FATAL CAR TO MOOSE COLLISIONS: REAL-WORLD IN-DEPTH DATA, CRASH TESTS AND POTENTIAL OF DIFFERENT COUNTERMEASURES

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ABSTRACT

Vehicle collisions with large animals constitute a high risk of serious or fatal injuries, for example in northern America, Europe and Japan. In Sweden approximately 5,000 car collisions with moose occur annually. The change of velocity and acceleration is in general very low, but the car structure is not designed for collision with large animals at high speed.

The objectives were to evaluate occupant response and vehicle structure in crash tests; to investigate the factors involved in real-world fatal crashes in Sweden; and to evaluate the potential of Autonomous Emergency Braking (AEB) to increase moose car collision avoidance and survivability.

Five crash tests were conducted with cars with different size and characteristics, such as glass and sun roof. A moose crash dummy was impacted at 70 km/h. The Swedish Transport Administration (STA) national database of fatal collisions was used to study fatalities (n=47) in collisions with moose during the period 2005-2016. The analysis focused on collisions where the primary cause of fatality was the collision with a moose.

The crash tests showed that a moose collision could be survivable at 70 km/h with an acceptable distance to the header structure. None of the tested cars had an intrusion by the moose into the occupant compartment. The results of the in-depth data analysis showed that a critical factor for a fatal injury was whether the roof was partly or completely ripped off. Downward deformation of the front header structure was also critical together with A-pillar deformation. In 24% of the accidents the moose was partly or completely trapped inside the occupant compartment. In 90% of the fatal collisions it was darkness or twilight. In more than 85% of the collisions, no evidence of braking could be detected prior to collision. All of the collisions occurred on rural roads and 83% of the fatalities occurred on roads with speed limits of 90 km/h or above. In eight accident scenes there were moose fences to prevent the moose to access the road. In those accidents, however, the fence was either damaged or had open sections.

The analysis of road-side area showed that in many of the moose accidents the side view was enough to allow detection of the moose by an AEB sensor. A critical issue is the ability of the sensors to detect the moose in darkness. The study of the potential for AEB with moose detection was conducted under the assumption that night vision sensors are available, such as infrared sensors or light amplifying technique. With a threshold of 70 km/h for car-moose collision survivability, the results of the analysis showed that AEB had a potential to save (~40%) 18 out of 47 lives.

It is suggested that road fencing is preferable on roads with speed limits above 90 km/h, and below 100 km/h, moose AEB has a potential to avoid fatal moose crashes.

INTRODUCTION

Yearly, the number of collisions with large animals is 1-2 million in the U.S. and one million in Europe (Niemi, Rolandsen et al. 2017). In Sweden, the number of moose vehicle collisions (MVCs) were 5874 in 2016 (Nationella Viltolycksrådet 2015). During the last 10 years in average 5 fatalities occur annually due to MVCs in Sweden.

Passenger cars are generally not designed to withstand an impact with a moose at higher speeds. MVCs entail high demands on the vehicle structure and are not included in standardized crash tests. They do not involve the main structure of the car front-end. In a MVC, the moose often directly hits the windscreen area, which is a weak part of the car structure (Björnstig, Bylund et al. 1984; Lövsund, Nilson et al. 1989; Williams and Wells 2005). The crash severity in terms of change of velocity is generally low in MVCs, typically 8-15 km/h even in high speed collisions (Jakobson, Lindman et al. 2015). In this range, the probability of an airbag deployment is low (Hussain, Hannan et al. 2006). Moose crash tests with cars show that interior intrusion can be extensive (Krafft, Kullgren et al. 2011; Jakobson, Lindman et al. 2015).

In a number of real-life collisions, it can be observed that the moose has penetrated the windscreen and got trapped inside the car compartment (Williams and Wells 2005). In moose crash tests, the dummy typically rotate over the car without penetrating the passenger compartment (Krafft, Kullgren et al. 2011). The direct hit from the moose is an injury risk itself in case of intrusion into the occupant compartment. Severe head and neck injuries occur in contact with intruding roof structures and the moose body itself (Eriksson, Björnstig et al. 1985; Björnstig, Eriksson et al. 1986; Farell, Sutton JR et al. 1996).

