Large Animal Crashes: the Significance and Challenges

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Abstract Crashes with large animals pose demands on vehicle design beyond standardised crash test methods. In some parts of the world, crashes with large animals are frequent and involve a relatively high risk of injury. The objective of this study is to identify the significance of the occurrence and the challenges of crashes with large animals, including evaluations using a crash test method simulating a vehicle-to-large animal crash. Statistics identify several important factors, such as impact speed, impact configuration, environmental factors and driver awareness. Occupant injuries of special focus are injuries to head, neck and upper extremities both by penetrating roof structure parts and by interaction with the large animal body, and cuts and scrapes by splintering glass or sharp edges. Tests using a large animal dummy illustrate the importance of structural integrity of the header and A-pillar area, as well as vehicle speed at impact. An increased impact speed not only drives the structural intrusion depth but also influences the timing of head impact towards the deformed area. As a complement to structural and restraint designs, future safety development challenges also include aspects of detecting and sensing large animals addressing occupant protection by mitigating and potentially avoiding the crash.

Keywords car crashes, crash statistics, large animals, moose dummy.

I. INTRODUCTION

The Insurance Institute for Highway Safety (IIHS) reports that in the USA during 2000–2007, about 1,500 people died in road crashes involving animals and that the numbers have increased over the years [1]. Furthermore, the proportion of fatal animal vehicle crashes is increasing per year, as seen using US fatality data, NASS FARS [2-4]. The Highway Loss Data Institute (HLDI) reports that the claim frequency and claim severity of animal strike has risen over the years in the USA, with a significant peak occurring in November [5]. Moreover, insurance companies in Australia have also reported a large increase in occurrence and cost [6]. A Canadian study estimates that vehicle-to-large animal collisions may cost society in general more than $200,000,000 annually, also confirming a rising trend [7].

In Sweden, during 2014, more than 46,000 crashes with animals were reported, of which 5,037 crashes involved moose [8]. On average, the large wild animal density (eg. mooses and deers) in Sweden is such that when driving at 90 km/h, you pass a large animal closer than 300 meters from your car every 23 seconds. A Canadian study estimates that probably between 4 and 8 large animal–vehicle collisions take place every hour in Canada [7].

The reasons that vehicle-to-animal crashes have severe consequences are due to a combination of crash types: a car striking an animal, then running off the road and hitting an object or overturning; or a direct crash resulting in the animal going through the windscreen [9]. A large proportion of injuries from animal–vehicle crashes in the US involve deer [9]. In Europe and Canada, moose and deer have been shown to be a considerable problem on the road [10-11]. In Saudi Arabia, collisions with camels are more prominent [12-13]. While in Australia, kangaroos and wallabies are the predominant animals involved in road crashes [6]. Bashir and Abu-Zidan [14] summarised that the mechanisms and patterns of human injuries caused by vehicles in different large animal crashes have similarities as well as differences. Injuries caused by kangaroos and deer are usually mild, whereas camels falling on the roof of the car cause cervical spine and head injuries to the occupant. The moose causes a typical rear and downward deformability of the vehicle roof.

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Vehicle-to-animal crashes usually occur in rural areas, during autumn, on straight roads, in clear weather, during dawn, dusk or night when animals appear suddenly [2-3][6][9]. The influence of vehicle speed on injury outcome has been highlighted in several studies [15-18]. In a Swedish study that analysed 667 real-world moose–passenger car crashes between 1995 and 2010, 90% of the severe or fatal injured cases were on roads with posted speed limits of 80 km/h or higher [18].

Based on 396 injured occupants of Volvo cars that were involved in large animal crashes in Sweden, Lövsund et al. [19] found that seatbelt usage significantly decreased risk for severe injuries. Also, two major injury-inducing mechanisms were identified: direct contact between the passenger's head and moose body; and glass splinters from the windscreen inducing face and arm injuries. A similar study was performed by Björnstig et al. [20] and concluded that the injuries were usually caused by the impact of the moose on the windscreen and front part of the roof, the severity of the injuries correlated with the extent of deformation in that area. Head and neck injuries dominated, especially among fatal injuries. Several other studies confirm that the most frequently injured body regions in vehicle-to-large animal crashes are the head, neck and arm [18][21][22].

Several general strategies to reduce vehicle-to-animal crashes have been proposed, including driver behaviour, animal behaviour by road area design, ITS devices and animal repellents, as well as reducing the number of animals [6][23]. Also, vehicle measures to extend the driver's view forward, such as dynamic control of the forward headlight pattern, night vision systems, remote sensing technology that detects animals, are suggested as well as technology to reduce vehicle speed prior to impact [2][9][11]. Addressing vehicle-to-large animal crashes specifically, the improvement of the vehicle crashworthiness, such as stronger glass, stronger roof and stronger support structures, especially A-pillars and header area, are proposed [9][18-20].

A typical Scandinavian moose (latin: *Alces Alces*), sometimes called an elk, is a large member of the deer family. A newborn moose weighs about 10 kg and a full-grown male might, in rare cases, weigh up to 1,000 kg, but with an average of between 300 kg and 400 kg. The moose's long and slim legs pose special compatibility issues when interacting with a passenger car, as illustrated in Fig. 1. The dimensions of a typical moose are about 1 m up to the underbelly, the centre of gravity is 1.35 m above the ground and with a total height of about 2.35 m. Some of these characteristics are shared with other animals, such as horses, large deer, cattle and camels, making this a global concern [14].

