

VARIATION OF CRASH SEVERITY AND INJURY RISK DEPENDING ON COLLISIONS WITH DIFFERENT VEHICLE TYPES AND OBJECTS

Helena Stigson, Anders Ydenius, Anders Kullgren
Karolinska Institutet, Sweden, Folksam Research, Sweden

ABSTRACT

Real-life crashes with cars fitted with on-board crash pulse recorders were used to study the influence of their collision partner, in both two- and single-vehicle crashes, on crash severity and injury risk. The crash severity was lower in single-vehicle crashes compared with two-vehicle crashes. Both average change of velocity and mean acceleration were lower and average pulse duration was longer in collisions with deformable objects compared with collisions with fixed objects. In frontal two-vehicle crashes the average change of velocity in crashes with passenger cars was 21.3 km/h, while it was 35.8 km/h in collisions with trucks. The difference corresponded to an increased average risk of MAIS2+ injury with almost 5 times. The corresponding values for mean acceleration were 6.3 g and 8.8 g respectively, which corresponded to a doubled risk. In rear-end crashes the average change of velocity in crashes with passenger cars was 9.8 km/h, while it was 16.3 km/h in collisions with trucks. The corresponding values for average mean acceleration were 3.7 g and 4.4 g respectively, meaning a doubled average risk of long-term whiplash injury symptoms. In frontal single-vehicle crashes the average mean acceleration in collisions with deformable objects was 4.5 g and in collisions with fixed objects 6.2 g. The increase corresponded to an almost three times higher average risk of an MAIS2+ injury.

Keywords: Accelerations, Accident Analysis, Change of Velocity, Crash Pulse Recorder, Injury Risk

IN 2001 THE EUROPEAN COMMISSION put up a goal regarding road casualty reduction within the EU member states. The number of road deaths shall be halved in 2010. To achieve this target lots of actions need to be taken. Head-on collisions, collisions with fixed roadside objects and side impacts at junctions account for most crashes with serious or fatal injuries (NHTSA 2005, SIKI 2005). However, the majority of long-term disabling injuries occur in rear impacts, often causing soft tissue neck injuries (Kullgren et al. 2002, Krafft 1998, Nygren 1984). Further knowledge of the interaction between roads and vehicles and how crash severity is influenced by the other vehicle or object is needed. Such knowledge and further understanding of the relation between crash severity and injury outcome can be improved by analyzing real-life impacts with recorded crash severity in terms of acceleration-time history.

Crash severity

The crash severity level a human is exposed to during a crash depends on several factors, such as relative velocity between the case vehicle and its collision partner, the mass and structure of the case vehicle and its collision partner, and the crash situation including impact angle, overlap etc. The collision partner could be a vehicle or roadside object. But the various crash severity parameters, such as change of velocity, mean and peak acceleration are differently influenced by these factors. The change of velocity is primarily influenced by car mass and only to a small degree influenced by the stiffness of the involved vehicles and objects, while vehicle acceleration depends on all the factors mentioned. Therefore the vehicle acceleration and change of velocity will be differently influenced by the collision partner depending on their mass and structure, such as stiffness. Such influences can be calculated on theoretical basis. But with help of real-life data with recorded crash pulses they could be verified under real-life conditions.

In most studies presenting correlation between crash severity and injury outcome, impact severity is described as change of velocity, ΔV , calculated from the vehicle exterior deformation and/or by for example using the law of conservation of momentum. One problem with such calculations is the lack of accuracy of the output. Studies of the magnitude of such errors often indicate standard deviations between 10% and 15%, but also a systematic underestimation of between 11% and 33% (Lenard et al. 1998, Nolan et al. 1998, Stucki and Fessahaie 1998, O'Neill 1994). The magnitude of the errors also depends on crash type and collision partner (Lenard et al. 1998, Stucki and Fessahaie 1998). The use of on-board measurement devices, such as crash pulse recorders, may help to improve the accuracy in such reconstruction calculations (Kullgren 1998). Such devices also entail us the possibility to measure acceleration during the crash phase. Previous studies, based on real-life collisions with cars fitted with crash pulse recorders, have shown that mean acceleration during the crash phase of a car crash well predicts and to a large extent influences the risk of being injured in collisions (Kullgren 1998, Ydenius and Kullgren 1999, Krafft et al. 2002, Krafft et al. 2005). Correlation between injury risk in frontal impacts versus crash severity (change of velocity, mean and peak acceleration) recorded by crash recorders has been presented by Kullgren (1998), Ydenius and Kullgren (2001) and Ydenius and Kullgren (2006).