The risk of hitting a moving moose crossing a road is influenced by vehicle speed, distance to the animal and light conditions. A number of studies support that MVCs usually occur on rural straight roads, with posted speed limit or higher, during dusk, dawn and night (Garret and Conway 1999; Joyce and Mahoney 2001; Williams and Wells 2005; Langley and Higgins 2006; Rowden, Steinhardt et al. 2008; Sulivan 2011) and with sudden appearance of the moose (Williams and Wells 2005). Even in situations with open space along the road side, the headlights of the car at night have limited ability to light up a moose along the road side area. The risk of a MVC in Canada is shown to be 2-3 times higher at night than during any time of the day (Garret and Conway 1999; Dussault, Poulin et al. 2006).

Studies of road factors such as posted speed limit, road surface, road alignment and presence of passengers are shown to influence the severity of injury (Joyce and Mahoney 2001; Seiler 2005).

An effective intervention to reduce MVC is a fence aimed at preventing the moose to access the road. Studies has showed an accident reduction of up to 80% on roads with such fences (Lavsund and Sandegren 1991). The use of road fencing has so far been prioritized on roads with high traffic density and with high posted speed limits. There are however drawbacks with fencing, such as installation and maintenance, costs and the risk of isolation of animals. Road fencing is therefore not the single solution on all kinds of rural roads.

Moose detection sensors are still uncommon and detection in darkness at the side of the road still has limitations. The existing moose detection systems use the same sensors as pedestrian detection systems. Active Pedestrian Safety Systems (APSS) have different types of sensors, including cameras (mono and stereo), laser scanners, near and far infrared cameras, RADAR and LIDAR (Hamdane, Serre et al. 2014). Sensors are often combined. The ability of sensors vary in terms of field of view (FOV) and range vary with the brand and sensor type. Hamdane, Serre et al. (2015) modeled APSS with camera sensors with FOVs from 20° to 45°, and a camera range of 40 m. A powerful mono camera system is Volvo S60’s Collision Warning with Full Auto Brake and Pedestrian Detection (CWAB-PD), which uses a mono forward-sensing wide-angle camera mounted behind the windscreen (FOV 48° and range 60 m).

The potential benefit of APSS in Volvo cars was recently tested by Vertal and Steffan (2016). If the vehicle speed was higher than 30 km/h they reported that the system could detect the pedestrian and reduce the vehicle speed if the movement of the pedestrian was smooth and predictable. Pedestrians without a reflective vest could be detected in good light conditions, and those walking at a speed up to 7.5 km/h could be detected, while higher speeds were not tested (Vertal and Steffan 2016). The movement of moose is not well explored, but typically they have higher speed than pedestrians and therefore early detection is crucial to mitigate risks. The autonomous system reached deceleration of 10 m/s^2, as did driver braking, and the car could achieve a car speed reduction up to 30km/h at the detection of the pedestrian (Vertal and Steffan 2016). This is probably the least level of speed reduction needed for survivability of MVCs.

The objectives were to evaluate occupant response and vehicle structure in crash tests; to investigate the factors involved in real-world fatal crashes in Sweden; and to evaluate the potential of Autonomous Emergency Braking (AEB) systems to increase moose car collision avoidance and survivability.

METHODS

This study combines car crash testing and analyses of real-world collision data. The deformation patterns and accident kinematics from the crash tests were compared with the deformation characteristics in the real-world collisions. The analyses of the crash tests and the real-world data were used in the subsequent study of the potential of AEB systems to increase the survivability in MVCs.

Crash test

The crash tests were conducted with a large moose dummy which is developed for vehicle-to-large animal collisions (Matstoms 2003). Various types of cars were tested to investigate the influence of car design in crashworthiness.

Five different car types were tested (Table 1). The test cars had various characteristics in terms of windscreen angle, sunroof and pre-crash distance between head and header structure (Figure 1). Car 1 was chosen to investigate the influence of a sunroof. Car 2 had a large glass sunroof and also a relatively flat windscreen. Car 3 was the smallest class of cars. Car 4 had a more upright windscreen. Car 5, a MPV, had a large windscreen compared to other test vehicles.