To better understand the kinematics and mechanisms of a large animal-to-passenger car crashes, a staged collision with a passenger car impacting a moose cadaver was performed in the mid-1980s [19][24]. Figure 2 shows the kinematics of the moose during the first 160 ms of the event. Most interaction occurs between the animal and the area of windscreen, A-pillar and header. Lövsund et al. [19] emphasise that the moose body enters further into the compartment than the car-body header is deformed during the dynamic event.

Fig. 1. Typical moose dimensions, put in relation to a passenger vehicle.

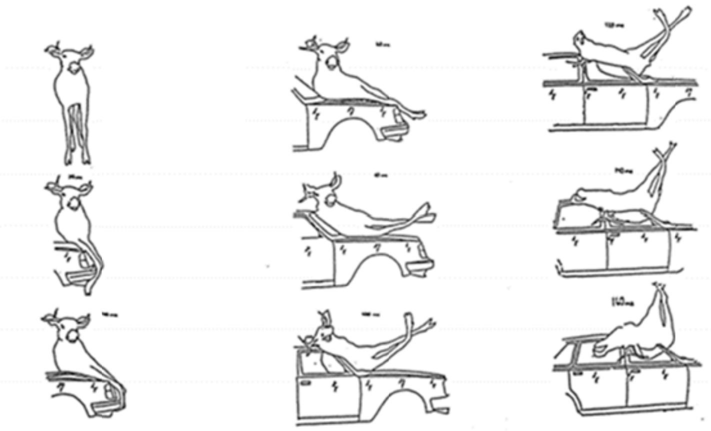

Fig. 2. Vehicle–moose interaction, up to 160 ms. Reprinted with permission from [19].

The moose cadaver test was used to develop the second-generation moose dummy. This dummy was made of 20 impermeable compartments of high pressure hoses containing water [19]. The first generation of moose dummy was made of electrical wires in bundles, with a wooden beam for spine [25]. The second-generation dummy was further developed into a third-generation dummy consisting of a total of 114 rubber discs connected by steel parts [26]. This moose dummy has been thoroughly evaluated and implemented into a test method [16]. In 2011 a test series of five vehicles was run using this test method [18]. Beside these activities, no standardised test method drives the safety development for occupant protection in crashes with large animals.

The objective of this study is to identify the significance of the occurrence and the challenges of crashes with large animals, including evaluations using a crash test method simulating a vehicle-to-large animal crash.

II. METHODS

This study combines real-world crash data and complete vehicle crash testing, focusing on the importance, significance and challenges of vehicle-to-large animal crashes. The real-world data comprises statistics of real-world crashes and in-depth studies of representative vehicle-to-large animal crashes that identify influencing factors and typical scenarios. This knowledge is fed into an understanding of the mechanisms and relevance of test set-up design, as well as providing input on occupant protection, including vehicle structural performance. Complete vehicle crash tests are run physically as well as virtually, using a large animal dummy that is representative of real-world vehicle-to-large animal crashes. Influences of vehicle design and impact speed are studied to gain knowledge on occupant protection and structural performance.

Real-world crash data

Volvo Cars' Statistical Accident Database contains Volvo passenger vehicles in Sweden collected based on repair cost level. Detailed information about the database is found in Isaksson-Hellman and Norin (2005).

Restrained front-seat occupants aged 11 years or older, with known injury severity (incl. uninjured) and who were involved in crashes during 2002–2012 (car model years 1999–2012) were selected for the analysis. On-road crashes, i.e. without initial roadway departure, where the initial collision was a frontal impact with a motorised vehicle (two-wheelers excluded) or with an animal were grouped and studied in terms of overall injury risk, crash characteristics and pre-crash parameters. Also, occupant injures in crashes with large animals were investigated. Descriptive statistics of the groups compared is shown in Table 1 in the Appendix.

The group with large animals includes collision objects, such as moose and horses. Small-/medium-sized animals are exemplified by deer, badgers and hares. The deformation of the car was coded in accordance with the SAE recommended practice CDC (Collision Deformation Coding) [27]. Parts of the vertical deformation coding are shown in Fig. 3, where G is deformation at windscreen area without the front part of the vehicle being deformed.

Fig. 3. Vertical deformation coding according to CDC, SAE J224.

Injury risk is defined as the number of occupants injured for a certain level of AIS [28] divided by the total number of occupants (injured as well as uninjured) in the group considered. Exact 95% binomial confidence intervals were calculated. Injury risk was calculated for the whole selection of cases as described as well as for a reduced sample, controlling for road type by restricting to cases where the crash occurred on roads with a posted speed limit of ≥70 km/h and also excluding crashes occurring at intersections. This restricted sample was also used when comparing pre-crash parameters for the different on-road crash types.

