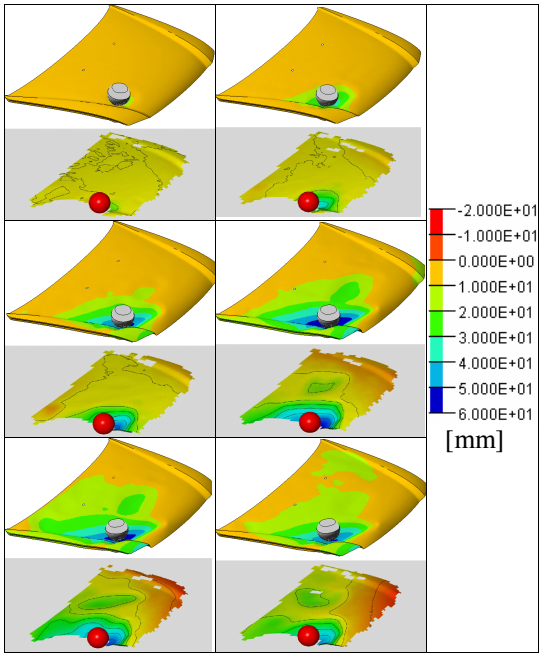

Figure 10. Displacement contours (point3).

Once the results of the reference cases were compared, the analysis was extended to all the test cases with the variations in the input conditions (see Table 1). The results obtained are shown in following tables:

Table 2. Experimental - Simulation results point 1.

Point 1 (front lock)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang °	Pos. mm	Test	Sim.	Test	Sim.
11.1	11.06	65	0	109.3	115.4	487.2	703.7
10.6	10.48	65	0	80.5	109.9	487.6	643.6
11.6	11.73	65	0	109.8	121.0	562.2	799.3
12.1	-	65	0	-	126.4	-	914.8
11.1	11.08	60	0	110.8	127.7	559.1	726.6
11.1	10.97	70	0	92.8	116.6	603.4	660.1
11.1	11.15	65	y-10	101.6	121.1	533.0	667.6
11.1	11.15	65	y+10	110.9	117.2	481.4	534.2

The system that launches the head form impactor against the bonnet allows reaching velocities higher than 12.1m/s. Nevertheless, when the system works close to this maximum threshold it is possible to have problems during the test. These problems appeared in this case. The system was out of control and then, it was not possible to know the real velocity achieved. Thus, it was decided not to use this test results. This problem only appeared in the point 1 since in the other cases the maximum velocity was 11.6m/s.

Table 3. Experimental - Simulation results point 2.

Point 2 (hinge)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang º	Pos. mm	Test	Sim.	Test	Sim.
11.1	10.98	65	0	146.6	151.0	988.9	955.3
11.1	11.19	65	0	146.4		937.1	
10.6	10.78	65	0	142.2	141.6	1038	838.8
11.6	11.8	65	0	157.4	159.5	1042.6	1080.1
11.1	10.96	60	0	143.8	146.3	1209.2	904
11.1	11.00	70	0	161.4	151.1	1142.3	972.7
11.1	11.11	65	y-10	129.7	148.1	883.4	896.8
11.1	11.10	65	y+10	152.8	164.6	1189.4	1000.1

Table 4. Experimental - Simulation results point 3.

Point 3 (supports)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang º	Pos. mm	Test	Sim.	Test	Sim.
11.1	10.91	65	0	124.1	130.6	1095	1087.5
11.1	11.13	65	0	120.5		937.5	
10.6	10.61	65	0	103.6	125.4	777.9	1013.7
11.6	11.47	65	0	132.6	137.4	1130.5	1158.8
11.1	11.16	65	y-10	121.0	138.8	954.4	1091.1
11.1	11.05	65	y+10	114.0	166.9	866	1181.7
11.1	10.93	65	x-10	126.0	157.7	1034.2	1405
11.1	11.17	65	x+10	146.6	127.1	989.2	987.1

Table 5. Experimental - Simulation results point 4.

Point 4 (motor)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang º	Pos. mm	Test	Sim.	Test	Sim.
11.1	11.03	65	0	194.2	207.2	1485.3	1627.8
11.1	10.97	65	0	200.2		1696.9	
11.1	11.22	65	0	213.8		1686.2	

The correlation (similar trends are seen for experiment and simulation results) is very good for point 2 and point 4 in both maximum acceleration and HPC and good for point 3, whereas the simulation results are overestimated in case of point 1. This point is close to the lock of the bonnet. In the blind simulation model, the lock system was modelled as a rigid body, this fact makes that the acceleration peaks and the HPC values were higher than the obtained in the physical tests.

These results leads to conclude that more information regarding the bonnets and the test rig would be needed to build the nominal simulation model. For instance, it is very important to know the material cards so material characterizations would be required.

STOCHASTIC ANALYSIS

The target of the study is the generation of knowledge about the influence on the pedestrian adult head criteria responses (according to the Directive 2003/102/EC [3], phase II) regarding slight experimental testing variations such as impact velocity, impact angle and relative impact position.

In the above sections, a deterministic approach has been shown. Simulations with the same experimental conditions have been performed and results of corresponding simulations and tests results have been compared. This study consisted in one simulation results vs. one physical test results comparison. With the stochastic approach, the level of results variations due to slight variation in testing configuration (sensitivity analysis) can be study. Correlation between experimental and simulation clouds can be checked as well as the robustness and accuracy of the simulation models.

