INJURY RISK OF VULNERABLE ROAD USERS IN CASE OF ACCIDENTS WITH CRASH BAR EQUIPPED OFF-ROAD VEHICLES

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ABSTRACT

Off-road vehicles with and without crash bars were tested with the EEVC-WG 10 proposed sub-systems test procedure for pedestrian protection in order to get a better understanding of the potential harm crash bars present to vulnerable road users. The tests with the child headform impactor revealed that HIC values in excess of 1000 (which is the proposed limit at 40 km/h) can already be attained at impact velocities as low as 20 km/h. With the upper legform impactor, the test requirements were not satisfied, the crash bars falling short by a factor 2 to 3. These results are compared with test on normal passenger cars. Findings from real accidents involving off-road vehicles with and without crash bars and vulnerable road users which had been obtained by the Accident Research Unit of Hanover Medical University are presented and discussed with respect to the results of the sub systems tests.

OFF-ROAD VEHICLES are gaining in popularity in Europe. Although the name suggests that they are driven outside of public roads, they are mainly used in normal traffic. According to a survey undertaken by us, around 60% of off-road vehicles in Germany are equipped with crash bars of massive construction.

Due to the design of their front face, off-road vehicles present a greater danger to vulnerable road users than normal passenger cars. If these cars are fitted with crash bars, the danger is even more acute. In this paper, the additional risk to vulnerable road due to vehicle mounted crash bars is investigated. For this purpose, two different approaches are used:

- Off-road vehicles with and without crash bars were tested by BASt according to the EEVC-WG 10 sub-systems test procedure. The results are compared with tests performed on normal vehicles;

- Real accidents involving off-road vehicles surveyed by the Accident Research Unit of Hanover Medical University are investigated.

The findings drawn from both investigations are discussed and compared.

SUB-SYSTEMS TESTS ON OFF-ROAD VEHICLES

The tests were performed using the test method developed by EEVC-WG 10 for assessing the protection afforded to pedestrians by cars. According to the test specifications [1] the following impact situations are simulated by means of sub-systems test procedures:

- Impact of the leg of an adult to the bumper,

- Impact of the upper leg of an adult to the bonnet leading edge,

- Impact of the head of a child and an adult to the bonnet top.

For the tests special impactors are used which have been developed by INRETS (legform), TRL (upper legform), and BASt (headform). Acceptance levels are defined for each kind of impactor test.

Figure 1 illustrates the parts of the body which are especially endangered by off-road vehicles with and without crash bars. The heights of the bonnet leading edge and the bumper were measured as described in the EEVC-WG 10 test procedure. For the passenger cars, the values represent a mean of the 10 cars in Germany with the highest sales figures in the first quarter of 1994. The values for the off-road vehicles were determined from the two off-road vehicles tested in the test programme of Series B. The body dimensions of the pedestrians were taken from DIN 33 402.