The measured pre distance between head and header structure is shown in Table 1. A HIII 50th male dummy was used on the driver's seat and the head acceleration was measured.

Crash tests were conducted with a moose dummy according to a test method developed by Swedish National Road and Transport research Institute, VTI (Matstoms 2003). The test speed was 70 km/h.

Table 1.
Crash test cars

Test no	Test vehicle	Model Year	Head distance to header structure (cm)	Wind screen angle
1	Volvo V70	2001	407	29
2	Peugeot 407	2006	380	24
3	Ford Focus	2005	362	27
4	Hyundai Santa Fe	2001	396	35
5	Opel Zafira	2000	412	29

Figure 1. Distance between head and header structure

Real-world collision data

The accident data used in this study was in-depth data from Swedish Transport Administration including accident data from the police and rescue services, as well as on-scene observations by special accident investigation teams. The accident investigators regularly conduct extensive investigations in case of a fatal accident. Restrained and unrestrained car occupants of all ages (none of the occupants were younger than 20 years) involved in a fatal MVCs were selected for the analysis, in total 47 fatally injured car occupants in 46 collisions (34 drivers, 12 front seat occupants and one rear seat passenger). The accidents occurred during 2005-2016 and included both collisions with moose and secondary impacts. However, the primary cause of death was established to be the collisions with the moose.

AEB analysis

In order to analyze the potential of reducing impact speed in moose collisions with AEB, a number of assumptions were made.

1. The camera sensors needed for moose identification was assumed to detect objects in darkness and have a longitudinal range of 60m and ±24° view angle (Figure 2). Except for pure night vision, this represent the performance level of today's technology for pedestrian detection. This corresponds to a maximum side view distance of 26 m. (Coelingh, Eidehall et al. 2010; Hamdane, Serre et al. 2014).

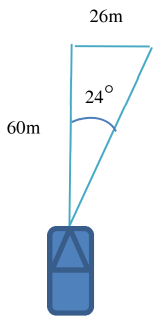

Figure 2. Sensor performance

2. The camera sensor is able to detect moose in dark conditions with e.g. IR technology or light amplifier.

3. The speed of moose is assumed to be 15 km/h.
4. The survivable impact speed in a modern car is 70 km/h.
5. AEB braking occurs during 1s when the time-to-collision ≥1s.
6. Mean deceleration for various road conditions.
    a. Dry – 0.9 g
    b. Wet – 0.7 g
    c. Snow – 0.3 5g
    d. Ice – 0.25 g

The maximum lateral sensor distance was set according to the assumed performance of the sensor and reduced if there were obstructing objects along the roadside. For each accident case, the available lateral distance was measured 60 m in front of the car prior to impact.

The impact speed was estimated by a series of expert evaluations, using witness information, deformation data, tire marks before impact and trajectory data after moose impact.

AEB sensitivity analysis

In the sensitivity analyses a range of values were considered for two input parameters: lateral vision distance and impact speed.

Parameter samples were generated randomly with given distributions for each accident.

The analysis was based on expert assessments of the car velocity at the time of the collision and the lateral vision distance. Sensitivity analyses were conducted to evaluate the effect of errors in these assessments. The following was assumed in an expert evaluations. Regarding impact speed, the errors had a normal distribution, with mean values per collision as assessed by the experts, and 95%-confidence intervals at +/-15 km/h of these means. In the case of lateral vision distance, the errors had likewise normal distributions, with means as evaluated by the experts and 95%-confidence intervals that were within +/-1 m of these means. In total, 10 000 random draws of speed and vision distance were implemented with the given distributions; subsequently, the number of cases resulting in a non-fatal collisions (<70km/h) was calculated per draw. Lastly, the 95%-confidence interval of the number of such successful outcomes was calculated. In each of the two sensitivity analyses, the other factor (impact speed and lateral distance) was kept constant.

RESULTS

Crash test

The distance between the head and the header structure showed a variation of 5 cm between the best and the worst performing car. The variation of the remaining distance after the crash test did increase to 25 cm (Table 2). The HIC value was well below critical values. The SUV had the largest remaining distance between head and header structure (Table 2).