Ydenius and Kullgren (2001) have also shown that a large duration of a crash pulse is not critical for the injury risk. The finding is important for the possibility of protecting car occupants in high speed crashes. With the use of deformable road side objects, such as deformable guard rails and lamp posts, acceleration levels may be kept below critical levels likely to cause serious or fatal injuries.

In rear-end crashes, correlation between injury risk and both mean acceleration and change of velocity have been found (Krafft et al. 2002, Krafft et al 2005). The influence of collision partner, both regarding kerb weight and frontal structure of the striking car in a rear-end collision, has been studied in real-life collisions (Krafft 1998). A heavier car seems to increase the injury risk of long-term disability from an AIS 1 neck injury, but there is a large difference in injury risk between different car models with identical kerb weight. Other vehicle parameters than kerb weight have effect on the injury risk. Krafft (1998) showed that car models with longitudinally mounted engines cause higher injury risk than cars with transversally mounted engines. Further knowledge from real-life data regarding the influence of collision partner on crash severity and thereby also on injury risks in rear-end crashes is needed.

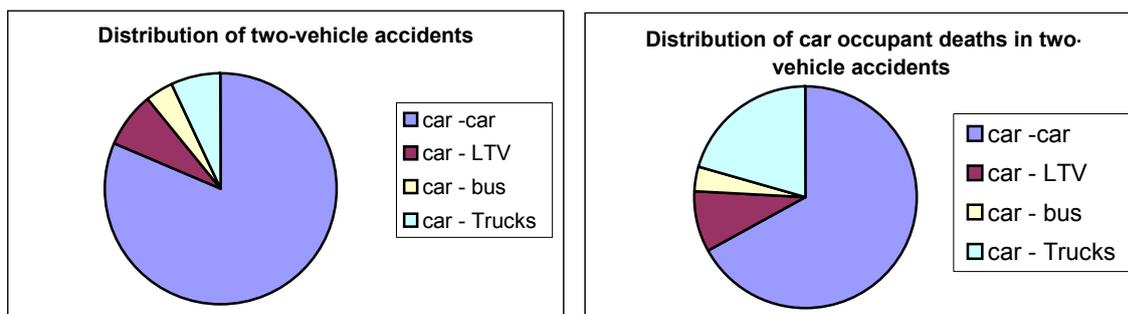


Fig. 1 - Distribution of two-vehicle crashes (Department of transport, 2005)

Two-vehicle crashes

The distribution of the total number of two-vehicle crashes differs from the distribution of fatalities. Collisions between cars and trucks are not so frequent, but they account for a large proportion of fatal injury crashes (Department of transport 2005, SIKI 2005, NHTSA 2004), see Fig. 1. The distribution of car occupant deaths in the US differs a lot from Europe. Two-vehicle crashes between cars and light truck vehicles (LTV) including MPVs, sports utility vehicles and light trucks, account for nearly the same number of car occupant deaths as in car-to-car collisions (O'Neill, 2004). There are large differences within vehicle fleets between Europe and the US, both concerning size and mass. Of all vehicles registered in 2005 the proportion of large vehicles is greater in the US than in the Northern European countries (BIL Sweden 2006, R. L. Polk Marketing Systems 2006). The average kerb weight