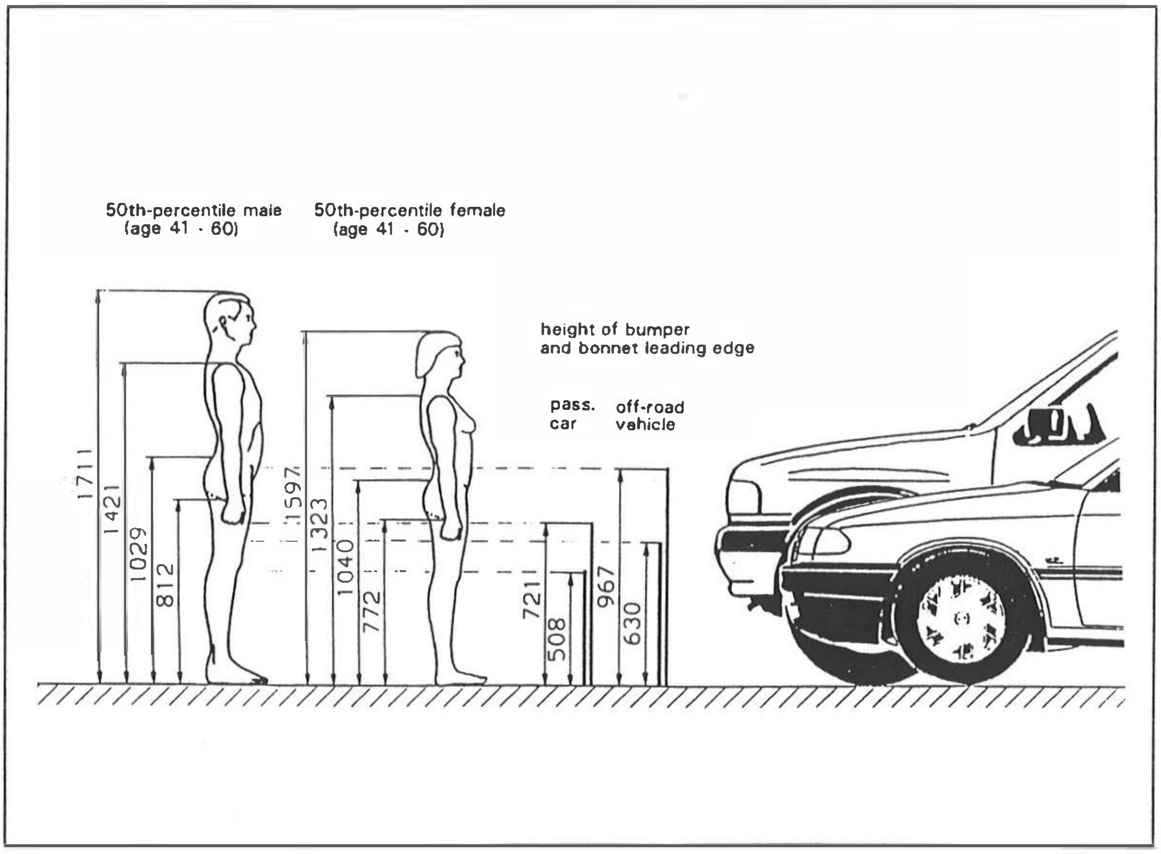

Figure 1: Dimensions of normal cars and off-road vehicles in comparison to pedestrians

As can be seen from Figure 1, crash bars represent a risk to the thigh, pelvis, and abdomen of adults. The height above street level of the upper tube can attain up to about 1,200 mm. Thus, crash bars represent a risk as well to the neck and head of children. With the EEVC-WG 10 test procedure, the behaviour of crash bars in a child's head impact and the adult's upper leg and leg impact can be assessed. This was done by BASt in two test series. The results were already reported in [2]. With respect to the following comparison with normal vehicles and the quantification of the additional risk, they are briefly summarised here again.

In a first approach, the injury potential of crash bars in a child's head impact was determined. The results shown in Table 1 demonstrate that especially crash bars with a large tube diameter (Car 3 and 4) are resulting in high HIC values even at low impact velocities. At impact velocities of 30 km/h, also bars with a smaller tube diameter (Car 1 and 2) are leading to HIC values exceeding the tolerance limit. For bars with a large tube diameter, the transition from tolerable HIC values (HIC ≤ 1000) to no longer tolerable HIC values (HIC > 1000) therefore takes place at impact velocities below 20 km/h and for bars with a small tube diameter at impact velocities between 20 km/h and 30 km/h.

Car	Exp.	Tube Diameter [mm]	v [km/h]	a max [g]	HIC
Car 1	S1	34	19.1	211.6	482
	S2	34	18.4	179.1	572
	S3	34	27.7 1)	378.4	1445
Car 2	O1	32	20.2	196.9	463
	O2	32	19.8	156.2	516
	O3	32 2)	20.2	341.5	1021
	O4	32	29.2 1)	313.0	1596
Car 3	M1	42	19.8	307.9	1174
	M2	42	19.8	281.7	965
	M3	32 2)	20.5	449.4	1811
Car 4	N1	43	19.8	382.1	2024
	N2	43/48 2)	19.8	409.6	1658
	N3	48	19.8	308.5	1220

1) increased impact velocity since HIC remained clearly below 1000 at nominal velocity of 20 km/h

2) connection of supporting element and tubes, or butt joint of tubes

Table 1: Child headform impactor, Series A crash bar test results

For a second test series (Series B), two off-road vehicles, Car 1 and Car 3, were procured. Car 1 represents an off-road vehicle with a relatively low bonnet leading edge. Crash bars mounted to this car are mostly of a less massive construction than bars for Car 3 which represents a typical car with a high bonnet leading edge. Whereas the crash bar for Car 1 was the same type in both test series, a more modern design was chosen in Series B for Car 3. These two cars were tested with all impactors of the EEVC-WG 10 test procedure. The legform impactors were kindly put at our disposal by INRETS and TRL through TNO channels.

The tests with the child headform impactor were performed at a nominal impact speed of 30 km/h, i.e. 75% of the required speed. The test results are listed in Table 2. Although the impact speed was reduced, all tests without crash bars resulted in HIC values exceeding 1000. This indicates that the bonnets of off-road vehicles are too stiff to meet the test requirements. If a crash bar is mounted to the vehicle, the HIC values rise up to a factor of six. The tests showed that the more solid crash bar construction of Car 3 resulted in a bigger increase of the HIC values.

Car	Exp.	crash bar	tube diam. [mm]	v [km/h]	a max [g]	HIC
1	KVKH	yes	34 [2)]	36.0 [1)]	247.0	2634
	KVKW	yes	34	26.3 [1)]	294.3	1368
	KVKW2	yes	34	30.2	352.1	3344
	KVOW	no	--	29.5	181.3	1654
	KVOH	no	--	30.6	194.7	1681
3	KPKK	yes	42/60 [2)]	31.3	694.0	6685
	KPKK2	yes	60	30.6	671.8	6070
	KPKM	yes	60	31.3	472.2	4573
	KPKA	yes	42	30.6	454.9	4287
	KPOM	no	--	30.6	168.9	1326
	KPOR	no	--	30.6	154.9	1085

1) impact speed more than 1.8 km/h below or above nominal

2) connection of supporting element and tubes, or butt joint of tubes

Table 2: Child headform impactor test results Series B

The tests with the upper legform impactor were performed at the nominal impact speed as defined in the EEVC-WG 10 test specifications. All impacts performed failed the pass criteria. Table 3 lists the maximum forces (acceptance level 4 kN) and the maximum bending moment (acceptance level 220 Nm). As a result, the cars with mounted crash bars clearly performed worse. Again, the more solid crash bar of Car 3 gave raise to the loadings by higher extend.