Volvo Cars regularly performs in-depth accident investigations of crashes of special interest. On-site investigations are carried out and detailed information is collected and recorded. This information includes the course of events, documentation of the scene of the accident and of the car and its occupants. Eleven in-depth real-world crashes with large animals were selected to provide understanding of influencing factors and important mechanisms. These crashes occurred during 2002–2003 and were all Volvo cars of model years 1999–2003. In total, 27 occupants were involved: 11 drivers, 6 front-seat passengers and 10 rear-seat passengers, of whom 5 were children aged 8–13 years old. A synthesis of the cases is provided, including a more detailed presentation of two of the cases.

Testing

A test method simulating a vehicle-to-large animal crash was used, reflecting the real-world situation. The test method comprises a large animal dummy, as shown in Figs 4–6. The large animal dummy was developed and validated by VTI, Swedish Road and Traffic Research Institute, Sweden [26]. The dummy has a total weight of 358 kg and is made of 114 rubber discs in total and various steel parts holding the pieces together. The rubber quality is soft (Shore 40°), rip-resistant and durable, and is originally used for protecting truck beds when hauling heavy and sharp rocks. The density is 1,050 kg/m^3, which corresponds well with a moose total density of approximately 1,000 kg/m^3 [26]. The local proper density is adjusted by various cavities carved in the rubber body, achieving life-like weight and compressibility. All components, including the shape of the body plates, rubber to rubber friction as well as the different wires are designed to mimic, as closely as possible, moose characteristics and are explained in detail in [26]. The validation was performed at vehicle speeds of 70–90 km/h.

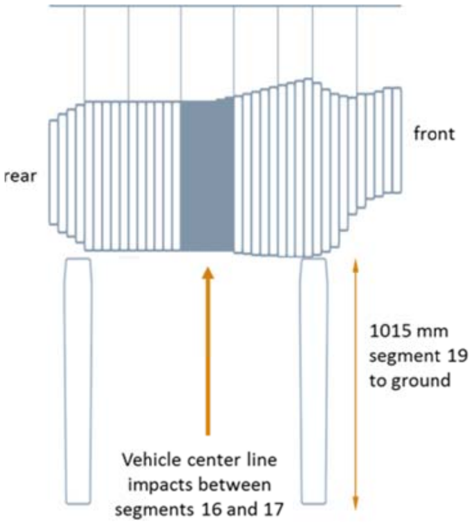

Fig. 4. Large animal dummy and test set-up.

The body consists of 36 rubber discs, all 50 mm thick but of varying areas, arranged vertically and numbered from the rear, as shown in Fig. 4. Two horizontally running wires keep the plates together. Each of the four legs consists of four 5 mm wires. Nineteen rubber discs cover each front leg, while the rear legs each have 20 rubber discs. Prior to impact, the dummy hangs from a releasing frame. The release mechanism is based on electrical magnets and the circuit is broken fractions of a second before impact. The height of the dummy is set so that the lower end of segment 19 is 1,015 mm from the ground. The vehicle centre is aligned between rubber plate segments 16 and 17, which is slightly behind the horizontal centre of gravity located at the 18th rubber plate.

Physical testing

Tests were run with two generations of vehicle designs (vehicle platforms), comparing mainly structural performance and studying the dynamics of vehicle-to-large animal crashes. Vehicle platform 1 was represented by a Volvo S80 (model years 1999–2006) and vehicle platform 2 was represented by a Volvo V70 (model years 2007–present). The weight of the test vehicles were 1,766 kg and 1,977 kg, respectively. The tests were comparable in terms of test set-up and vehicle speed of 70 km/h. Hybrid III 50th percentile crash test dummies were positioned as front-seat occupants. Photos of the test set-up, before testing, are shown in Fig. 5.

Fig. 5. Test set-up: side view (*left*) and front view (*right*).

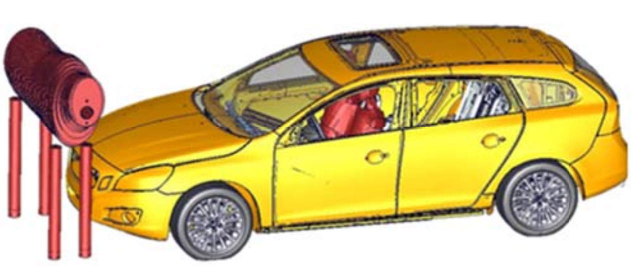

Fig. 6. Computer simulation set-up for virtual testing.

Virtual testing

Virtual testing was run as a complement to the physical testing, using the same test method. The FE model of the large animal dummy was developed and validated by Broms and Johansson [29]. The test set-up is shown in Fig. 6. Although detailed models are available for estimating occupant response, focus was placed on the structural response of the body structure. In particular, the effect of initial vehicle speed was studied by using virtual testing of a platform 2 vehicle (vehicle similar to the physical test). In this study, structural deformation was evaluated for vehicle-to-large animal crashes at an impact speed of 70 km/h and 80 km/h. The combination of horizontal and vertical maximum dynamic intrusion of the header, i.e. the connecting roof structure between A-pillars, was recorded at the vehicle centreline as well as at the lateral position of the driver head centre of gravity.