of the new sold passenger vehicles in the US is 1750 kg compared to 1420 kg in Sweden. In two-vehicle crashes the differences in size, mass and height of the vehicles will influence the crash severity (Hollowell et al. 2002, Hibino et al. 1996, Evans, 1991). Joksch et al (1998) has shown that in two-vehicle crashes involving a passenger car the fatality rate is higher in crashes with LTVs than with passenger cars even if their masses were identical. Collisions with different vehicle types often result in underride/override due to geometric mismatching, and thus increases the risk for occupant compartment intrusion and thereby injury risk. Furthermore, Kullgren et al (2001) has shown the influence of mass and structure for different size categories on injury risk in the other vehicle, where small cars appear to be somewhat stiffer than large passenger cars. Further knowledge of how size and vehicle type influence the acceleration in real-life crashes is needed in order to better understand the different injury outcomes in real-life crashes.

Single-vehicle crashes

Collisions with fixed objects in the roadside area constitute a major problem since they account for between 18 and 42 percent of all fatalities in Europe (ETSC 1998, Department of Transport 2005, SIKI 2005). The same problem has been found in Victoria, Australia, and in the US, where this collision type accounts for more than one third (Delaney et al., 2003) and more than one fifth (IIHS, 2005) of all fatalities. Many studies from different countries have found that trees account for the vast majority of fixed objects leading to fatalities (Evans 1991, Delaney et al. 2003, IIHS 2005). The intention with using deformable objects instead of non-deformable ones is to lower vehicle acceleration in a crash. The resulting vehicle acceleration in a crash must always be kept below critical levels likely to cause an injury. Crash tests indicate reductions in vehicle acceleration for many types of such objects (Steffan et al. 1998, Kloeden et al. 1999, Ydenius and Kullgren 2001). In crash tests with three different types of guard rails and crash barriers Ydenius et al (2001 A) showed that the type of barrier has large influence on the mean acceleration.

Furthermore, in a collision with narrow objects like poles and trees, the load will often be concentrated to only a small part of the car. Therefore only a minor part of the energy absorption structure will be involved (Durisek et al 2004). Durisek et al. (2005) showed different vehicle response in crash test with poles depending on impact location. The vehicle response to impact depends on characteristics of the involved part of the vehicle front. Further attention needs to be paid on the performance of deformable objects under real-life conditions, especially regarding their influence on vehicle acceleration and thereby injury risk.

Aims

The aims with this study were to present differences in average crash severity depending on collision partner, and to compare those differences to injury risks, both in frontal and rear-end two-vehicle crashes and in single-vehicle crashes into fixed and deformable objects.

MATERIAL AND METHODS

Crash recorder data from the Swedish insurance company Folksam were used to determine average change of velocity and mean and peak accelerations of cars depending on their collision partner. The average crash severity was determined for front seat occupants in both frontal and rear-end two-vehicle crashes, and for front seat occupants in single-vehicle crashes into various roadside objects. The two-vehicle crashes were divided according to the size of the collision partner, see Table 1, from very small cars to trucks. The single-vehicle crashes were divided according to type of object, see Table 2, with special reference to whether the object was deformable or not. In total 417 occupants in frontal crashes, whereof 244 in two-vehicle and 173 in single-vehicle crashes, and 189 occupants in rear-end crashes with recorded crash pulses were included.

Impact severity was measured with a crash pulse recorder (CPR), which measured the acceleration time history in the impact phase. The study includes both frontal and rear impacts where the acceleration was measured in the principle direction of force within +/- 30 degrees. Crash pulses were filtered at approximately 60 Hz. Change of velocity and mean and peak accelerations were calculated from the crash pulses. Since 1992, CPRs have been installed in approximately 220,000 vehicles comprising 4 different car makes and 29 models in Sweden aimed at measuring frontal and rear

impacts. The car fleet has been monitored since 1992, and every frontal crash with a repair cost exceeding 5000 EUR and all rear-end crashes, irrespective of repair cost, has been reported.