The legform impactor results are listed in Table 4. It should be noted that the impactor used in these tests was the 1993 INRETS prototype legform impactor. Unlike the results obtained with the other impactors, the crash bars did not demonstrate to have a negative influence on the loadings of the legform impactor. The bending angles (limit 15°) and shearing displacements (limit 6 mm) were generally higher without crash bars. For the accelerations (limit 150 g), the results did not show any general trend. As a result, it can be stated that at least the risk of ligament ruptures in the knee seems to be lower if off-road vehicles are equipped with crash bars.

Car	Exp.	crash bar	tube diameter [mm]	impactor mass [kg]	v [km/h]	max. force (sum) [kN]	max. bending moment [Nm]
1	HVKA	yes	34	14.8	36.7 1)	9.91	823
	HVKM	yes	34	14.8	41.0	9.50	638
	HVKK	yes	34 2)	14.8	36.7 1)	8.37	682
	HVOM	no	--	14.8	41.0	7.31	454
	HVOR	no	--	14.8	41.0	6.18	296
3	HPKA	yes	42	14.8	41.0	11.24	992
	HPKM	yes	60	14.8	41.0	9.98	909
	HPKK	yes	42/60 2)	14.8	41.0	10.49	666
	HPOM	no	--	14.8	38.2 1)	6.03	450
	HPOR	no	--	14.8	41.0	6.86	480

1) impact speed more than 5% below or above nominal (i.e. 40.0 km/h, resp. 40.7 km/h)

2) connection of supporting element and tubes, or butt joint of tubes

Table 3: Upper legform impactor test results Series B

Car	Exp.	crash bar	v [km/h]	a max [g]	bending angle [°]	displacement [mm]
1	LVKA	yes	39.6	166.8	46.2	11.3
	LVKM	yes	40.0	168.2	9.6	2.4
	LVKK	yes	40.0	240.1	45.2	11.0
	LVOM	no	42.1*)	178.1	53.9	13.0
	LVOR	no	43.2*)	99.6	47.1	11.5
3	LPKM	yes	40.0	126.5	10.7	2.7
	LPKA	yes	40.0	104.7	12.1	3.0
	LPKK	yes	41.0	292.0	34.9	8.6
	LPOL	no	41.0	251.7	47.8	11.6
	LPOM	no	40.0	131.3	47.2	11.5

*) impact speed more than 1.8 km/h below or above nominal

Table 4: Legform impactor test results Series B

DISCUSSION OF THE SUB-SYSTEMS TESTS

A quantification of the additional danger caused by crash bars shall be made in two respects:

- In comparison to off-road vehicles without crash bars,
- In comparison to normal passenger cars.

Normal passenger cars have been included because they are found to be equipped with crash bars in growing numbers. The rating should be made in a way that for normal passenger cars an averaged impactor loading for the respective kind of impact is determined. For this purpose, results from investigations by BASt and TRL are used. Then it is investigated at which impact speeds similar loadings are to be expected for off-road vehicles with and without crash bars.

CHILD HEADFORM IMPACTOR - Tests with the child headform impactor were performed by BASt on nine different passenger cars which had a total market share of more than 30% in Western Europe in 1990 [3]. The tests were performed at an impact speed of 40 km/h. The values obtained can be expected to be representative for current cars. The HIC values range from 600 to 7000. To average over such a big range seems not to be very meaningful. Figure 2 shows that around one half of the 75 tests resulted in a HIC of below 1400 and one half in one above that value. Thus, in the following 1400 should be taken as the HIC value to be expected in tests on normal cars.