III. RESULTS

Real-world crash data

Statistics of real-world crashes and in-depth data analysis provided understanding of mechanisms as well as relevance of test set-up design. In the statistical data set, crashes with large animals (n=446) were compared to crashes with small- and medium-sized animals (n=288), frontal crashes with passenger cars (n=1430) and frontal crashes with heavy vehicles (n=186). First, regarding overall occupant injury risk, proportions of a set of pre-crash parameters and crash characteristics were compared for the four groups. Then, occupant injuries in crashes with large animals were investigated. Information from in-depth studies of 11 crashes with large animals offered complementary insights into mechanisms.

Front-seat occupant MAIS2+ injury risks for on-road collisions with large animals, small-/medium-sized animals, frontal collisions with passenger cars and heavy vehicles were investigated, respectively. The results are displayed in Table 2 in the Appendix. It was noted that occupants in collisions with large animals were at the same risk as in frontal collisions with passenger cars. No front-seat occupant sustained a MAIS2+ injury in collisions with small-/medium-sized animals, while the highest MAIS2+ injury risk was found in frontal collisions with heavy vehicles.

In addition, the MAIS2+ risks were examined controlling for road type. When restricting the sample to crashes taking place on roads with a posted speed limit of ≥70 km/h, and excluding crashes occurring at intersections, the MAIS2+ front-seat occupant injury risk in frontal collisions with passenger cars was higher than in collisions with large animals, although no significant difference was found (see Table 2 in Appendix).

With respect to pre-crash parameters, some differences between animal crashes and frontal collisions with vehicles are seen in the statistical data. Table 3 in the Appendix displays the proportion of five pre-crash parameters, comparing the four groups in the restricted sample of crashes taking place on roads with posted speed limits of 70 km/h and higher and not at intersections. A substantially higher frequency of vehicle-to-animal crashes occurred in darkness, dusk or dawn as compared to vehicle-to-vehicle crashes. There was also relatively higher occurrence of vehicle-to-animal crashes on dry roads as compared to vehicle-to-vehicle crashes. The proportion of drivers reporting a speed at impact of higher than 60 km/h differed greatly between vehicle-to-animal crashes and vehicle-to-vehicle crashes. In vehicle-to-animal crashes 80–90% of the drivers reported a high-speed crash, whereas in vehicle-to- vehicles about 35% of the drivers reported same. Regarding drivers' self-reporting *not* braking before impact, the highest share (29%) was found among vehicle-to-small-/medium-sized animals, while in the vehicle-to-vehicle crashes only 8% reported that they did not apply the brakes. Concerning self-reported distraction at impact, 10–13% of the drivers in vehicle-to-animal crashes reported that their attention was directed to something else than on the driving task, while the corresponding figure for drivers in vehicle-to-vehicle crashes was 26–28%.

Looking into specific cases, additional influential factors and mechanisms can be seen. Among the 11 in-depth vehicle-to-large animal cases, all occurred on rural roads, with posted speed limits of 70–110 km/h. All but one occurred in dusk or darkness. Dazzling light was reported as an influencing factor in at least two cases and obstructed view was reported as well. Although half of the crashes occurred on dry roads, rain or snowfall was reported as an influencing factor in five of the cases. Half of those with known braking or steering before the impact did not apply the brakes or steered away. In most cases it was reported that the large animal suddenly appeared from the left or right side of the road. In one case it appeared suddenly while standing still on the road. In all but one case, the most pronounced vehicle deformation was at the A-pillar and header area and the windscreen broke. In a single case where the impact was more towards the vehicle front, the front windscreen was intact.

Differences in crash characteristics with regard to vehicle frontal structure deformation are illustrated using the vertical deformation coding according to CDC (Fig. 3, [27]) for the complete statistical data set. Figure 7 shows a comparison of the four subsets of collision object crash categories: large animals, small-/medium-sized animals, passenger car and heavy vehicles, respectively. A striking difference can be noted in deformation pattern comparing the four crash categories. As can be seen in Fig. 7, the vertical deformation pattern 'G', where only the header and A-pillar area are deformed, represented 72% of the crashes with large animals, while it is almost non-existent in vehicle-to-passenger car crashes and only in a small portion of crashes with small-/medium-sized animals and heavy truck crashes.

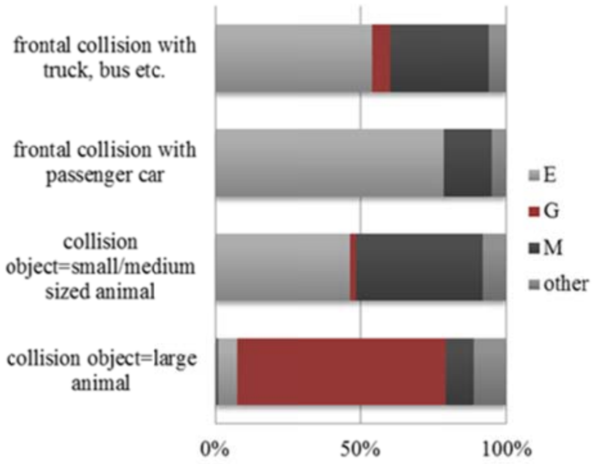

Fig. 7. Vertical deformation pattern distribution per crash category.