Stochastic pre-processing: stochastic modelling and sampling

Four stochastic analysis were performed, one per point of impact. The values of dispersion considered for the impact conditions covers the ones used in the experimental tests at each point. Thus, the next tables show the set of input parameters as well as the considered variability:

Table 6. Stochastic variables - Point 1 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±1m/s	11.1m/s	[10.1,12.1]	Veloc
Impact angle	±5º	65º	[60º,70º]	Ang
Impact point position X	± 10 mm	0 mm	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm	[-10,10]	Pos_Y

Table 7. Stochastic variables - Point 2 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±0.5m/s	11.1m/s	[10.6,11.6]	Veloc
Impact angle	±5º	65º	[60º,70º]	Ang
Impact point position X	± 10 mm	0 mm.	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm.	[-10,10]	Pos_Y

Table 8. Stochastic variables - Point 3 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±0.5m/s	11.1m/s	[10.6,11.6]	Veloc
Impact angle	±2º	65º	[63º,67º]	Ang
Impact point position X	± 10 mm	0 mm.	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm.	[-10,10]	Pos_Y

Table 9. Stochastic variables - Point 4 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±0.2m/s	11.1m/s	[10.9,11.3]	Veloc
Impact angle	±2º	65º	[63º,67º]	Ang
Impact point position X	± 10 mm	0 mm.	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm.	[-10,10]	Pos_Y

In this last case (point 4), the variability of the input variables considered matches with the allowed range of tolerances established by the standard [3] for the tests. Thus, the variability obtained in the tests results at point 4, which were performed with the same impact conditions can be analyse through this study. For the study the reference model built by a blind validation presented above was used.

Once the stochastic variables were identified in the reference model, the next step was to get a set of simulation cases in accordance with one of the sampling methods available [6]. The "Optimal Latin Hypercube" method was chosen in order to provide better coverage of the multivariate space with less simulation runs (30 per point of impact, total 120 simulations cases). Uniform distributions for the ranges established in the table above were defined to account for the estimated variability.

Before starting the set of simulation runs, the resultant values to be extracted and analysed were defined. As the main interest was to know the sensitivity of pedestrian adult head criteria, evaluation files .sto and .crit were built in order to get the maximum acceleration pick, time at this maximum acceleration pick and the HPC value.

Stochastic post-processing: sensitivity analysis

The results were analysed with several approaches, and valuable conclusions resulted from the different analysis carried out.

Following tables show the main statistics of the outputs or properties, resulting from the different clone model runs at each point:

Table 10. Stochastic results statistics - Point 1.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	9.77866E+01	1.30101E+02	1.15357E+02
HPC	30	5.53438E+02	8.81923E+02	7.03893E+02
TIME_ MAX-ACC	30	3.00047E+00	4.20028E+00	3.69039E+00
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	6.94042E+00	8.31786E+00	0.0721056
HPC	30	8.33078E+01	9.73500E+01	0.138302
TIME_ MAX-ACC	30	3.19323E-01	3.88878E-01	0.105376

Table 11. Stochastic results statistics - Point 2.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	1.40797E+02	1.68239E+02	1.52388E+02
HPC	30	8.03288E+02	1.14861E+03	9.46985E+02
TIME_ MAX-ACC	30	5.30068E+00	9.20039E+00	7.33040E+00
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	6.32505E+00	7.82325E+00	0.0513376
HPC	30	7.43241E+01	8.94827E+01	0.0944922
TIME_ MAX-ACC	30	1.56135E+00	1.60564E+00	0.219039

Table 12. Stochastic results statistics - Point 3.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	1.23533E+02	1.67693E+02	1.41284E+02
HPC	30	9.59821E+02	1.43727E+03	1.14476E+03
TIME_ MAX-ACC	30	2.10027E+00	4.70008E+00	2.99370E+00
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	1.29068E+01	1.47524E+01	0.104416
HPC	30	1.02722E+02	1.34482E+02	0.117476
TIME_ MAX-ACC	30	7.23537E-01	8.65761E-01	0.289194

Table 13. Stochastic results statistics - Point 4.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	1.80371E+02	3.18280E+02	2.54933E+02
HPC	30	1.42373E+03	2.41783E+03	1.89340E+03
TIME_ MAX-ACC	30	1.02005E+01	1.08004E+01	1.03638E+01
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	3.37991E+01	3.99696E+01	0.156785
HPC	30	2.18702E+02	2.68302E+02	0.141704
TIME_ MAX-ACC	30	8.32636E-02	1.15837E-01	0.0111771

From the tables, some results are concluded by looking at the [standard deviation/mean] ratio. This ratio is an estimation of the sensitivity of the parameters in terms of ratio variability. Values of around 1, present a percentage of sensitivity from the mean of 100%. Different behaviours can be observed at the different points of impact.

Not so high sensitivities can be seen. At point 2 (close to the hinges) and point 3 (close to the supports - rubber mountings) the most sensitive parameter is the time at the maximum acceleration (>20%). This variation can be produced due to a second impact of the head form owing to the input variations. At point 1 (close to the lock) no major variations can be seen (maximum ≈13% in the case of HPC). And finally, at point 4 (close to the motor block) the most sensitive parameters are the acceleration pick and the HPC value (≈15%).

