RUN OFF ROAD SAFETY

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ABSTRACT

Run off road events are frequent and can result in severe consequences. The reasons for leaving the road are numerous and the sequence the car is subjected to differs in most events. The aim of this study is to holistically address safety improvement in run off road events, presenting methods for evaluation as well as examples of countermeasures for the whole sequence from normal driving to post-crash.

Real world data, comprising statistical and in-depth crash data as well as driving data from Volvo Cars' database in Sweden, forms the basis for understanding of influencing factors and mechanisms related to occurrence of the event as well as occupant injury. Countermeasures are presented along with the test methods which were developed based on the mechanisms identified. The test methods include road off road avoidance test methods, complete vehicle crash tests, and rig tests; such as occupant positioning using a robot rig and vertical loading tests using a drop tower rig.

Countermeasures addressing run off road safety are developed and verified using the identified test methods and integrated into vehicle design. Examples of systems addressing road departure avoidance aspects are Driver Alert Control and Lane Keeping Aid. Countermeasures specifically addressing occupant protection are occupant positioning by detecting run off road events and activating an electrical reversible safety belt pretensioner, as well as unique energy-absorbing functionality in the seat. Post-crash measures are enhanced by added activation of eCall in some run off road scenarios.

Optimally, avoiding the run off road is most beneficial and this study provides some initial steps illustrated by production systems. However, if run off road occurs, one priority is to reduce vertical occupant loadings when landing on the wheels after a free-flight, a rollover or when going into a ditch and impacting an embankment. This type of loading could result in thoracic-lumbar spine fractures. The design of the unique energy absorbing functionality in the seat, put into production 2015, will help provide important enhanced occupant protection. Additionally, injury outcome is influenced by the occupant position during the event: head and arms flinging around impacting the interior, bent postures reducing the tolerances of spinal injuries, and sub-optimal occupant positioning relative to protection systems. The unique run off road detection and safety belt pretensioning early in the events, together with the seat backrest's side supports, will assist the occupant to stay positioned during the event and help improve protection.

This study is based on a holistic approach to safety, covering the whole event from normal driving to crash care, introducing world first production technology enhancing occupant protection in these diverse and complex events. It goes beyond standardized safety evaluation of today and it provides an illustrative example on how safety systems can take action across the entire crash sequence and the interaction of different types of systems adding to the effect of addressing real world protection needs.

INTRODUCTION

Run off road events are frequent and can result in severe consequences. In the United States, single vehicle roadway departure crashes accounted for about 20% of all police-reported crashes (Wang and Knipling, 1994). In Germany, 33% of all fatal crashes were run off road crashes (Statistisches Bundesamt, 2011). In Sweden since 2003, single car crashes is the most common type when it comes to fatal accidents (Hillerdal, 2011). Injuries can be sustained to any body part (Jakobsson et al. 2014). Among injury types highlighted as related to run off road events are thoracic and lumbar spine injuries. Although found in all crash situations, Jakobsson et al. (2006) showed that AIS2+ thoracic and lumbar injuries were mostly found in multiple events; a high proportion of the cases being run off road crashes.

Occupant posture, such as forward bending was highlighted as an influencing factor, with the injury mechanism of spinal axial loading with different degree of flexion leading to compression and anterior wedge fractures, especially seen in run off road events with complex occupant kinematics.

In the context of crash avoidance, numerous test methods and evaluation procedures address situations triggering potential run off road crashes, such as sleepiness (Anund et al., 2009 and 2011, Fors et al, 2013) and distraction (NHTSA, 2010, Hanowski, 2011, Fitch et al. 2013). Additionally, test methods evaluating specific technology such as Electronic Stability Control (ESC) and Lane Departure Warning (LDW) are found within legal and public domain testing. However broad test methods addressing run off road safety effectiveness on multiple factors influencing causation (driver behaviors, friction, weather, etc) in the avoidance phase are scarcer, although first steps are taken e.g. within the Advanced Crash Avoidance Technologies Program at NHTSA (Gordon et al., 2010).