Table 2.
Head distance to header structure (cm)

Test	Head distance (cm)	Remaining distance (cm)	Head	
			Acc_{3ms} (g)	HIC 36
1	41	2	42	73
2	38	12	56	120
3	36	5	44	127
4	40	26	7	3
5	41	15	93	440

The crash test showed variation in roof tear from 0-15 cm, the SUV had the lowest roof tear (Figure 3).

Table 3.
Teared roofline (cm)

Test		Roof tear left	Roof tear right
1	Volvo V70	3	0
2	Peugeot 407	24	15
3	Ford Focus	17	7
4	Hyundai Santa Fe	0	0
5	Opel Zafira	8	10


Fig 3. Peugeot 407

Fig 4. Ford Focus


Fig 5. Volvo V70


Fig 6. Hyundai Santa Fe


Fig 7. Opel Zafira

Car deformation in real-life collisions

Figure 8 shows the number of fatalities in relation to the car deformation characteristics. The three most important factors for a fatal outcome were the amount of roof tear and vertical deformation of the roof and whether the moose was trapped in the occupant compartment or not. A large portion of the fatalities (31/47) occurred in case of large roof tear and in combination with large vertical roof deformation. Large roof deformation alone accounted for 10 fatalities. Downward roof deformation without roof tear was strongly correlated with deformed A-pillars. A trapped moose was most often (10/47) combined with roof tear and large vertical roof deformation.

In all moose collisions in this dataset, the main contributing factor for a fatal outcome was a collision with a moose. However, a large number of collisions was followed by a secondary impact on the side of the road. In 32 of 47 collisions the car left the road and hit other objects on the side of the road (Table 4).

Table 4.
Number of fatalities with additional post collision

Secondary collision	Number
Yes	32
No	15
Total	47

Two fatalities were excluded from Table 5, one rear seat occupant and one driver in which the collision deformation was unknown. In the vast majority of the collisions (85%) there were major downward deformations of the front roof structure (Table 5).

In collisions with major downward roof deformations and minor roof tear, a large portion of A-pillars had severe deformation, 57% (8/14). As a comparison 35% (9/26) of the collisions with major downward roof deformations a roof tear >10cm also had severe deformed A-pillars.

In 23% (11/47) of the collisions the moose was trapped in the occupant compartment (Table 5). A trapped moose was not necessarily completely inside the passenger compartment. There were combinations of trapped moose in the car compartment; either trapped for a certain distance along the road and then thrown off the car, or trapped completely in the car compartment until stop.