Then, the next stage is looking for the input variables whose scatter is responsible for this output variability.

The correlation matrix is one of the outputs offered by ADVISER [6] to the user, showing relationships between the problem parameters. The linear correlation matrices can be seen in the following figures:

	Point 1				Point 2			
	vel	ang	posX	posY	vel	ang	posX	posY
MAX-ACC	0.84	0.099	0.47	-0.2	0.6	0.18	0.29	0.67
HPC	0.92	-0.22	-0.091	-0.28	0.86	0.21	0.28	0.37
TIME_MAX-ACC	-0.32	-0.11	-0.87	0.21	-0.075	0.26	-0.16	0.75

	Point 3				Point 4			
	vel	ang	posX	posY	vel	ang	posX	posY
MAX-ACC	0.18	-0.15	-0.52	0.6	0.45	0.25	-0.76	-0.23
HPC	0.4	-0.0057	-0.81	0.25	0.48	0.31	-0.78	-0.12
TIME_MAX-ACC	-0.12	0.03	0.25	-0.68	-0.39	-0.038	-0.15	0.083

Figure 11. Linear correlation matrices.

Looking at the correlations higher than 0.5 (in absolute value), the stochastic input variables more clearly related (linearly) to the variability of the output parameters are different at each point of impact.

At point1 the most influence variable is the velocity on the maximum acceleration and the HPC value. The variation of x position is the following influencing factor, but in this case the influence is on the time at the maximum acceleration. This effect is due to a second impact of the head form as results of the variation of the x position.

Similar effect can be seen at point 2. The most influence variable is the velocity on both the maximum acceleration and the HPC value and the variation of the y position on the maximum acceleration and the time at this maximum acceleration. This point 2 is closed to the hinges. The variation of the y position has two effects. One is that the first impact point is closer to the hinge so the acceleration peak is increased. And the other effect is the opposite; the first impact point is farther to the hinge and the acceleration peak is later in time.

This last effect appears again at point 3; the variation of the y position has a big influence in the maximum acceleration and the time at this maximum acceleration. But also the variation of the x position has a big influence in the HPC value.

Finally at point 4, the most influence variable is the variation of the x position on the maximum acceleration and the HPC value. The x position variations makes that the point of impact is closer or farther to the motor block highest point and then has a direct effect on the acceleration peak and then in the HPC. As closer is the impact point to the motor block highest point, higher is the acceleration peak.

Another calculation can be done in terms of the norm of the regression coefficients, for the input variables. Using the stochastic post processing of ADVISER [6], is presented the next **Error! Reference source not found.**, that represent the global relative influence in the variability of the model of each one of the input variables taken into account in the study.

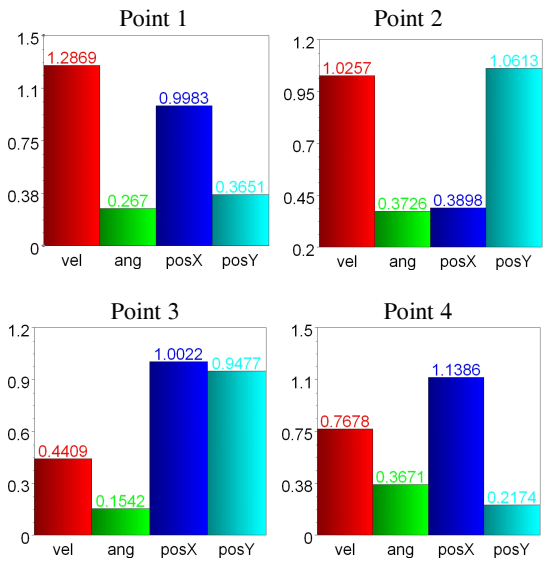

Figure 12. Global sensitivity rating. Point 1.

Input parameters like velocity of impact and impact position (in X or Y direction depending on the point of impact) are the most sensitivity variables whereas the angle of impact has not so much influence in the responses for all the points of impact.

All the results (test, simulation and stochastic results) are plotted on scatter plots to highlight relationships between responses and variables. Only scatter plots of variables with a correlation value higher than 0.5 in absolute value (see Figure 11) are shown since lower values do not show a clear relation. Blue dots are used for simulation results, red dots for experimental results and black triangles for stochastic results.

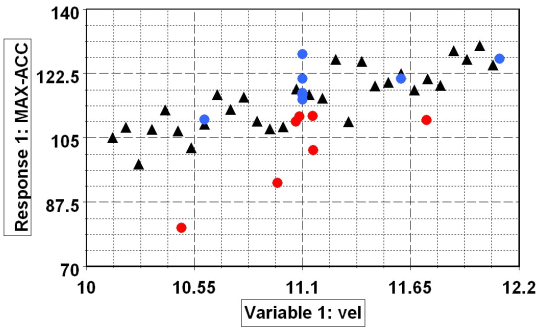

Figure 13. Scatter plot; Point 1 – Acceleration peak [g] vs. Velocity [m/s]

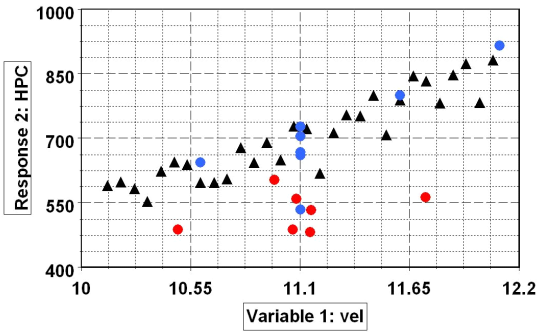

Figure 14. Scatter plot; Point 1 – HPC vs. Velocity [m/s]

As it was advanced in the linear correlation matrices (Figure 11) at point 1, only the velocity has a very high influence on the maximum acceleration and the HPC value in a direct and positive correlation. This means that increasing the impact velocity affects in an increasing of these values.