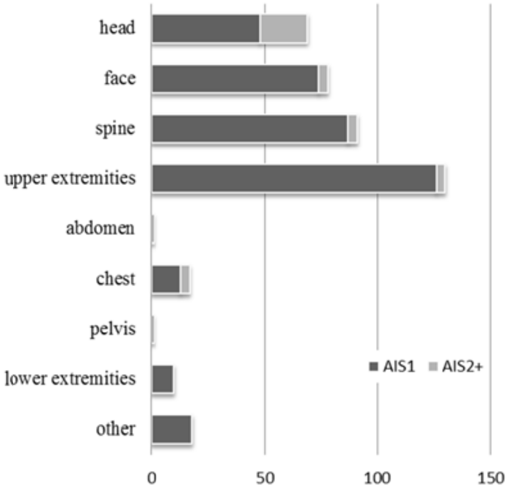

Fig. 8. Occupant injury (N=415) distribution per body part, for the 200 front-seat occupants in vehicle-to-large animal crashes.

In the subset of 446 vehicle-to-large animal crashes (comprising in total 446 drivers and 187 front-seat passengers), 146 drivers and 54 front-seat passengers sustained at least one injury. The 200 front-seat occupants sustained in total 415 injuries, distributed per body part as shown in Fig. 8. The vast majority of the occupant injuries are minor (AIS1) injuries, accounting for 378 of the 415 injuries, mainly found in upper extremities, spine, face and head. Cuts/lacerations are the most common AIS1 injury type (39%), followed by strain/sprain (20%) and pain without specified injury source (19%). Typically, cuts/lacerations are found on upper extremities (55%) and face (26%), while Strain/sprain are seen almost exclusively in the spine (96%). Among the AIS2+ occupant injuries, 22 are graded moderate (AIS2), and 15 are graded serious or greater (AIS3+). Of the AIS2+ injuries, 68% are to the head and face, and the remaining are evenly distributed to the spine, upper extremities and chest. Of the AIS 2+ injuries, 48% are fractures, half of them in the head or face, with 22% of the fractures found in the spine, 17% in the upper extremities and 11% in the chest. Beside these fractures, and except for one upper extremity laceration, one chest rupture and one chest suffocation, all the AIS2+ are injuries to the head, such as concussions, lacerations and haemorrhages.

Among the 11 in-depth cases with 27 occupants, none of the rear-seat occupants sustained injuries more serious than cuts resulting from splintering glass. Among the front-seat occupants, one driver was uninjured. This is the only case involving a red deer (Latin: *Cervus*), which is a large deer, but smaller than a moose. This is also the only case among the in-depth cases where the windscreen was not broken; however, there is large deformation to the vehicle front and hood. The injuries for the other 16 front-seat occupants are mainly of level AIS1, including cuts and laceration to mainly head, face, arms, including hands and fingers, as well as minor neck injuries that are mainly pain related. The mechanism behind the cuts or laceration injuries are mostly due to direct contact with sharp edges, such as parts of the windscreen, or by splintering glass projected towards the occupant. One of the three occupants with injuries exceeding AIS1 died due to critical head injury by direct loading, while the other two sustained serious-severe neck injuries. The mechanism behind these serious-severe injuries, such as head injuries and neck fractures, but also arm and hand fractures, are likely due to interaction with intruding roof structures or direct interaction with the body of the large animal intruding into the compartment during the crash sequence.

Two typical real-world cases are presented below. They are both typical vehicle-to-large animal crashes from a mechanism point of view. Both of them impacted a moose of a weight of approximately 350–400 kg. In case 1 the vehicle impacted the moose centrally on vehicle while driving at approximately 70 km/h. While in case 2 the vehicle impacted the moose to the left of the vehicle's front while driving at approximately 90 km/h. As can be seen from Figs 9 and 10, the deformations at the bumper level and the vehicle front were minimal. This reflects the interaction with a low-weight part of the animal; its long legs. Hence, when the moose body contacted the windscreen/A-pillar/header area, a limited reduction in speed had taken place.

Fig. 9. In-depth case 1.

Fig. 10. In-depth case 2.

In case 1 (Fig. 9) a restrained 56-year-old male driver of a Volvo V70 (MY -00) was driving at approximately 70 km/h on a rural road in rain and darkness. Suddenly a moose appeared on the road. The driver tried to steer away, but did not apply the brake. The moose was impacted centrally by the vehicle, the windscreen broke and the header and A-pillars were deformed. After the crash, the car stayed on the road. The driver, being the only occupant in the vehicle, sustained finger laceration only, due to the splintering glass.

In case 2 (Fig. 10), a restrained 60-year-old male driver of a Volvo V70XC (MY -01) was driving at approximately 90 km/h on a straight rural road in darkness, without streetlights. The road was wet due to rain. Suddenly the moose appeared from the left; the driver took no action in braking or steering manoeuvres. The impact of the moose was on the left side, and the moose kinematics was similar to the moose in case 1, interacting with the header and A-pillar area. After the crash, the car ran off the road. The driver, being the only occupant in the vehicle, sustained lacerations on fingers as well as in the face, due to the splintering glass.