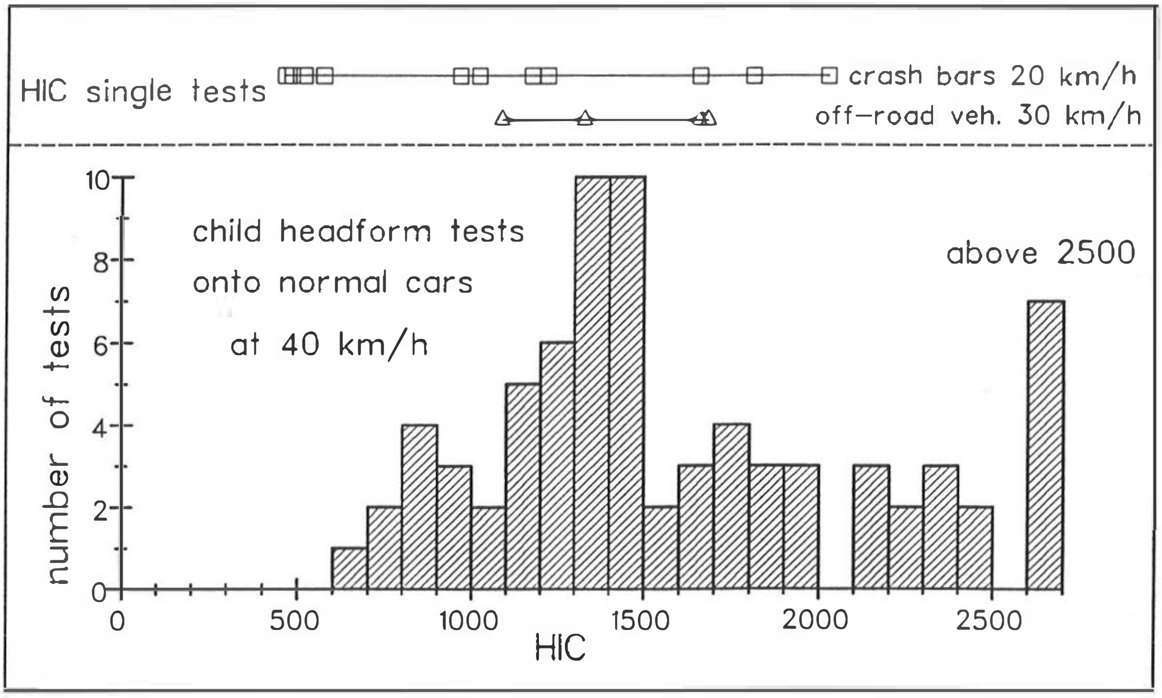

Figure 2: HIC values obtained with the child headform impactor in tests on normal cars, off-road vehicles, and crash bars

The tests on the off-road vehicles without crash bars resulted in HIC values from 1085 to 1681 at an impact speed of 30 km/h (c.f. Figure 2). Each two tests are below and above 1400. Therefore, it can be assumed that when impacting the bonnet leading edge of an off-road vehicle at 30 km/h the loading to the child's head is comparable to that of impacting a normal vehicle at 40 km/h.

It has been reported in [2] that HIC might not be a proper injury criterion for impacts to crash bars. This was because of a very short calculation interval for HIC (i.e. 0.9 ms to 2.9 ms), head acceleration exceeding 250 g even at HIC values below 1000, and a very local loading to the head. Neglecting these objections, we will focus on HIC values for the further discussion. In case of the direct impact to the crash bar, the HIC values at 30 km/h are considerably higher than 1400 (test KVKW yields a lower value but the impact speed was 3.6 km/h below nominal, cf. Table 2). Data from test series A (Table 1) show that crash bars of bigger tube diameter (Car 3 and 4) yield HIC values of about 1400 at speeds as low as 20 km/h. HIC values obtained with crash bars of smaller tube diameters (Car 1 and 2) are below 1400 at impact speeds of 20 km/h and considerably above 1400 at 30 km/h. The tests at enhanced speed were only performed at less stiff points of the bars. Thus, it can be concluded that with crash bars of smaller tube diameters a loading distribution similar to normal cars can be expected at around 25 km/h.

To compare the loadings, it has to be taken into account that the impact velocity of the child's head to the bonnet top of a normal car is lower than the collision speed of the vehicle and the pedestrian. The reduction in head impact speed is dependant on the car's shape and the height of the child. In case of an impact to the bonnet leading edge or to the crash bar, the head impact speed should be equal to the collision speed, and therefore higher than in the first case. Despite these differences, it can be stated that in case of a real accident at the following collision speeds a similar loading to a child's head is expected:

- Collision with normal car at 40 km/h,
- Collision with off-road vehicle at 30 km/h,
- Collision with crash bar equipped car at 20 km/h.

UPPER LEGFORM IMPACTOR - Tests with the upper legform impactor on normal cars were performed by BASt (3 cars) [4] and TRL (4 cars) [5]. The cars of both investigations were randomly selected models of the 80's. Compared to the tests with the headform impactor, the differences between the cars did not show to be as big. The results can thus be assumed to be comparative to those expected from the current car population.

Figure 3 shows that the two tested off-road vehicles are within the bandwidth of regular cars. Mounted with crash bars they performed considerably worse. The bending moments were raised by a higher extent than the forces. In the following, the worsening of the test results in the presence of crash bars should be discussed compared with off-road vehicles without crash bars. An equivalent collision speed cannot be determined since tests at lower impact speeds are not available. Tests performed by Lawrence [6] indicate that forces and bending moments increase linearly with velocity. Taking the mean value of the results from the off-road vehicle tests with and without crash bars and doing linear extrapolation, it turns out that a loading which occurs at 40 km/h without crash bars can be expected with bars already at 27 km/h for equivalent forces and at 21 km/h for equivalent bending moments. The equivalent speed can be rounded to be 25 km/h.