At point 2, not only the velocity shows a high influence on the maximum acceleration and the HPC value (Figure 15 and Figure 16) but also variations in the y-position lead to high variations on the maximum acceleration value.
This effect is due to the location of point 2 (close to the hinge). Small variations of y-position lead to an impact position closer to the hinge, a very rigid area, so the acceleration peak (first contact between the headform impactor and the bonnet) is increased.

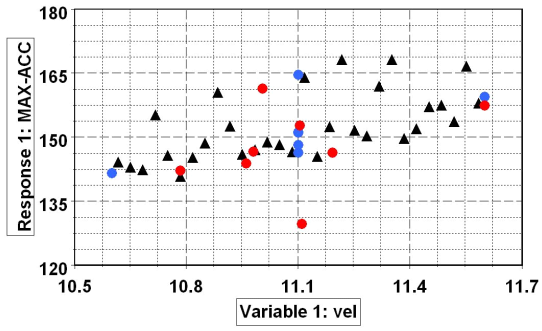

Figure 15. Scatter plot; Point 2 – Acceleration peak [g] vs. Velocity [m/s]

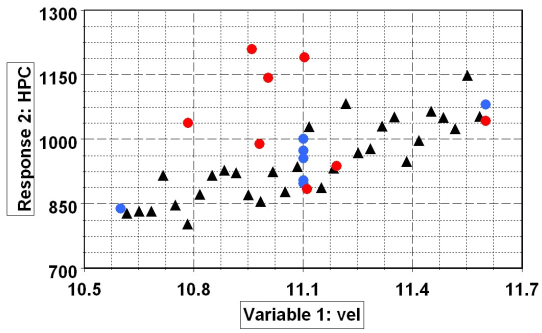

Figure 16. Scatter plot; Point 2 – HPC vs. Velocity [m/s]

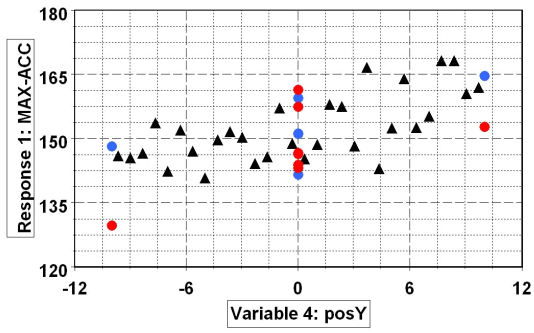

Figure 17. Scatter plot; Point 2 – Acceleration peak [g] vs. y-Position [mm]

The influence of the velocity in the HPC is higher than in the maximum acceleration. This is due to the fact that the variation of the velocity does not only increase the severity of the impact (increase the acceleration peak) but also modify the shape of the acceleration curve leading to higher increments of HPC than maximum accelerations. The formula used to calculate the HPC is identical to that used to calculate the Head Injury Criterion (HIC):

$$\mathbf{HPC} = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a\,dt \right]^{2.5} (t_2 - t_1) \qquad (1).$$

where ‘a’ is the resultant acceleration as a multiple of ‘g’, and t1 and t2 are the two instants (expressed in seconds) during the impact, defining the beginning and the end of the recording for which the value of HPC is a maximum. The difference between HPC and HIC is that for HPC, values which the time interval (t1 - t2) is greater than 15ms are ignored for the purposes of calculating the maximum value.

Looking at the linear correlation matrix related to point 3, the velocity is not the variable with more influence in the output parameters but the position.

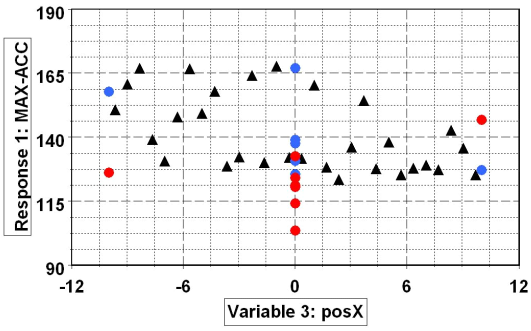

Figure 18. Scatter plot; Point 3 – Acceleration peak [g] vs. x-Position [mm]

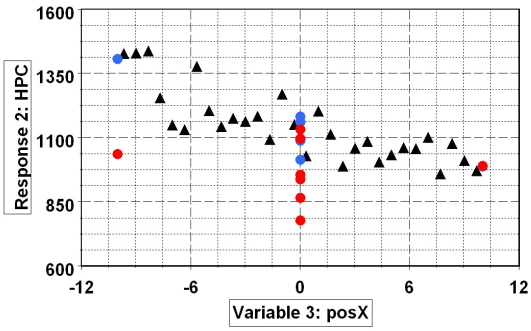

Figure 19. Scatter plot; Point 3 – HPC vs. x-Position [mm]