Testing

The dynamic sequence of a vehicle-to-large animal crash test is illustrated in Fig. 11, showing snap-shots of the positions of the large animal dummy in the test with the platform 2 vehicle. For comparison, the corresponding vehicle crash pulse, specifically the longitudinal sill acceleration and velocity, is shown in Fig. 12. It can be seen that during the first part of the event, the dummy-vehicle interaction has minor influence on the vehicle speed reduction. This is first seen when the body of the dummy contacts the header and A-pillar area. This interaction lasts for about 60 ms, with a maximum deceleration of 50 m/s^2. Thereafter the dummy's rotation continues around the header and up and above the roof. During the whole event, the vehicle speed is reduced from 70 km/h to 62 km/h by the large animal interaction (Fig. 12) and the deceleration level is considerably lower than the activation levels of conventional frontal impact protection restraints, such as airbags and pre-tensioners.

Fig. 11. Dynamic sequence of large animal dummy interaction with passenger vehicle, platform 2 vehicle test.

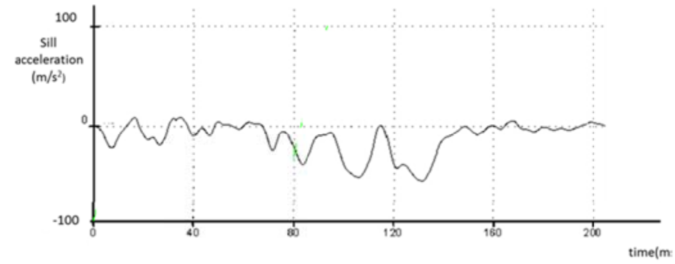

Fig. 12a. Longitudinal vehicle acceleration at sill vs. time, platform 2 vehicle test.

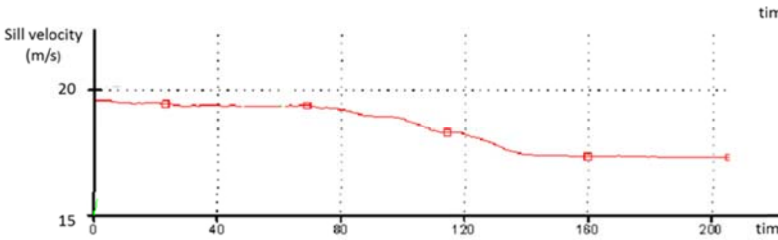

Fig. 12b. Longitudinal vehicle velocity at sill vs. time, platform 2 vehicle test.

Comparison of two vehicle design generations

A comparison of two vehicle design generations was made using the physical as well as the virtual test method. Important vehicle design and occupant protection aspects are seen, in particular highlighting the structural integrity of the A-pillars. Structural deformation is mainly in the area of A-pillars and header (Figs 13 and 14). The structural design differences between the two vehicle generations have an influence on deformation extent.

Fig. 13a. Photos of platform 1 vehicle after test at 70 km/h.

Fig. 13b. Photo of platform 2 vehicle after test at 70 km/h.

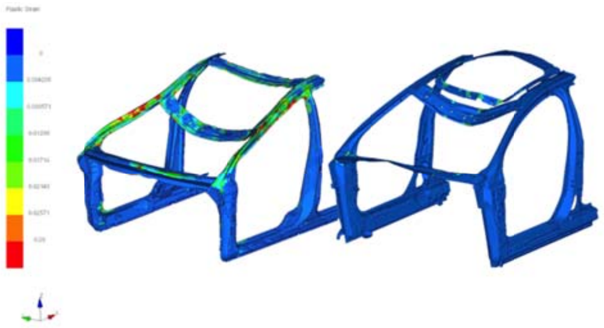

Fig. 14. Comparison of car body deformation after vehicle-to-large animal dummy virtual test; platform 1 (*left*) and platform 2 (*right*).

Comparing photos from the physical tests, it can be seen that the extent of deformation is less in the platform 2 vehicle (Fig. 13b) as compared to platform 1 (Fig. 13a). In neither of the tests did the front-seat occupants impact their heads into the large animal dummy or the vehicle interior structure. The airbag was not deployed, which is *per* specifications given this low acceleration event.

Virtual testing provides a good complement to the physical test, enabling more situations to be tested, and also providing a more detailed comparison of car body deformation. Car body maximum dynamic intrusion is displayed in Fig. 14. Major deformation on A-pillars influences the deformation of the header and roof bow (at the B-pillar level) for the platform 1 vehicle. However, for the platform 2 vehicle the deformations of the A-pillars are less, also influencing the deformation pattern on the roof, especially the roof bow (at the B-pillar level) (Fig. 14). Measuring the maximum dynamic intrusions of the header measured at the vehicle centreline, the platform 2 vehicle is 36% lower than the platform 1 vehicle. As the platform 2 vehicle tested has a sunroof, a special check was made to ensure that this did not influence the results.

Vehicle speed influence

The virtual crash test method was used to provide insight into influence of vehicle speed at impact. Two simulations were run at at 70 km/h and 80 km/h, respectively. This increase of speed increases the maximum dynamic intrusion by up to 25%. The highest maximum dynamic intrusion (as well as relative increase) is seen in the header at the vehicle centreline. This is also pronounced by the vehicle position centric to the large animal dummy. The intrusion recorded at the driver head centre of gravity is somewhat lower, both in absolute numbers as well as relatively from an increase of speed point of view. It is clear that even a small decrease in speed at impact to a large animal will have important influence on maximum dynamic intrusion and hence help to reduce the likelihood of head interaction.