Leaving the road can result in a variety of more or less complex events. While some vehicles quickly come to a rest position without any severe event, other vehicles leave the road into a free flying event, landing on the wheels or continue into a roll or turn-over event or interact multiple times with the environment. In-depth studies in Austria highlight the effect of guardrails leading the vehicle to "take off" as well as vehicles jumping into road side objects such as traffic sign poles or overpasses (Tomasch et al., 2010). Jakobsson et al. (2014) reported that important mechanisms addressing run off situations include drifting and avoidance of animals on the road. Being a complex event, not one single test method addresses this whole area of concern. Some parts of some events, such as skidding sideways and impacting a tree, are addressed in standardized lateral pole impact tests. Additionally, standardized frontal barrier tests address parts of events ending up into a large rock or a brick wall. However, neither influence of potential change in occupant posture before impact, nor reasons for leaving the road are covered in these standardized crash tests.

Addressing run off road safety poses a variety of challenges, ranging from understanding the reasons for leaving the road to means of evaluating the potential injury outcome, all put into the overall context of run off road safety. The objective of this study is to address run off road events, presenting methods for evaluation as well as examples of countermeasures addressing the whole sequence from normal driving to post-crash. This is done by summarizing influencing factors and mechanisms to target when developing test methods; and briefly presenting some newly developed test methods along with production systems/technology addressing run off road safety.

INFLUENCING FACTORS AND MECHANISMS

Based on real world data, crash causation mechanisms and injury causing mechanisms were identified and presented by Jakobsson et al. (2014). The purpose of these mechanisms was to, in a structured way, address the complex and diverse area of run off road safety and to guide development of test methods with a holistic approach.

There are several reasons for leaving the road exemplified by driver distraction, sleepiness and fatigue, inadequate speed and vehicle interaction in relation to the traffic situation and maneuver for avoidance of animal crashes and other objects on the road (Najm et al., 2002, Liu and Subramanian, 2009, Jakobsson et al., 2014). Factors potentially influencing crash causation of run off road events are essential to take into account in test method developments targeting evaluation of road departure avoidance.

For the run off road situations, especially occupant kinematics as well as occupant retention were highlighted and differ from on-road occupant protection situations. The occupant kinematics, longer duration and less acceleration as compared to on-road crashes, exposes especially the upper extremities and the head for non-optimal positions from a protection point of view. Occupant retention addresses the upper body positioning during the run off road event.

Several potential injury causing mechanisms are seen during the wide and diverse types of events. Analyzing real world data, Jakobsson et al. (2014), highlighted the different types of environments, such as rough terrain, ditch types and whether multiple events occur, as important mechanisms contributing to the occupant injury. Numerous different impact objects are probable as well as differences in impact configuration, including complex rollover events. Complex vehicle kinematics due to the run off road environment, occupant kinematics and occupant retention affect the occupant posture which depending on the impact, influences the occupant injury consequences in run off road crashes. Important occupant protection mechanisms concern impacts to interior structures, vertical loading on the occupant through the seat, as well as keeping the occupant in a favorable position during the event (Jakobsson et al. 2014 and 2015).

TEST METHODS

Based on the identified factors and mechanisms, a variety of test methods were developed to address occupant protection aspects as well for evaluating technology assisting the driver to stay on the road. The whole context is described in Jakobsson et al. (2014) and the test methods specifically addressing the countermeasures presented in the present study will be covered in this chapter.

Road Departure Avoidance Test Methods

Systems addressing road departure avoidance aspects, such as Driver Alert Control (DAC) and Lane Keeping Aid (LKA), are tested with virtual methods, simulator tests as well as test track and on-road tests. Driver representation is important in all types of test methods. Depending on the level of critical event and repeatability issues, the choice of method is made.

The virtual test methods consist of virtual representations of the driver as well as the vehicle and environment (Gordon et al., 2010; Markkula, 2015; Benderius, 2014). The driver model is designed based on knowledge from testing with drivers in specific real world situations, and can be more or less advanced, depending on the application. Virtual test methods allow that a large number of tests can be performed using the same model just varying the vehicle systems or the environment. Other benefits are the possibilities to use it in early phase technology developments.