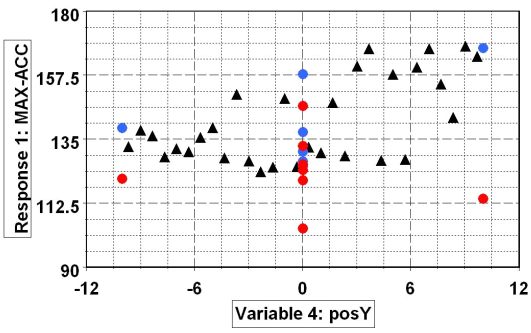

Figure 20. Scatter plot; Point 3 – Acceleration peak [g] vs. y-Position [mm]

At point 3, contrary to what append in the other points, the velocity has not clear influence in the maximum acceleration and the HPC value whereas the position variation presents a direct correlation. This point of impact is close to the rubber mountings, positive increments of the impact position in x direction leads to move away the impact point from the stiffer point that are the rubber mountings. Thus, the acceleration peak as well as the HPC value decreases.

In the case of impact point 4, variations of the input variables taken into account (velocity of impact, angle of impact and position of impact – x and y directions) match with the allowed range of tolerances established in the standards [3].

Variations of the velocity and the impact position in x direction are the ones with more influence in the maximum acceleration and the HPC value in a direct and positive correlation in case of the velocity (Figure 21 and Figure 22) and in a direct and negative correlation in case of x position (Figure 23 and Figure 24).

Looking at the results obtained, e.g. in the case of HPC, it can be observed that small variations of these input variables ($\Delta V=\pm 0.2$m/s and $\Delta X=\pm 10$mm) lead to differences in the HPC value of even 1000 (from HPC≈1400 to HPC≈2400). These variations (allowed range of tolerances established in the standards [3]) can not be detected by experimental tests since the testing system are not allowed performing variations within these ranges under control.

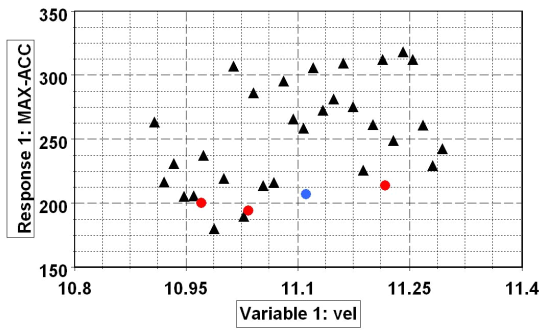

Figure 21. Scatter plot; Point 4 – Acceleration peak [g] vs. Velocity [m/s]

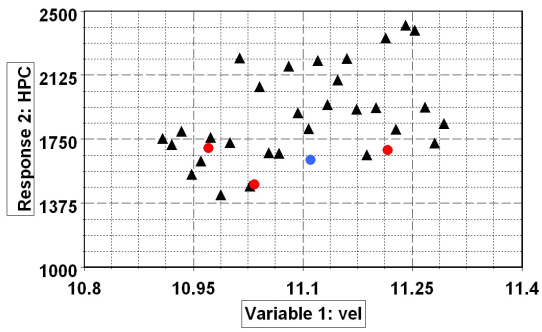

Figure 22. Scatter plot; Point 4 – HPC vs. Velocity [m/s]

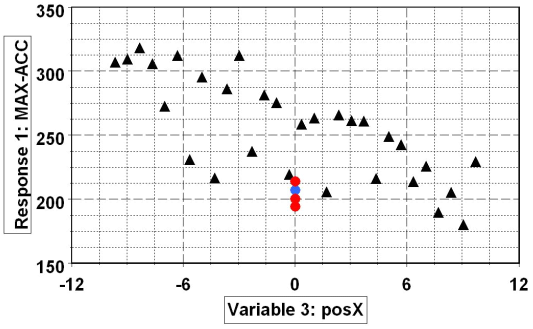

Figure 23. Scatter plot; Point 4 – Acceleration peak [g] vs. x-Position [mm]

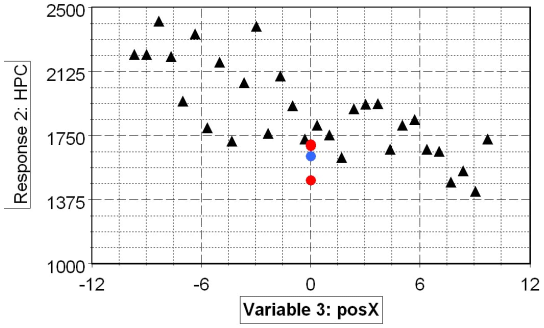

Figure 24. Scatter plot; Point 4 – HPC vs. x-Position [mm]

In this specific case, all HPC values are higher than 1000 so this point would not pass the standards. But there are other cases where this HPC variability is around 1000. So it would be a good point or a bad point depending of the different tolerances achieved in the experimental conditions. Even performing sensitivity analysis via physical tests is not possible to cover a wide range of parameter variations since it would mean among others, high costs and time.