Regarding to the collision partners and objects a mix of vehicle sizes and types were included and categorized in different size classes based on a combination of wheelbase, total length and width, see Equation 1 (from Ydenius et al. 2001 B). Passenger cars were split into four classes; Superminis, Small Family Cars, Large Family Cars and Executive Cars. The SUVs, MPVs and light trucks were summed into one group denoted LTVs. Large trucks and buses were also summed into a separate group, see Table 1. In the single-vehicle crashes the objects were divided in five groups, see Table 2. Table 1 and Table 2 also present average kerb weight of the cars fitted with crash recorders divided into groups with different collision partners. For each average value of crash severity, a 95% confidence interval was calculated.

$$\text{Size index} = \text{wheelbase} + 0,4(\text{total length}) + 1,5(\text{width})$$

Equation 1

Table 1. Average kerb weight for cars in frontal and rear-end crashes with other vehicles in various categories

Collision partner	Frontal crashes		Rear-end crashes	
	Average kerb weight (kg)	n	Average kerb weight (kg)	n
Superminis	1250	16	1250	8
Small Family Cars	1240	45	1160	53
Large Family Cars	1250	54	1230	30
Executive Cars	1270	89	1240	57
LTVs	1160	12	1200	29
Buses and Trucks	1310	28	1140	12
Total	1250	244	1200	189

Table 2. Average kerb weight for cars in single-vehicle crashes and definitions of objects

Collision partner	Definition	Average kerb weight (kg)	n
Deformable guard rail	Semi-rigid guard rails and flexible guard rails	1200	23
Poles	Deformable poles and rigid poles	1290	26
Deformable objects	Deformable guard rail and poles	1240	49
Roadside area	Ditch, embankment and slope	1270	53
Trees		1300	28
Other rigid objects	Rigid guard rails, fences, stones, cliffs etc.	1260	43
Fixed object, total	Roadside area and Trees, Other rigid objects	1280	124
Total		1260	173

In order to relate the differences in average crash severity to injury risk, average change of velocity and mean acceleration were compared with injury risk curves. The comparisons were made for rear-end and frontal crashes separately. In frontal impacts a study from Ydenius and Kullgren (2006) was used, see Fig. 2 and Fig. 3. In the paper from Ydenius and Kullgren risk curves for MAIS1+, MAIS2+ and MAIS3+ injuries for belted occupants versus various crash severity parameters are presented. In the study approximately four fifth of the cars were fitted with driver airbags. Both crashes with and

without intrusion into the occupant compartment were included. Thus the injury risk curves only show the correlation between injury risk and crash severity based on vehicle acceleration. In this study only risk of an MAIS2+ injury versus change of velocity and mean acceleration is used. For rear-end crashes a study by Krafft et al (2005) was used, see Fig. 4 and Fig. 5. In that paper risk of whiplash injuries with various symptom duration was shown. In this study only risk of whiplash symptoms for more than one month is used. By correlating the average values of crash severity to injury risk for the various collision partners, changes in risk could be estimated.

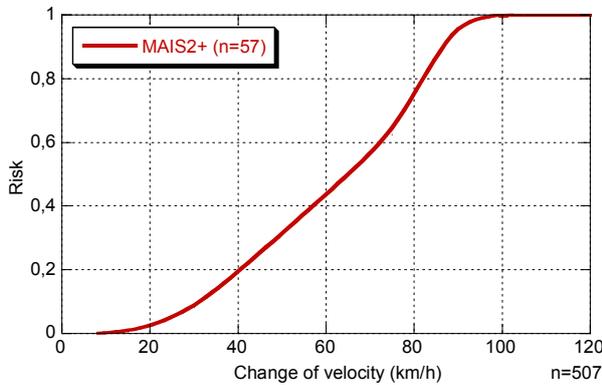


Fig. 2 - Risk of an MAIS2+ injury in frontal impacts versus change of velocity for front seat occupants (from Ydenius and Kullgren 2006).