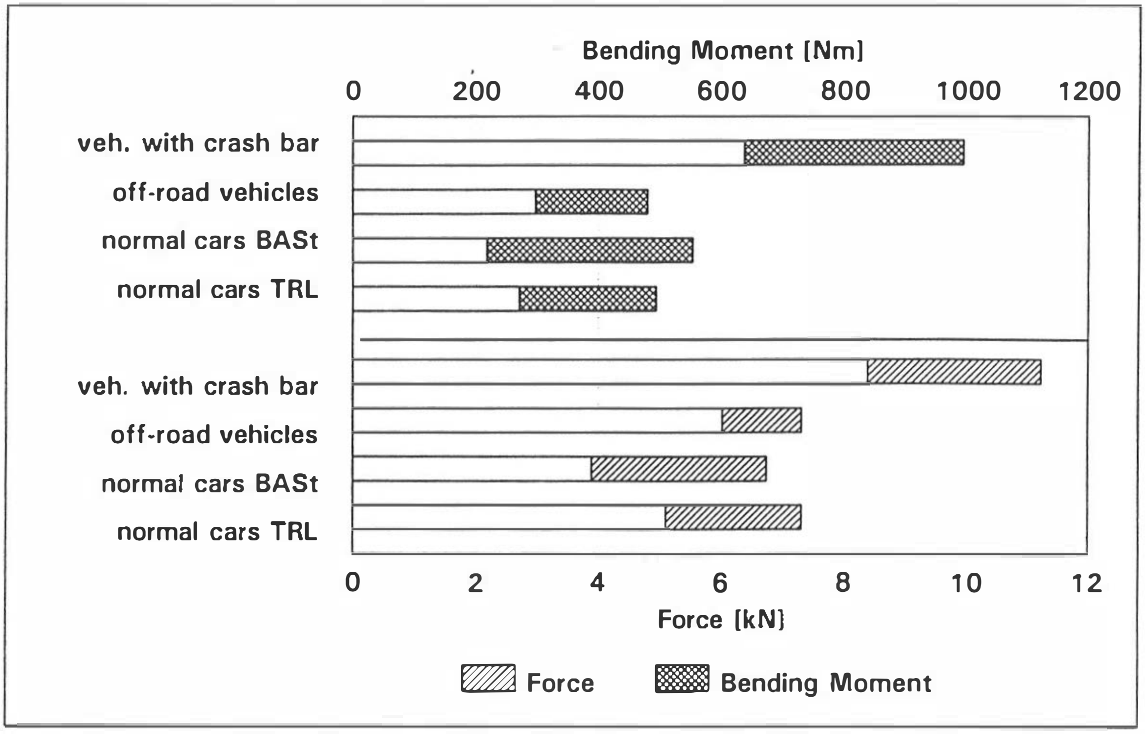

Figure 3: Range of test data obtained with the upper legform impactor in tests onto normal cars and off-road vehicles with and without crash bars

The upper legform impactor was constructed to simulate the impact of the femur. Due to the high bonnet leading edge of off-road vehicles, direct impacts of the pelvis should occur more frequently (cf. Figure 1). It can be assumed that a speed equivalence as for the femur can also be valid for pelvis impacts. It can be concluded that for femur and pelvis impacted with the bonnet leading edge, the following collision speeds are equivalent:

- Collision with normal car or off-road vehicle at 40 km/h,
- Collision with crash bar equipped car at 25 km/h.

LEGFORM IMPACTOR - Legform impactor tests with three normal cars were performed by BASt [4]. The bandwidths of the results are given in Figure 4. These show that the results obtained on off-road vehicles with crash bars are of the same magnitude as those from normal vehicles. Off-road vehicles without crash bar showed a higher loading to the kneepiece. So it has to be concluded that crash bars can reduce the loading to the knee.

It should be discussed how this finding is to be interpreted. The impactor was designed to simulate the leg impact to the bumper of normal cars. On normal cars the bumper is within the height of the tibia. Therefore, the impactor is only equipped with an accelerometer at its tibia part. When impacting an off-road vehicle (with or without crash bar) the first bumper-impactor contact occurs in the femur part of the impactor. This results in a relatively low acceleration of the tibia. As a matter of fact, the accelerometer readings are not directly comparable to those of normal cars. By mounting a crash bar onto the off-road vehicle, the point of first contact can be raised even further. With regard to the loadings in the kneepiece, it can be stated that the further it is away from the initial point of contact the more the loading is reduced.

This has to be kept in mind when considering the legform impactor results. Because of the high point of first contact when impacting the crash bars, the tibia and knee are out of direct danger, but, as demonstrated before, by simultaneously increasing the risk to the femur.