CONCLUSIONS

The pedestrian subsystem tests were chosen in APROSYS SP7 as demonstrator for a Virtual Testing procedure, because virtual testing turned out to be predictive for the pedestrian head form assessment using accurate material and CAD data.

Experimental adult head form impacts against bonnet structures were performed. The test matrix was defined so the level of results variations due to slight variation in testing configuration (sensitivity analysis testing) as well as the level of repeatability for same testing configuration could be analysed. Slight variations in the velocity and angle of impact as well as the impact positions (in x and y directions) were taken into account (Table 1) and their effects on the maximum acceleration and HPC values were studied. On the other hand, four different points of impact were considered (Figure 2) so it was possible to analyse the effects of the variations of the input parameters on the outputs in different impact situations.

At the same time, blind simulations according to the tests carried out were performed. When performing blind simulations the need to provide as much information as possible is essential. But limited data (material, boundary conditions…) from physical test can be provided and no validation results to adjust the nominal simulation model are available.

In order to check if the simulation model predicts closely enough the physical tests, simulation and test results were compared for all cases. Very good correlations were obtained for the reference cases (test conditions according to the Directive 2003/102/EC [1], phase II) in terms of the shape of the acceleration curves as well as absolute peak values (see Figure 4 to Figure 7). This analysis was extended to all the test cases with the variations in the input conditions. For these cases, the accuracy of the models was not so high like in the reference cases. The correlation is very good for the points of impact 2 and 3 but in the case of point 1 the simulation results were overestimated (see Table 2 to Table 4).

In order to provide additional data about the mechanical behaviour of the bonnet and the positioning and kinematics of the head form a new system for measuring three-dimensional deformations was employed. Thanks to this system, deformation contours as well as maximum deformations of the bonnet during the physical tests could be measured and compared with the ones obtained by the simulation model (Figure 9 and Figure 10).

Results of these comparisons (acceleration vs. time curves, HPC values and deformations) pointed out the capability of the simulation model to reproduce the physical tests. It is important to remark that this simulation model was not validated. It was not tuned after comparison with the test results.

Next step was to perform a study of experimental testing variation using stochastic models. The effects of these variations were quantified using stochastic analysis. Four stochastic analysis were performed, one per point of impact. The values of dispersion considered for the impact conditions covers the ones used in the experimental tests at each point.

The stochastic variables more clearly related (linearly and quadratically) to the variability or sensitivity of the responses are clearly the impact

velocity and the position (in x and y directions) being the less related the impact angle in the ranges studied. This has been confirmed by the correlation matrix, scatter plots and global sensitivity rating. Again, this effect is different for the different points of impact selected. Thus, the most relatively sensitive input parameters with global sensitivity rating greater than 0.7 are:

- Point 1: velocity and x-position
- Point 2: velocity and y-position
- Point 3: x and y-position
- Point 4: velocity and x-position

It is very interesting the analysis of the results obtained at point of impact 4. In this case, variations of the input variables taken into account (velocity of impact, angle of impact and position of impact – x and y directions) match with the allowed range of tolerances established in the standards [3]. These variations are allowed when physical tests are performed. Within this study three tests were carried out. The required velocity (according with the standards) is 11.1±0.2m/s and the achieved ones were: 11.03m/s, 10.97m/s and 11.22m/s. These variations in the achieved velocity led to slight variations in the HPC values (see Table 5). Nonetheless, though the stochastic analysis where variations of all the input variables were taken into account, it can be seen that the variability of the results is higher (variations in the HPC value of even 1000 were obtained, see Figure 22 and Figure 24).

Even performing sensitivity analysis via physical tests is not possible to cover a wide range of parameter variations since it would mean among others, high costs and time. Virtual testing covers a wider range of vehicles and boundary conditions not yet available for real testing.

Nowadays, minds are changing progressively towards virtual testing and simulation is already state of the art technology within the automotive industry. Nevertheless, relationship between real testing and virtual testing is globally seen as a necessary coupled approach. Real testing is still needed to demonstrate virtual testing capabilities by comparison to real testing with a necessary feedback. And also virtual testing provide an added value for real testing as it induce improvements of experimental testing.

An important issue for further studies would be to analyse how virtual testing could result in cost reductions and increase competitiveness for European car manufacturers by substituting a range of real tests by virtual testing. And in a step by step process, to study the possibility of a higher content of virtual testing within the existing or within future homologation procedures.

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PREPARING THE FUTURE FOR FUNCTIONAL SAFETY OF AUTOMOTIVE E/E-SYSTEMS

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Paper Number 09-0445

ABSTRACT

The development of different sensor technologies and powerful signal processing procedures allows the automotive industry to develop new E/E-based safety systems, which may assist and protect drivers and also other traffic participants in very complex situations. The complexity of possible use cases for safety systems on the one hand generates on the other hand a variety of feasible safety concepts to prevent these systems from malfunctioning. But which safety concept is adequate for a specific safety system? It is not conceivable to standardize all possible safety concepts, but to give guidelines to the engineers of how to develop new safety concepts; the automotive industry has started to standardize the process of developing safety – related E/E systems. This paper gives insight into the ongoing standardisation work within ISO TC22/SC3/WG 16 functional safety and how companies have started to apply the draft standard and consequently how this standard may initiate the development of a new state of the art within the area of functional safety in the long term.