In tests evaluating warnings (e.g. Driver Alert Control) and vehicle interventions to prevent road departures by drifting (e.g. LKA), driver reactions on these warnings and interventions are evaluated. The driver reactions can be tested both on test tracks and in driving simulators (Petersson and Svanberg, 2013) while the whole run off road scenario only can be tested in a driving simulator for test repeatability as well as safety reasons. Data from the test track tests can be used to build a driver model to incorporate into a virtual test method, which provides an additional tool beneficial when evaluating a large number of specific scenarios of e.g. run off road speeds and angles. The evaluation target in this testing is to avoid road departures as such, with a special focus on the drifting behavior.

The Driver Alert Control and Lane Keeping Aid systems target pre-crash driver states such as sleepiness, fatigue and distraction as these are identified as important pre-crash parameters in run off road crashes. Test methods evaluating these aspects comprise test track and on-road testing and using driving simulators. For sleepiness testing the set-up is usually a several hour long drive on a highway (speed limit 110km/h) where the driver just drives the car, with no critical situations or distraction tasks induced. The tests can be designed using different levels of sleep deprivation (over several days) and the characteristics of the participants are carefully selected. The evaluation target during the test is typically to decrease the time driving in a sleepy state. For distraction testing, the driver is asked to repeatedly perform a number of secondary tasks sequentially, exemplified by using in-vehicle HMI, such as phone or radio. The evaluation target is to increase drivers' eyes-on-road and reduce glances over a certain duration time on the secondary tasks. A description of a related test method is described in Ljung Aust et al (2013).

Occupant Protection Complete Vehicle Test Methods

Three complete vehicle crash test track methods, called Ditch, Airborne and Rough Terrain were developed to simulate some main run off road vehicle kinematics potentially causing occupant injury. These methods can be used for evaluating the consequences of combination of low acceleration and high acceleration parts of the event on vehicle and restraint system performance as well as provide insight into potential occupant kinematics. The tests were run at Volvo Cars Safety Centre in Sweden, using Test Track 2 which is a moveable covered test track with semi-directional electrical propulsion system. The tests were run towards the outdoor crash test environment, where different run off road scenarios are built. The car is launched from the test track, just before entering the run off road scenario, by a position triggered system. Crash test dummies are used as human representation in the tests. Important feature of a crash test dummy for this purpose is good flexibility in shoulders and upper body, hence the Thor dummy with modified shoulder (Törnvall et al., 2008) was used.

During the Ditch method the vehicle is launched at 80 km/h and drifts with an angle of 12-15 degrees into a ditch (Figure 1). The ditch is 80 cm deep with a slope of 30-40% from the road surface. Approximately 20 m after leaving the road, entering the ditch and traveling along the bottom of the ditch, an embankment is reached forcing the vehicle into an upward motion. The embankment has the same slope as the ditch, and represents a crossing road. This test method captures the characteristics seen in real world cases when the vehicle is drifting into the ditch in a rather narrow angle, travels in the ditch, thereafter impacting an embankment leading to underbody interaction to ground, causing high vertical loading into the occupant through the seat.

During the Airborne method the vehicle is launched at 50-80 km/h leaving the road in a range of angles (30 degrees in Figure 1) into a steep slope introducing a phase of free flight of the vehicle, before landing on smooth surface and continue onwards. The height difference is 80 cm, resulting in a hard impact on the wheels, causing vertical forces.

During the test method called Rough Terrain the vehicle is launched at 70-80 km/h perpendicular from the road into a rough terrain environment (Figure 1). The rough terrain causes a bumpy ride producing substantial lateral vehicle motions (rolling motions) in combination with vertical and longitudinal vehicle motions.
In all the three crash test track methods, the occupant will be subjected to acceleration changes in different directions and intensities through the event, due to the vehicle kinematics in several directions simultaneously. This could expose the different parts of a restrained occupant (especially the upper extremities and head) to potential impacts to the interior, partial ejection as well as changes in upper body positions posing the spine into flexed postures.