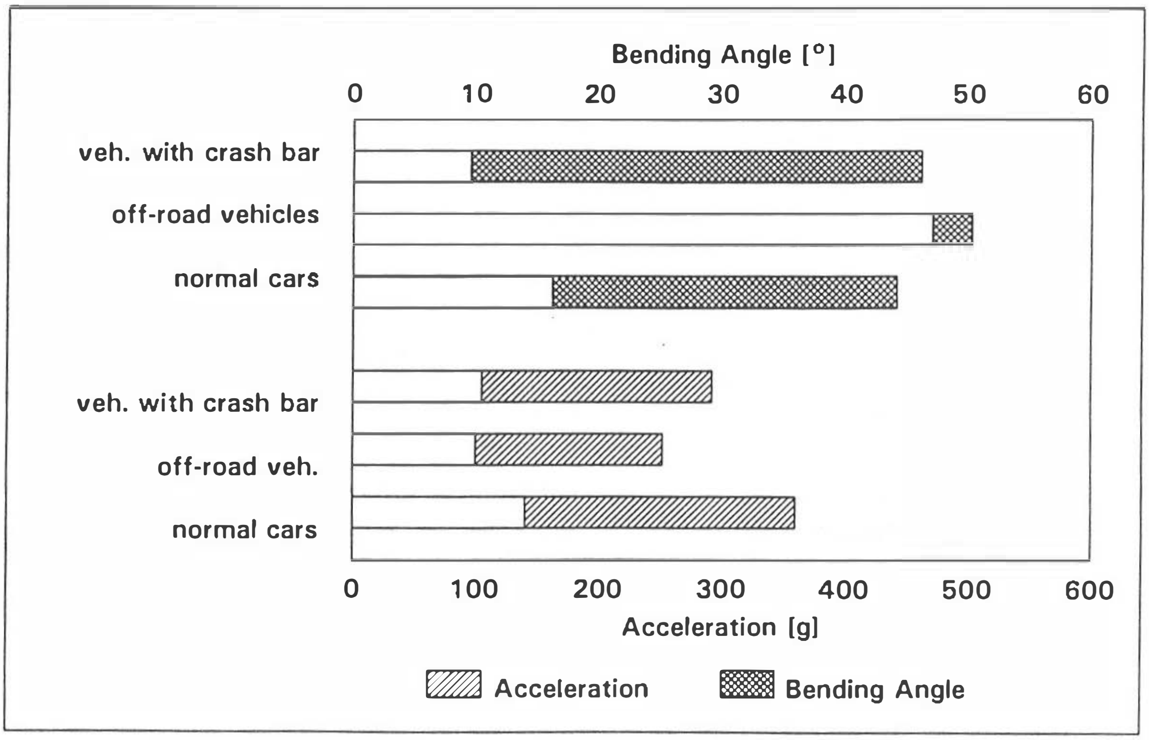

Figure 4: Range of test data obtained with the legform impactor in tests on normal cars and off-road vehicles with and without crash bars

REAL ACCIDENTS WITH OFF-ROAD VEHICLES

Commissioned by the Federal Highway Research Institute (BASt), around 1000 traffic accidents have been documented annually by the Accident Research Unit of Hanover Medical University. The working method of the team is described in [7].

off road vehicles with crash bar
collision speed 7 km/h, pedestrian, aged 54; injuries: contusion pelvis AIS 1, abrasion knee AIS 1, fracture toes AIS 1.
collision speed 13 km/h, bicyclist, aged 11; injuries: contusion upper leg AIS 1.
collision speed: 33 km/h, pedestrian, aged 54; fracture ala of the ilium AIS 2, fracture acetabulum AIS 2, small contusion pelvis AIS 1, contusion lumbar spine AIS 1, ligamentary injury knee AIS 2.
collision speed 40 km/h, pedestrian, aged 8; abrasion ankle joint AIS 1, abrasion pelvis AIS 1.
collision speed 46 km/h, bicyclist, aged 37; contusions lower extremities AIS 1, laceration upper leg AIS 2, closed fracture fibula AIS 2, Weber-C fracture tibia AIS 3.
collision speed 69 km/h, pedestrian, aged 30; no injuries to lower extremities/pelvis (pedestrian jumped in front of the car).
collision speed 77 km/h, bicyclist, aged 73; fracture 10th and 16th vertebra AIS 2 (first impact at the corner of the car).

Table 5: Accidents involving off-road vehicles with crash bars and pedestrians or bicyclists, injuries to the lower part of the body

off-road vehicles without crash bar
collision speed 10 km/h, bicyclist, aged 23; no injuries to lower extremities/pelvis.
collision speed 18 km/h, pedestrian, aged 7; abrasion knee AIS 1.
collision speed 20 km/h, bicyclist, aged 47; abrasion knee AIS 1, abrasion ankle joint AIS 1, contusions upper leg AIS 1.
collision speed 27 km/h, bicyclist, aged 59; major contusion pelvis AIS 1, contusions lower extremities AIS 1.
collision speed 37 km/h, bicyclist, aged 45; abrasion sacrum AIS 1, contusion lumbar spine AIS 1.