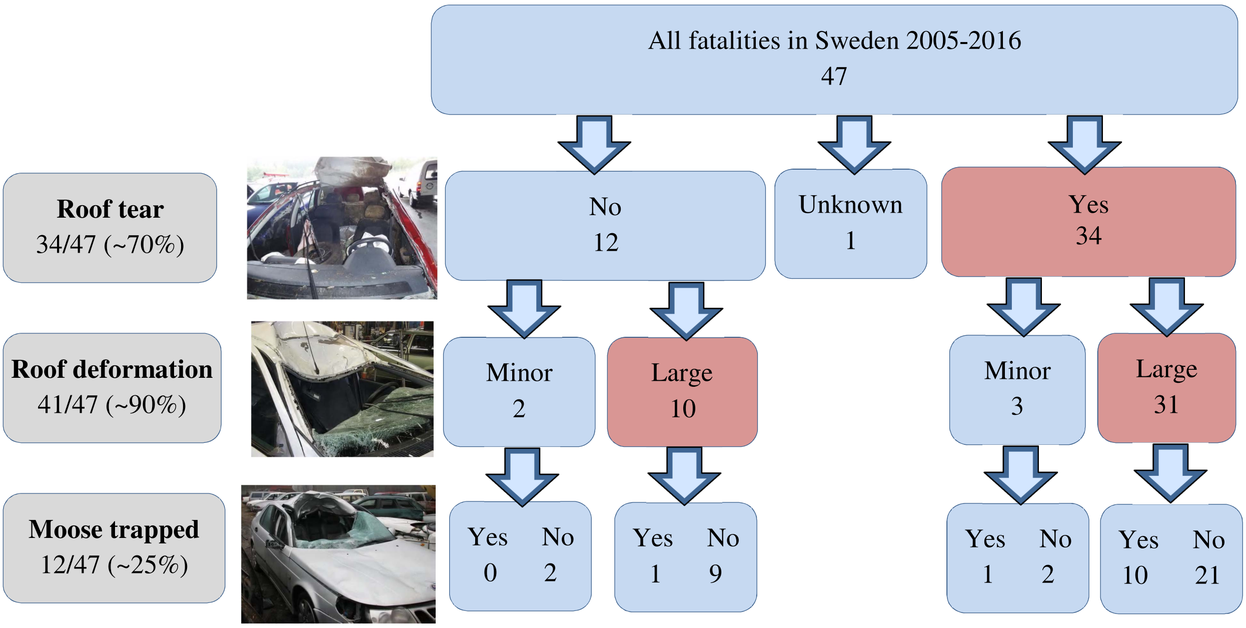

Figure 8. Number of fatalities divided into groups of roof tear along door frame, downward deformation of header structure and moose trapped.

Table 5.
Roof tear on victims side/downward roof deformation & moose trapped – driver/front seat passenger (n=45)

Number of front seat occupants Roof tear (cm)	Roof deform. minor	Roof deform. major	Moose trapped
Roof tear 0	2	11	1
Roof tear 1-10	2	3	2
Roof tear 11-30	0	3	1
Roof tear 31-50	0	6	2
Roof tear >50	1	17	5
Moose trapped	1	10	11

The results from the crash tests indicated a less lateral roof deformation on the car with sunroof. Table 6 shows a larger proportion of major roof deformation than cars without sunroof.

Table 6.
Roof downward deformation vs presence of sunroof

Number of cars (n=45)	Sunroof	
	Yes	No
Minor roof deformation	2	3
Major roof deformation	5	35
Total	7	39

Road related parameters

The most common MVC type was on a straight road with the moose coming from the right side (Figure 9). The large portion of fatal moose collisions from the right side (66%) may be explained by the difficulties to detect a moose from the right side compared to the left side. The most demanding situation is a collision in combination with overtaking at high speed and also with an obstructed view. Two collisions occurred during overtaking.

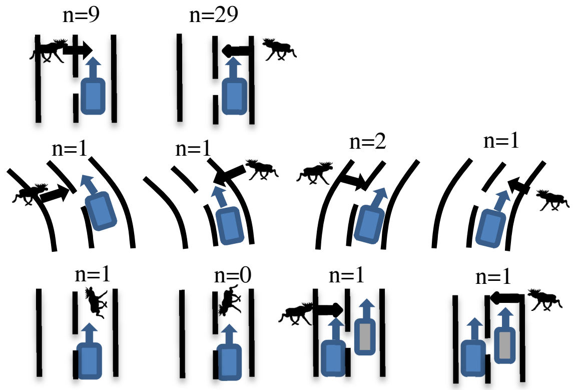

Figure 9. Collision type and number of fatalities per collision type

A large portion of fatal MVCs occurred during darkness or in twilight (Table 7). The drivers often found that the moose appeared very suddenly. This is reflected by the large number of fatalities with no braking prior to collision.

Table 7.
Number fatalities with pre impact braking and lighting condition

Lighting condition	Pre imp. braking	No braking	Total
Daylight	2	3	5
Twilight (Dusk/dawn)	0	8	8
Darkness	5	29	34
Total	7	40	47

The majority of the fatal moose collisions occurred on 90 km/h roads (Table 8). In eight of the collisions the road side was equipped with a moose fence. But in all of those there were either damages to the fence, opening in the fence due to road conjunctions or fence termination.

Table 8.
Posted speed limit

Speed limit (km/h)	Moose fence		Total
	Yes	No	
70	0	4	4
80	0	4	4
90	2	24	26
100	3	3	6
110	3	3	6
120	0	1	1
Total	8	39	47

An analysis of available side view (Table 9) shows that more than 70% (34/47) of the accident scenes had an unobstructed view of 5 m or more.