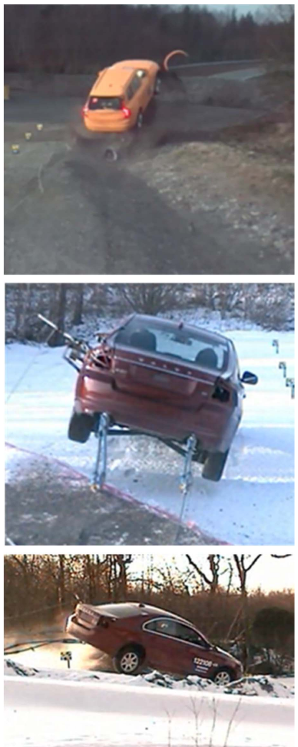

Figure 1. The complete vehicle Run off road crash test methods; Ditch (top), Airborne (middle) and Rough Terrain (bottom).

Occupant Protection Rig Test Methods

Rig test methods were developed to replicate sequences from the whole vehicle test methods in a repeatable and reproducible way. The two main areas of interest were the occupant kinematics when subjected to varieties of loading directions and intensity, and the vertical occupant loading. Two rig test methods were designed to address these two areas.
A robot controlled test setup, called 'Robocoaster', was used to simulate occupant kinematics. It provides a flexible and multi-purpose test set-up evaluating occupant positioning and occupant retention. A vehicle seat and restraint system is mounted on a multi-axial robot (ABB IRB 6600 industrial robot) and can be used together with a crash test dummy (Figure 2). The robot can be programmed to, in repeatable manner, simulate the occupant kinematics in one of the three test track methods, or any variations of a run off road crash, within the limitations of the robot used.

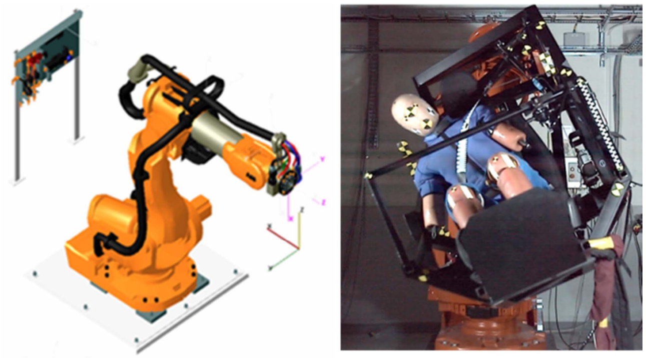

Figure 2. Rig test method 'Robocoaster'.

A rig test method simulating the vertical loading through the seat was developed (Figure 3). It provides a simplified and repeatable test set-up for vertical occupant loading, which can occur at hard landing on the wheels after a free flight or during the undercarriage interaction, e.g. with the embankment in the Ditch method. A seat is attached to a frame which moves on vertical rails on a drop tower. The desired vertical acceleration in the physical test set-up is achieved by releasing the frame from a specific height and stopped using the deceleration-sled principle of bending steel. The rig test method also has a virtual counterpart. A crash test dummy is positioned in the seat during test. For the physical test, a HIII 50%-ile male dummy is used while in the virtual test-set up the BioRID (50%-ile male) is used. The z-component of the pelvis accelerometer is monitored and used as the injury criteria measure 'vertical occupant acceleration'. The test method is described in detail in Jakobsson et al. (2015).

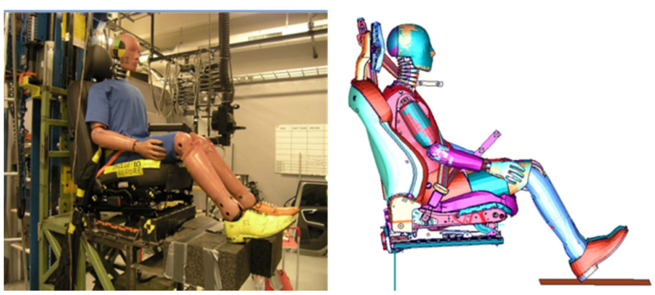

Figure 3. Rig test methods for vertical occupant loading; physical test setup (left) and virtual test setup (right).

COUNTERMEASURES

Countermeasures addressing run off road safety, which are integrated into vehicle design, were developed and verified using the test methods. As illustrated in Figure 4, the countermeasures address run off road safety in a holistic way. Examples of production systems addressing run off road avoidance aspects during normal driving are Driver Alert Control and Lane Keeping Aid. Countermeasures specifically addressing occupant protection are occupant positioning by detecting run off road events and activating an electrical reversible safety belt pretensioner, as well as unique energy-absorbing functionality in the seat. Post-crash measures are enhanced by added activation of eCall in some run off road scenarios.