Table 6: Accidents involving off-road vehicles without crash bars and pedestrians or bicyclists, injuries to the lower part of the body

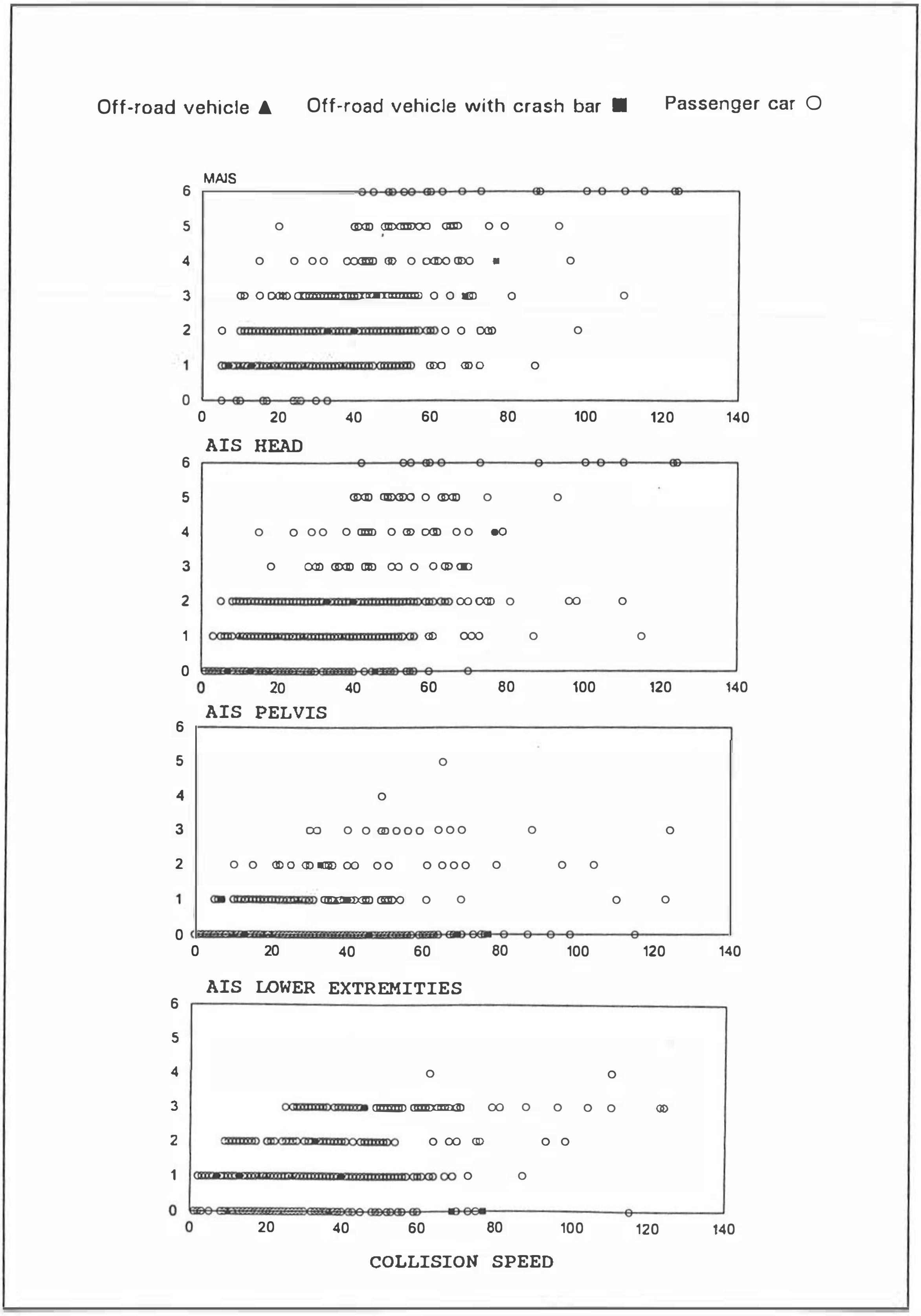

Figure 5: Injury severity as a function of speed in accidents involving pedestrians and bicyclists and normal cars or off-road vehicles with and without crash bars

For this study, motor vehicle accidents involving pedestrians or bicyclists were investigated for the years 1985 to 1993. A total of 1659 accidents in which the vulnerable road user was struck by the front face of a passenger car is comprised in the accident sample. Among them are 7 cases involving off-road vehicles with crash bars (0.4%) and 5 cases involving off-road vehicles without crash bars (0.3%). A brief overview of the accidents and the injuries to the lower part of the body is given in Tables 5 and 6.

The few cases collected thus far preclude a statistical evaluation. Therefore, they are looked at as single cases. In Figure 5 the injury severity in relation to the collision speed is shown in comparison to normal passenger cars. For off-road vehicles (with or without crash bars) the overall injury severity MAIS shows no significant behaviour. Head injuries tend to be less severe in accidents with off-road vehicles. This is obviously related to the shape of the car which leads to a different kinematics of the vulnerable road user. It should be noted that no direct head impact of a child to a crash bar is documented in the accident sample.