Table 9.
Number of accidents with lateral unobstructed view

Unobstructed view sensor	Number
0-2 m	5
2-5 m	8
5-10 m	15
>10 m	19
Total	47

Potential reduction of collisions with AEB

Assuming a survivable impact speed ≤70 km/h, Table 10 shows that AEB could prevent 18 fatalities (~40%), and further 3 in combination with a modern designed car.

Table 10.
Potential of reducing impact speed below 70km/h with AEB

Number of fatalities	Without AEB	With AEB
≤ 70 km/h	3	21
> 70 km/h	44	26
Total	47	47

Sensitivity analysis

The estimation of impact speed is difficult mainly because the relatively low crash severity and energy involved in a MVC. Also the measured lateral unobstructed view was associated with errors since it is partly measured from photos and satellite views. Therefore a sensitivity analysis was conducted to investigate the how these errors influence the AEB potential in saved lives.

The 95%-confidence interval for the number of non-fatal outcomes with AEB with lateral vision distance kept constant was between 16-24 (Table 11), assuming collision velocities with distributions of N(µv,15), where µv was the value in km/h per accident as assessed by a group of experts.

Table 11.
Sensitivity analysis ±15km/h impact speed, 95% CI, number of fatalities below 70km/h provided with 1s AEB

Number of fatalities	Without AEB	With AEB
≤70 km/h	3	16-24
>70 km/h	44	23-31
Total	47	

The 95%-confidence interval for the number of non-fatal outcomes with AEB with the impact speed kept constant was 20-22, assuming lateral vision distances with distributions of N(µd,1), where µd was the value in m per accident as assessed by the experts (Table 12).

Table 12.
Sensitivity analysis ±1m side area measure, 95% CI, number of fatalities below 70km/h provided with 1s AEB

Number of fatalities	Without AEB	With AEB
≤70 km/h	3	20-22
>70 km/h	44	25-27
Total	47	

DISCUSSION

A comparison between the moose crash tests and the real-life collisions showed that the moose test dummy never was trapped in the passenger compartment while in 25% of the real-life collisions it was. A possible reason could be that the dummy construction with a number of rubber disks allows it to roll over the header structure. Other tests can confirm this behavior (Jakobsson et al. 2015). In real world the moose is more viscous (Nilson and Svensson 1986).

A large part of the fatalities occur with a secondary collision into the road side area. The change in velocity in a MVC is typically 8-15 km/h (Krafft, Kullgren et al. 2011; Jakobson, Lindman et al. 2015). A high impact speed therefore gives a quite large remaining speed and a secondary impact can be quite severe. In a MVC the driver has limited maneuver capability and the data in this paper contained examples of cars travelling uncontrolled more than 200 m after the moose collision. There is therefore a need to investigate those moose collisions that are not fatal in the first impact but lead to severe secondary impacts.

Moose detection sensors for autonomous braking need a certain distance of unobstructed view to detect a moose in the side area. This is analyzed in this study but there are special circumstances that do not appear when detecting e.g. vehicles or pedestrians. The detection is sometimes done by a radar sensor in combination with cameras in the windscreen. Moose collisions, which not seldom occur on rural roads equipped with guard rails, can be a problem for sensors. Guard rails may obstruct sensors in the lower part of the vehicle front end which is a common place for radar sensors. The cameras in the windscreen are not as sensitive for obstructing guard rails. This analysis did not take into account the obstruction by guard rails.

Since a vast majority of moose collisions occur in darkness, the animal detection with today's camera technology is not possible without additional light. In this study it was assumed that the technology has the possibility to detect the moose as long as there are no obstruction and a range defined by the performance of today's AEB cameras.

Out of 47 fatalities, 7 occupants were unbelted. One study by Timothy M. et al. (1996) shows that seat belt use is associated with reduced injury in MVCs. However the crash severity in MVCs is generally low, typically 5-15 km/h shown in studies based on crash recorder data (Krafft, Kullgren et al. 2011). The same crash recorder data also showed less than 10% risk for MAIS2+ injuries at a change of velocity of 15 km/h (Stigson, Kullgren et al. 2012). Therefore the seat belt use probably has limited effect on the fatality outcome in the accidents included in this study.