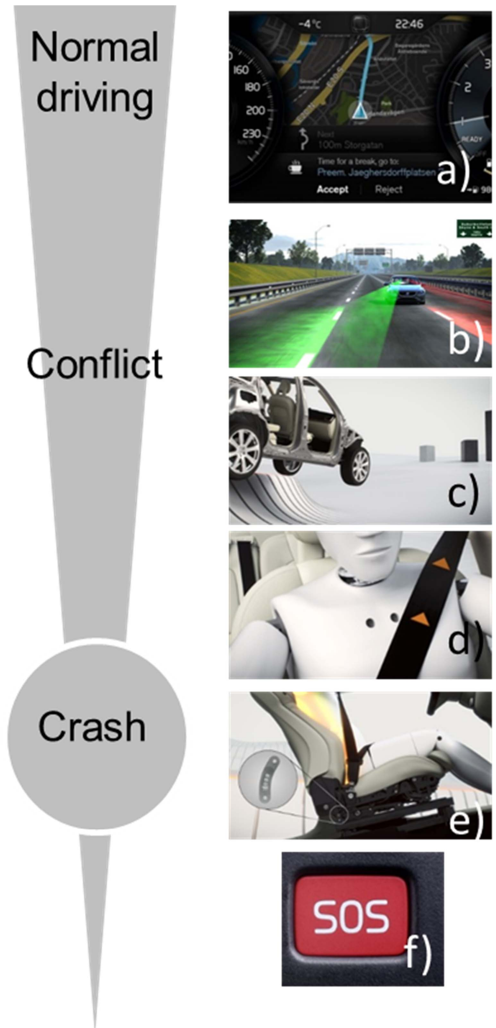

Figure 4. Holistic approach including countermeasures; Driver support system exemplified by a) Driver Alert Control with Rest Stop Guidance and b) Lane Keeping Aid, occupant protection systems exemplified by c) run off road detection, d) electrical reversible safety belt pre-tensioning and e) energy absorbing functionality in seat, and f) post-crash measure such as eCall activation.

Driver Alert Control detects and warns tired or inattentive drivers. In the 2015 Volvo XC90, it is enhanced with a new Rest Stop Guidance (Figure 4a), which directs the driver to the nearest rest area. Lane Keeping Aid (Figure 4b) helps the driver stay on track by applying extra steering torque if the car is about to leave the lane unintentionally. As a post-crash measure, eCall offers safety benefits in providing information to the Call Center who can contact the occupants in the car as well as call for assistance when needed (Figure 4f). Real world activation of eCall is dependent of detection capabilities including interpretation of the detection. Conventional triggering of eCall is based on activation levels for pyrotechnical devices, e.g. pretensioners and airbags. Triggering in situations beyond those requires knowledge of the event. Run off road events are challenging being diverse and complex. The test methods developed and presented in this study provide such knowledge and have been used to further refine the eCall activation capabilities included in the 2015 Volvo XC90.

For occupant protection, controlling the occupant position together with the energy absorbing functionality provides benefits in a large range of situations. By keeping the occupant in an upright posture while cushioning a potential vertical enables a combined benefit since the spine in more tolerable when straight. The details on detection algorithm and activation logic, as well as the electrical reversible safety belt pretensioner and seat design are presented below.

Detection Algorithms and Activation Logic

The new detection algorithms in the restraint control module are able to detect new run off road scenarios, such as Ditch, Airborne, and Rough Terrain. This is enabled by using sensor data from the vehicle's restraint control module along with information from the vehicle bus. As compared to prior vehicles, no hardware is added, while extensive work on algorithms has been carried out. A major challenge is to address all relevant real world crash scenarios and take action to help protect the vehicle occupants accordingly. The sensor functionality is an important step towards addressing crashes beyond the standardized crash test methods. In order to make this happen and to control the triggering, data from complete vehicle real world like events are necessary. Hence, the development of the complete vehicle test methods was essential for this important functionality. Sensor data gathered from the complete vehicle crash tests was taken as input to the calibration process, wherein algorithm parameters were tuned in multiple simulation loops. The input data set included both scenarios where activation of one or more protection components is required (Fire tests), and scenarios where there shall be no activation of protection components (No Fire tests), in order to assess the robustness of the algorithm methods and the calibration. The development of detection algorithms and activation logic is further described in Nilsson et al. (2014).