INTRODUCTION

Safety turns out to be one of the key issues of future automobile development. New functionality not only in the area of driver assistance but also in vehicle dynamics control as well as in active and passive safety systems increasingly touches the domain of safety engineering.
With the trend of increasing complexity, software content and mechatronic implementation, potentially there are increasing challenges from systematic faults and random hardware faults. When is a safety-related E/E-system reasonably well-engineered in order to avoid malfunctions? Being able to answer this question satisfactorily may help to accelerate market introduction of new safety technology.
Standardisation has been started to give guidance to the automotive industry to maintain the very high safety level that has been reached within the last years also for the coming generation of new safety systems. Currently in the state of a committee draft, the upcoming international standard ISO CD 26262 will summarise processes and methods that may help to establish comparable standards of processes within the entire automotive industry. As these standards cover the complete lifecycle of a vehicle it will take some time until the described procedures will have shown their effectiveness in daily work.

Standardization Effort on Functional Safety within the Automotive Industry

In contrast to other industries like aviation, rail or process industry, the topic of functional safety has only started to be discussed in detail a few years ago within the automotive industry. This can be explained by two main arguments. Firstly, the known risks based on failure mechanisms of cars are to a large extent still controllable by a driver. In most cases a driver can bring his car to a safe state by just stopping it. In contrast to that failures during a flight or a release of toxic material in a chemical plant normally lead directly to extremely risky situations. Secondly, the development process of the car industry allows an intensive testing phase with produced cars, before the product can be purchased by a customer. In contrast to that, a plane shouldn't have remaining critical faults already at the very first flight.
Nevertheless the development of new safety systems within automotive industry like active safety systems, driver assistance systems and currently the electrification of the powertrain, lead to new functionality, which is mainly based on E/E-systems. Failures in these systems may have also an impact on vehicle safety, as the competence of these systems is growing. Currently available standards on functional safety like IEC 61508 are not especially dedicated to the automotive industry. An application of the IEC 61508 within different companies would not lead to a harmonization of functional safety, as too many interpretations have to be made. But to reach a harmonized standard

with respect to functional safety should be the goal of normative work. Therefore a Working Group "Functional Safety " has been established within ISO TC22/SC3/WG16 to develop such a standard on functional safety for the automotive industry. 9 countries are actively involved in that working group, i.e. Belgium, Canada, France, Germany, Italy, Japan, Sweden, United Kingdom and USA. Currently a draft international standard ISO DIS 26262 is in preparation and may be expected to be published in Q3/2009.
For all companies not involved so far in that standardization, the publication of a DIS (draft international standard) gives the possibility to apply the standard and to give feedback to the working group via the national standardization bodies.

The Approach of ISO 26262

The standard ISO 26262 is divided into 9 volumes, describing the management of functional safety, core processes within product development as well as supporting processes and "ASIL"-oriented and safety-oriented analyses (see Figure 1). The term "ASIL" leads to the approach of that standard. The Automotive Safety Integrity Level (ASIL) is derived by doing hazard analysis and risk assessment. Right at the beginning of a development the intended functions are analyzed with respect to possible hazards. What may happen if malfunctions arise within different operational situations?
The estimation of risk, based on a combination of the probability of exposure, the possible controllability by a driver and the possible severity outcome of a critical event, leads to an ASIL, which will be given to a corresponding safety requirement that will be generated to avoid this risk.
There are four possible levels (A,B,C or D) of an ASIL to specify the requirements of this standard and safety measures for avoiding an unreasonable residual risk with D representing the most stringent and A the least stringent level.

How to integrate a safety process into an installed E/E development process

As outlined above, the ASIL attribute is used to give guidance for choosing adequate methods, procedures, etc, within the necessary steps in an E/E development process, production and after sales in order to reach a certain level of integrity of the product.
Does the introduction of a process for functional safety change the complete E/E development? Certainly not. Currently used processes show, that cars are manufactured with a very high safety level. The standard ISO 26262 aims to give guidance for complementing current processes, which are used for safety-related systems.

How to get started with ISO 26262

The main challenge is to get started with a new standard. Changing running processes during a development is very difficult in practice and cannot always be recommended.
Companies which have started to apply the ISO committee draft have experienced the challenge to implement the new requirements. Usually pilot projects are chosen to demonstrate the changes due to the ISO 26262. The experience shows that the tasks within a concept phase according to ISO 26262 are quite easy to be applied. Moreover we can already state that the tasks of doing hazard analysis and risk assessment as well as deriving functional safety concepts right at the beginning of a development are seen as very valuable tools to create stable safety concepts. A stable concept already designed in the concept phase is also seen to reduce potentially the effort of eliminating remaining faults in later phases.
More difficulties for implementing the ISO 26262 requirements arise within later development phases. Mainly due to the integration topics of a pilot project into an environment, that has not yet been developed to the same standard. In future car line projects many of these problems will be solved, because the aim is to have the complete car developed to the same standard. But still also a new car line is not completely a new car. There are still many basic systems that won't be changed from former car lines. And systems that are already installed in millions of cars showing, that they are proven in use should not be changed just for fulfilling a new standard. This problem has also been addressed within the ISO 26262. Systems that will be used without changes in following projects are still in line with the ISO 26262, if they have shown their integrity already in the fleet. That means that the full alignment to the ISO 26262 standard will take time until all E/E safety-related systems in a car will be developed accordingly. For the companies that are starting with implementing ISO26262 it is important to understand the guiding idea of this standard. Try to analyse the possible malfunctions of your system right at the beginning of a development, setup the corresponding safety requirements and make sure that these requirements are fulfilled during the development and following phases. And do not forget the good engineering judgement. As the experience of companies that have already started with applying the ISO 26262 draft version show, getting started with it will still afford many times the good engineering judgement to integrate the guiding idea of ISO 26262 into the currently used processes.