For pelvis injuries, no influence of the car can be detected from Figure 5. Concerning leg injuries, the crash bar equipped vehicles are found to be at the lower end of the tolerance range, indicating an increased risk of severe leg injuries at lower speeds.

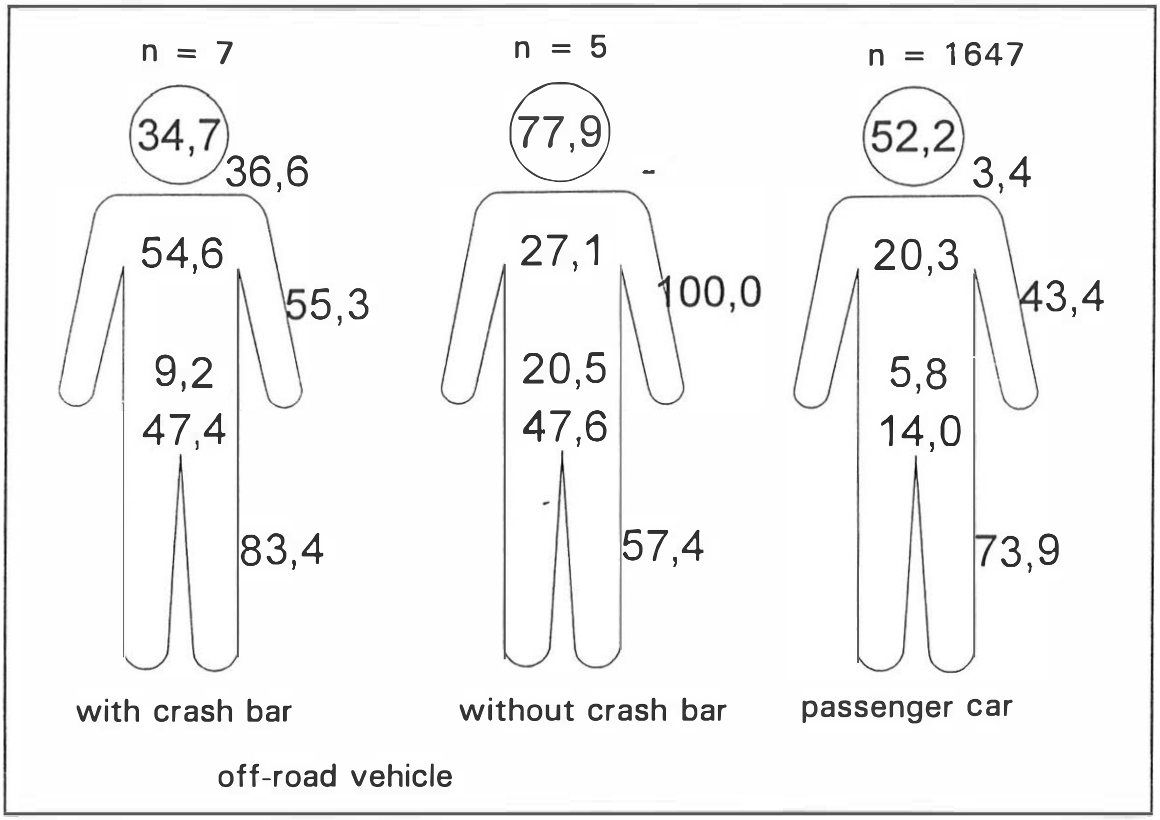

Figure 6: Frequency of injury to different body parts of the vulnerable road user in accidents involving pedestrians and bicyclists and normal cars or off-road vehicles with and without crash bars

The small number of cases makes it difficult to quantify the additional risk for vulnerable road users from Figure 5. Despite the reservations due to the small numbers, another figure should be added. Figure 6 shows the parts of the body injured in the accident sample as a result of statistical weighting (Note: in the Hanover accident data set, minor injuries are underrepresented when compared with the official accident statistic of the Hanover area. Therefore, in the statistical weighting, injuries of a low AIS grade are taken into account to a higher extent). As a result, pelvis injuries occurred more frequently with off-road vehicles. This can be directly related to the higher bonnet leading edge. No increased risk of pelvis injuries could be detected if the off-road vehicles were equipped with crash bars. Leg injuries were found to be more frequent when a crash bar is mounted to the car.

CONCLUSIONS

Crash bar equipped off-road vehicles represent a new trend in the car fleet. Our investigation indicates that they strongly increase the risk of injury in accidents with pedestrians or bicyclists. The sub-systems tests clearly showed an increased risk of child's head and adult's leg and pelvis injuries. The finding in respect to leg injuries was established by real world accidents. Due to the small number of cases collected by now, the increased risk for child's head impact could not be established thus far, but the sub-systems test results are convincing by its own. The risk of injury in a child's head impact to a crash bar equipped car at 20 km/h is expected to be equal to this in an impact to a regular car at 40 km/h or to an off-road vehicle without crash bar at 30 km/h. In respect to adult's leg or pelvis injuries it figured out that in an impact to an crash bar at 25 km/h the same injury severity is expected as in an impact to a car without crash bar at 40 km/h.

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