IV. DISCUSSION

Crashes with large animals pose demands on vehicle design beyond standardised crash test methods. The challenges include dealing with 'objects' appearing suddenly and 'objects' that interact differently with the vehicle as compared to most other objects. Particularly, the direct impact to the animal poses a more challenging threat to the vehicle occupant protection.

The consequences from a vehicle-to-animal crash could be caused by the direct impact of the animal and/or a secondary impact due to extensive vehicle manoeuvre or the animal impact. Situations resulting in run off road crashes due to evasive maneeuvres for avoiding an animal crash were not included in this study. These situations are important to consider as well when addressing the whole scope of occupant protection in vehicle-to-animal crashes.

The real-world data presented in this study supports prior studies' findings, emphasizing that the vehicle-to-animal crashes mostly occur at rural roads, at higher speeds, in relatively clear weather and road conditions and usually in darkness. The driver seldom has a chance to take action, not because he/she is distracted but because of the animal's sudden appearance. Although the pre-crash factors are similar when comparing vehicle crashes to large and small-/medium-sized animals, the vehicle deformation pattern and occupant injury consequences of such a crash are very different. The smaller and lighter animals interact with the bumper and end up on top of the hood, while the larger animals, with their long legs in combination with their heavy body, will interact with the windscreen area close to where the occupant is seated.

Especially in parts of North America, northern Asia and northern Europe, crashes with large animals of moose, elk and large deer types are frequent. Other large animals are horses, cattle and camels, making this a global issue. The typical characteristic of a moose is a high centre of gravity due to long and slim legs, which will have limited interaction with a passenger vehicle front. Although height can vary, these properties are shared with the other large animals as well. The kinematics of the large animal dummy, as shown in Fig. 11, provides insight into the dynamics of this event. Bashir and Abu-Zidan [14] reviewed literature on vehicle-to-large animal crashes in different countries, and summarised that the mechanisms of injury vary with size and height of the animal and can be serious.

As shown in the real-world data analysis, when impacting an animal the driver is not at a significantly higher overall injury risk as compared to when impacting another vehicle. Nevertheless, the front-seat occupants in a vehicle-to-large animal crash are exposed to typical injury patterns and mechanisms highlighting the significance of these events. Occupant injuries of special focus are injuries to head, neck and upper extremities, together with cuts and lacerations. The mechanisms behind the most severe injuries (head injuries and neck fractures) as well as the less severe arm and hand fractures are mainly due to interaction with intruding roof structures, or direct interaction with the body of the large animal intruding into the compartment during the crash sequence. The mechanism behind the cuts or laceration injuries are mostly due to direct contact with sharp edges, such as parts of windscreen, or by splintering glass projected towards the occupant. These injuries account for the vast majority of the injuries and although of low severity, with respect to threat to life, they can cause great pain and suffering. In addition, long-term consequences with respect to the healing process and scars are important aspects.

From an occupant protection perspective, the worst case is when the large animal body interacts with the vehicle at the height of the A-pillar, and thus close to the occupant's head. The test method used in this study provides insight into these mechanisms and serves as a test method for evaluating typical vehicle-to-large animal crashes. The test method used in this study uses the third generation of large animal dummies. Extensive studies were made to choose the material most representative of animal characteristics during impact, leading to the choice of rubber elements. The design has been shown to be durable, and the method repeatable and reproducible [16]. The published validation work based on both moose cadaver testing and real-world data comparison [19][24] is supported by comparing the real-world crash outcome (Figs 9 and 10) with the test vehicle deformations (Figs 13–14) presented in this study. The test method was validated in vehicle speeds of 70–90 km/h. Due to the durability of the rubber animal dummy, the validity can be questioned at high severity events, since a real moose will be less durable and thus the characteristics will change. Also, the speed level for which the large animal dummy is biofidelic depends on the characteristics of the vehicle, i.e. for more resistant vehicles, the speed level will be lower than for those vehicles used in the validation.

The test method captures the loading characteristics based on the typical large animal kinematics when sideways interacting with the vehicle. A typical passenger vehicle-to-large animal interaction comprises low-energy interaction with the front part of the vehicle, the animal body interacting with the header and A-pillar area and thereafter unloading by continuing the rotating motion up and over the vehicle roof. In some situations in the real world, however, the animal will be trapped inside the compartment.

The validation of the virtual method was performed by Broms and Johansson [29]. In the present study, deformation patterns from the physical and the virtual test method for the same vehicle at 70 km/h are shown in Figs 13–14. The overall deformation pattern is similar, however a somewhat stiffer response in the virtual testing is seen. This is in line with previous experience, stating that simulation models generally display a stiffer response compared to the physical tests. In this case, this effect is partly related to the windscreen cracking that can be observed in tests, which require sophisticated models in order to be captured in computer simulations and, partly related to that material failure, cannot always be captured in a realistic manner.