Electrical Reversible Safety Belt Pretensioner

If a run off road scenario is detected, an electrical reversible safety belt pretensioner is activated, provided the occupant is belted. The safety belts are electrically tightened to retract and keep the occupants in position (Figure 4d). The electrical reversible pretensioner has two force levels, which are used depending on the estimated severity of the scenario (i.e. medium force in low severity events, high force in high severity events). Full retraction is achieved within 250 ms, belt force is up to 300 N, and the belts are kept firmly tightened as long as the car is in motion. Once the run off road scenario has ended, as determined by global acceleration level, the belt tension is released. The electrical reversible pretensioner forces are strong enough also to retract forward leaning occupants (Lorenz et al. 2001, Develet et al. 2013).
In case of a sufficiently severe secondary impact in the course of a run off road scenario, e.g. to a tree, an embankment, another obstacle or a rollover event; the pyrotechnical safety belt pretensioners will be activated on all seven seating positions, provided the occupants are belted. Additionally, other restraints, such as airbags and inflatable curtains will be activated when needed.

Seat Design

An important part of the run off road safety package is the all new seat design as introduced in the 2015 Volvo XC90. The protruding side bolsters of the seat backrest helps to provide occupant support together with the safety belt retraction. The seat has been designed addressing spinal protection in case of a vertical load through the seat. A deformation element is built into the inner rear part of the seat connection to the seat frame. In case of vertical loads, the seat will slide in the slot while deforming the deformation element (Figures 4e and 5). The deformation element allows for a controlled vertical deformation of up to 25 mm. The space under the seat is cleared to allow for total occupant movement up to 150 mm. This movement is achieved mainly by compressing the seat foam and extending the springs in the seat cushion, which together with the deformation element provide energy absorption. The deformation element is triggered by force during the event. The force is dependent on occupant weight in combination with acceleration amplitude and direction. Vertical forces of a certain limit will trigger the deformation of the element as well as allow the occupant to move into the seat cushion. These vertical forces can occur in rollover events when landing on the wheels, as a result of a free flight event or any other crash sequence where there is a vertical force component, such as in the Ditch test situation. The deformation element also plays a part in the Whiplash protection system (WHIPS), activated by the torque occurring when the occupant sinks into the seat backrest during the rear end impact event.

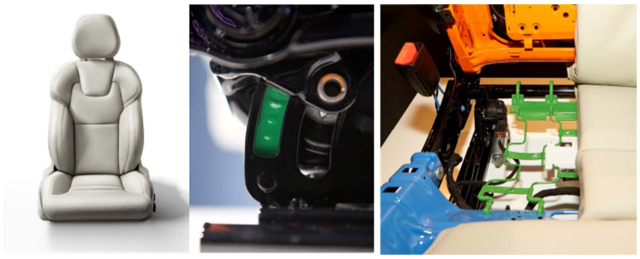

Figure 5. Overview of seat design including side bolsters (left). Close-up views of energy absorption functionality; side view of deformation element (middle), top view of seat cushion including springs (right).

Figure 6 shows a comparison of vertical occupant acceleration, comparing the new seat design to a prior Volvo seat, available in e.g. Volvo S40, XC70, S80, S60 model years 2011-2013. The rig test method for vertical occupant loading, simulating a sequence from the embankment interaction during the Ditch whole vehicle test, is used for this comparison. The seat is exposed to a maximum acceleration of approximately 90m/s2, pulse duration about 100ms and 'change of velocity' of 6,5m/s. In this loading situation, the vertical occupant acceleration is reduced by 32% in the new seat design as compared to the reference seat. The chosen situation is representative of a situation where spinal injuries can occur in real world crashes.