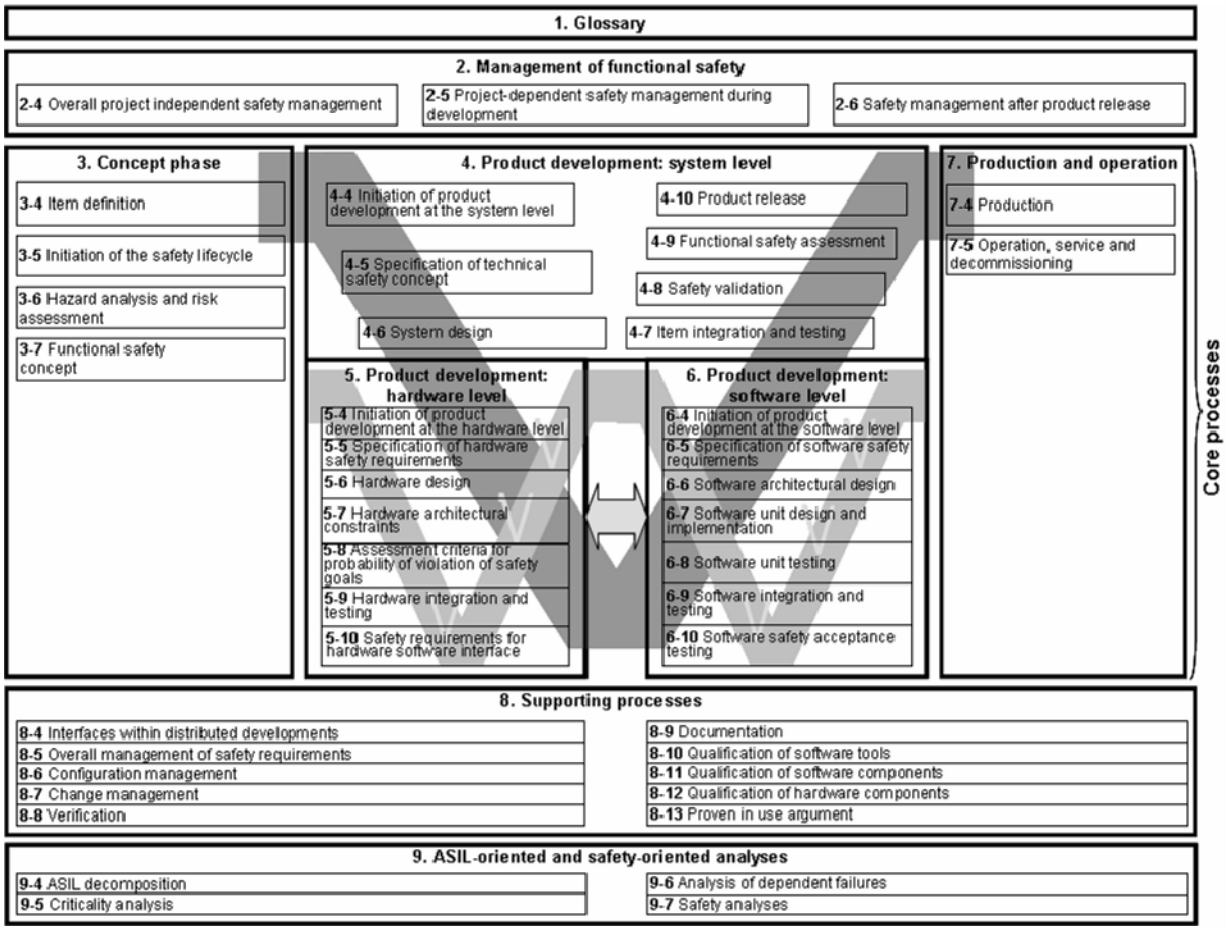

Figure 1. Overview of ISO 26262-1 to -9

CONCLUSIONS

With the upcoming publication of the automotive draft standard ISO DIS 26262, the automotive industry initiates the development of a new state of the art within the area of functional safety. Companies that have already experienced the application of preliminary draft versions within pilot projects can state the valuable benefit of using the described methods to systematically create safety concepts. As this standard is a process standard, it will take some time until this standard will be fully integrated into the existing E/E-processes. The combination of carry over systems and new systems will also imply that not all systems in a car line need to be developed according to the same standard. In case of constellations that are not explicitly described in the ISO 26262, it is important to understand the guiding idea of the standard and to use the good engineering judgement to steadily improve the processes used for safety-related E/E systems. If the ISO 26262 is understood as a means to improve functional safety and not as a burden in terms of a bundle of requirements that have to be fulfilled additionally, the benefit will be seen very soon.

Using the standard with the right attitude may lead the automotive industry to a new state of the art in the area of functional safety in the long term.