Important vehicle design and occupant protection aspects emphasise the performance of the header and A-pillar area. The structural integrity in this area influences the deformation extent. The vehicle design changes made between vehicle platform 1 and 2 result in a lower maximum dynamic intrusion, up to 36% at the header centreline, especially due to less deformation on A-pillars, which also influences the deformation of the head and roof bow. In neither of the physical crash tests did the occupant impact their head, and only in a few of the real-world cases (all of the real-world cases were of platform 1 type of vehicles) did the occupant sustain severe injuries due to direct interaction, illustrating that both tested vehicle types are relatively well designed vehicles for this crash situation. This was supported from a real-world study performed by Folksam in Sweden [18], comparing Swedish cars (Volvo and Saab) to a variety of non-Swedish cars of similar size. Folksam [18] found that the amount of occupants injured and with medical impairment was 25% lower in a Swedish-made car as compared to other vehicles.

The influence of vehicle speed at impact is shown from real-world data to have a significant influence on injury consequences. In the present study, two different speeds were evaluated using the virtual crash test method. An increased impact speed not only drives the structural deformation but also influences the timing of head impact towards the deformed area. Besides the influence of impact speed, several important pre-crash factors are highlighted in this study. Technical developments for addressing these issues will require a combination of countermeasures targeting the mobility of the large animals (e.g. fencing) as well as vehicle technology assisting the driver in detecting and sensing large animals. with the goal of further strengthening occupant protection by mitigating and potentially avoiding the crash. In addition, measures addressing post-crash aspects are of importance for the consequences of a vehicle-to-animal crash. For best results, measures in all these areas should be combined, together with vehicle structural and restraint developments.

V. CONCLUSIONS

Crashes with large animals pose demands on vehicle design beyond standardised crash test methods. Although more frequent in some parts of the world, they can occur globally, and generally the challenges are sudden appearance and vehicle interaction higher up on the car body than when interacting with other vehicles or small-/medium-sized animals. Real-world data identifies important factors, such as impact speed, impact configuration and environmental factors. Particularly relevant occupant injuries are those to the head, neck and upper extremities. Injury mechanisms include interaction with deformed roof structures or the large animal body, as well as cuts and lacerations by splintering glass or sharp edges. A test method simulating vehicle-to-large animal crashes was used to illustrate structural performance and occupant protection. Vehicle design as well as impact speed influences the structural performance when impacting a large animal. Safety developments addressing large animal safety include structural and restraint designs, together with detection and sensing of large animals for mitigation and potential crash avoidance altogether.

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VII. APPENDIX

TABLE I

DESCRIPTIVE STATISTICS (MEAN ± STANDARD DEVIATION) OF OCCUPANT AGE, STATURE AND CAR MODEL YEAR FOR THE FOUR SUBSETS

	Collision with large animal, n=446		*Collision with small/ medium sized animal, n=288*		*Frontal collision with passenger car, n=1430*		*Frontal collision with heavy vehicle, n=186*	
Variable	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Occupant age	49	13.5	47	13.7	46	13.9	47	13.9
Occupant stature	177	8.0	178	8.7	178	8.7	177	9.6
Car model year	2005	3.2	2006	3.5	2005	3.2	2004	3.2

TABLE 2

FRONT-SEAT OCCUPANT MAIS2+ INJURY RISKS PER CRASH CATEGORY, WHOLE STATISTICAL DATA SET SAMPLE AND RESTRICTED SAMPLE OF CRASHES ON ROADS WITH POSTED SPEED LIMIT OF 70 KM/H AND ABOVE, AND EXCLUDING CASES AT INTERSECTIONS

	Collision with large animal				Collision with small-/ medium-sized animal		Frontal collision with passenger car				Frontal collision with heavy vehicles			
	n	Risk MAIS2+	95% lower	95% upper	n	Risk MAIS2+	n	Risk MAIS2+	95% lower	95% upper	n	Risk MAIS2+	95% lower	95% upper
Restrained front-seat occupants with known injury severity, age >11 years crash years 02–12, model years 99–12	446	0.0404	0.0241	0.063	288	0	1430	0.0385	0.0291	0.0498	186	0.0699	0.0377	0.1166
As above + Crashes on roads with posted speed limit ≥70 km/h and not at intersection	420	0.0492	0.0256	0.0669	264	0	492	0.0772	0.0552	0.1045	71	0.0986	0.0406	0.1926

TABLE 3

PROPORTIONS OF PRE-CRASH PARAMETERS PER CRASH CATEGORY, RESTRICTED SAMPLE OF CRASHES ON ROADS WITH POSTED SPEED LIMIT OF 70 KM/H AND ABOVE, AND EXCLUDING CASES AT INTERSECTIONS

	Collision with large animal	Collision with small-/ medium-sized animal	Frontal collision with passenger car	Frontal collision with heavy vehicles
Lighting condition = darkness/dusk/dawn	81.6	74.6	35.7	34.3
Road condition=dry	64.5	72.0	56.3	54.3
Self-reported driver distraction	13.2	10.2	28.0	25.7
Self-reported speed at collision >60 km/h	79.1	89.0	34.9	35.7
Self-reported driver’s braking=no	16.2	28.8	8.4	20.0