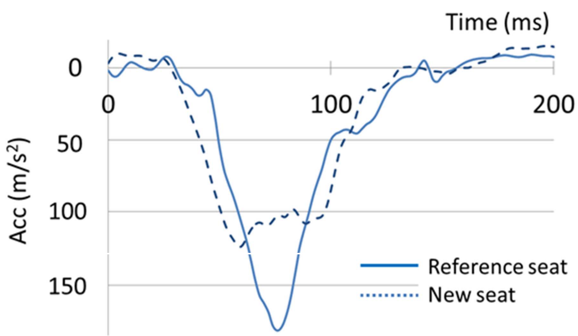

Figure 6. Pelvis vertical acceleration comparing new seat and reference seat using the virtual loading rig test method (Jakobsson et al. 2015).

DISCUSSION

This study addresses the area of run off road events which has, up until now, been in limited focus within automotive development. Test methods as well as countermeasures addressing the whole sequence in run off road events present a first step within this area and will help to reduce real world consequences. The study presents a holistic approach, including production systems addressing run off road avoidance aspects during normal driving, countermeasures specifically addressing occupant protection post-crash measures.

A holistic approach is necessary when addressing run off road safety. The reasons for running off the road are several and the characteristics of the events are numerous. The way behind this study was to base the knowledge of real world situations, identifying influencing factors and possible mechanisms, developing test methods and by this creating both a deeper understanding as well as countermeasures. This process is described further in Jakobsson et al. (2014).

Optimally, avoiding a run off road event is most beneficial and this study provides some initial steps illustrated by the Lane Keeping Aid and Driver Alert Control production systems. Further steps are needed to address all the reasons for running of the road and offer support in those situations. In addition, prototype road departure avoidance technologies have been presented, however so far not ready for production. The challenges mainly concern detection issues; identifying the large variety of different types of road edges and to separate them from e.g. cracks and other damages on the road.

Figure 6 shows that by adding energy absorbing functionality in the seat together with improved clearance under the seat, vertical occupant acceleration can be substantially reduced in situations where thoracic and lumbar spine injuries could occur in real world situations (Jakobsson et al. 2015). Combining this with keeping the occupant in an upright posture will help reduce spinal injuries even further. Injury outcome is influenced by the occupant position during the event: head and arms flinging around impacting the interior, bent postures reducing the tolerances of spinal injuries, and sub-optimal occupant positioning relative to protection systems. The unique run off road detection and safety belt pretensioning early in the events, will assist the occupant to stay positioned during the event and help improve protection. This is a robust way of addressing occupant protection in run off road situations, keeping the occupant in a controlled position, enabling the protective safety systems to help the occupant in different upcoming events.

The present study goes beyond standardized safety evaluations of today. Firstly, it is an area that still is to be addressed in regulatory and consumer testing. Secondly, it combines in an effective way safety of the total sequence of an event; including active, integrated and passive safety technology. Both of these are necessary in order to improve the relatively large amount of injuries occurring in these types of events. Obviously, run off road being complex and diverse events, a limitation of this study is that not all events and potential consequences are addressed. However, the approach of this study and methods developed based on influencing factors, provide a path to build further studies and countermeasures on. Going beyond standardized safety evaluation of today, it provides an illustrative example on how safety systems can take action across the entire crash spectrum and the interaction of different types of systems adding to the effect of addressing real world protection needs.

CONCLUSIONS

This study is based on a holistic approach of safety, covering the whole event from normal driving to crash care, introducing world-first production technology enhancing occupant protection in these diverse and complex events. It goes beyond standardized safety evaluation of today and it provides an illustrative example on how safety systems can take action across the entire crash spectrum and the interactive play of different types of systems adding on the effect of addressing real world protection needs.

Unique test methods including complete vehicle run off road crash tests, and rig tests addressing occupant positioning and vertical loading using a robot rig and a drop tower rig, respectively, are developed to evaluate the countermeasures as introduced in the 2015 Volvo XC90. The world-first run off road protection package includes detection of run off road events and activation of an electrical reversible safety belt pretensioner, together with unique energy-absorbing functionality in the seat. The cascade of countermeasures covering the whole event from normal driving to crash care systems, also including systems acting to avoid crashes such as Driver Alert Control and Lane Keeping Aid as well as added activation of eCall will provide improved safety in an important number of run off road events.

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