A conclusion shared by others (Björnstig, Bylund et al. 1984) is that the head to header structure distance is one of the most important factors influencing the injury risk in MVCs. Direct contact with the moose body itself as well as interaction with deformed roof structures (Jakobson, Lindman et al. 2015) are important factors and they all target the strength of the header structure and roof area. Since the change of velocity is low in those crashes, the most important issue is to not allow high speed intruding surfaces in order to avoid the occupant head. If the construction of the car can deal with a moose up to approximately 70km/h, a large part of remaining crashes can be mitigated with either technical car systems or moose fence.

There are few studies that describe the fatality risk in MVCs with regard to impact speed. Speed limit is an indicator of survivable impact severity but variations in average speed during the day, with higher speeds at night (Lundström and Routsalainen 2008), making it an inadequate severity parameter. The chosen threshold for survivable MVCs at 70 km/h is supported by a study from New Foundland, which shows that the risk of severe injuries was 2 times higher in speeds of 80 km/h or higher (Joyce and Mahoney 2001). The cars used in the crash test were, however, not from the last generation of cars. The crash test cars were model year 2000-2006. The average model year from the real-world data was 2001. It is reasonable to believe that the survivable speed in MVC has slightly increased for a modern car. A survivable speed of maybe 75 km/h instead of 70 km/h would in this study increase the effect of an AEB system.

Ungulate studies from US, Australia and Sweden (Langley and Higgins 2006; Rowden, Steinhardt et al. 2008; Jakobson, Lindman et al. 2015) confirm the accident pattern with darkness and animals appear suddenly together with interaction up on the car body. The findings from these studies are also that although the car construction can be improved, this accident type put demands on the car in high speed MVCs.

The potential in saved lives in MVCs with night vision AEB is much dependent on the road side area. On unfenced roads the road authorities need to secure the side area even from lower vegetation to achieve an unobscured visibility for the sensors.

Despite its effectiveness, road fencing is not the single solution on all kinds of roads. On roads with lower traffic density it is too costly to cover the road side with moose fences. There are also disadvantages associated with fencing. Fencing increases the isolation of wildlife and may become ineffective when animals are determined to cross a road, force the barrier and eventually get trapped inside the fenced corridor (Nilsson 1987; Seiler, Cederlund et al. 2003). There is consequently a need for a shared responsibility among the road authorities and car manufacturer's. MVCs on roads with lower speed limit have to be solved by improved car design. MVCs in higher speeds can be mitigated by Autonomous Emergency Braking or road fencing.

Limitations

In this analysis of real-world collisions an assumption was made regarding the speed of a walking moose. There is almost no data which explain the moving pattern of a moose moving over a road. The assumption was made that the moose was moving at constant speed at all times unless otherwise was obvious from the data.

Since the deformed energy on the car is quite small in MVCs, typically 5-15 km/h in delta-V, it is difficult to determine the true impact speed. The spread in judgement can of coarse be greater than ±15 km/h in real life but can be seen as an approach to evaluate the potential of a night vision AEB.

The weight of the moose was not known which influence the judgement of the impact speed as well.

Unobstructed view for sensors is not only a matter of obstruction from objects along the road. In many situations the side areas can be designed with positive or negative slope along the roadway. This study have not taken into account, limitations of sensor range in lateral direction.

A limitation is that the car collision safety for moose collisions is not included. Although newer cars may offer better crash performance in moose collisions, there is only limited knowledge of the effect of improved car roof design on fatally injured occupants.

CONCLUSIONS

Results based on crash test

- Dummy head acceleration was not exceeding lethal levels in any tested car which indicates that 70km/h is survivable in moose car collisions in a modern car.
- Larger head distance to header indicates a lower injury risk.
- The variation in roof deformation shows a potential to construct the roof with the purpose to maximize remaining distance between head and roof in moose car collisions.

Results based on real-world collision data

- The most common moose car collision occurred on a 90km/h straight dry or wet road and in darkness, and the driver did not brake prior to impact.
- Night vision AEB has the potential to reduce approximately 40% of moose car collisions in Sweden.
- It is suggested that road fencing is preferable on roads with a posted speed limit above 90 km/h,

and below 100 km/h, moose AEB have a potential to avoid fatal moose crashes.

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