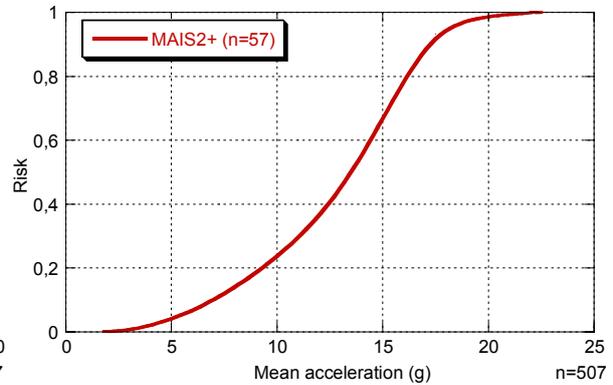


Fig. 3 - Risk of an MAIS2+ injury in frontal impacts versus mean acceleration for front seat occupants (from Ydenius and Kullgren 2006).

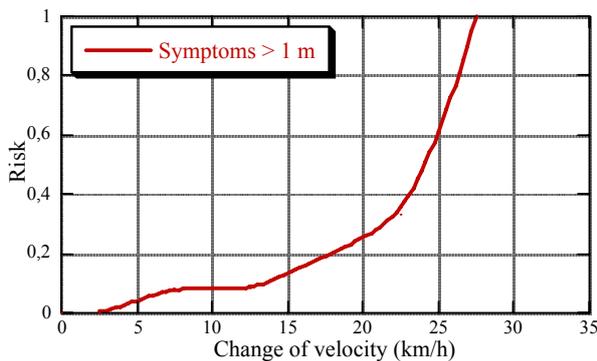


Fig. 4 - Risk of whiplash injury with symptoms for more than one month in rear-end crashes versus change of velocity (from Krafft et al 2005).

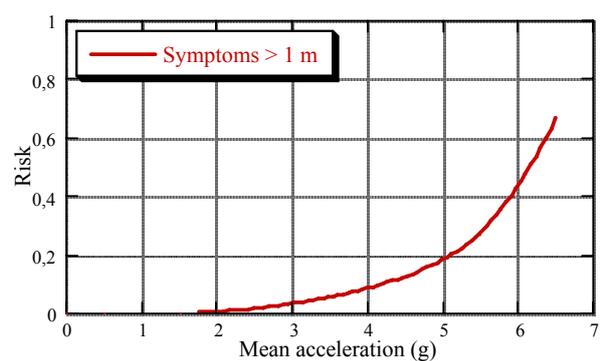


Fig. 5 - Risk of whiplash injury with symptoms for more than one month in rear-end crashes versus mean acceleration (from Krafft et al 2005)

RESULTS

In frontal two-vehicle crashes the average change of velocity for front seat occupants in vehicles with crash recorders varied in accordance with the mass of the collision partner, see Table 3. Highest average change of velocity was found in crashes with Trucks, 35.8 km/h, and lowest in crashes with Superminis, 18.2 km/h. It appears like the mean acceleration is not following the same pattern, although the highest average mean acceleration was found in crashes with Trucks, 8.8 g, and lowest in crashes with Superminis, 5.5 g, see Table 3. Crashes with Small Family Cars appear to have generated somewhat higher mean acceleration than Large Family Cars.

In rear-end crashes the average change of velocity was similarly influenced by car mass, while only small differences were found for mean acceleration, see Table 4. Hence, the average pulse duration was longer in collisions with trucks. The average change of velocity for all frontal two-vehicle crashes was twice as high as the value of all rear-end crashes, while the corresponding

difference for mean acceleration was 40%. In rear-end crashes collisions with Trucks generated the highest average change of velocity of 16.3 km/h.

In single-vehicle crashes average mean acceleration was 41% higher in collisions with trees and fixed objects compared to collisions with deformable objects, see Table 5. Collisions with trees had the highest average change of velocity and mean acceleration, while collisions with poles had pulses with lower average mean acceleration and longer duration than collisions with other objects.

When comparing the average crash severity measurements with injury risk curves some changes could be identified. In frontal two-vehicle crashes the increase in average change of velocity between collisions with passenger cars (21.3 km/h) and with trucks (35.8 km/h) corresponds to an increased average risk of MAIS2+ injury with almost five times (from 3% to 14%). The corresponding increase in mean acceleration (from 6.3 g to 8.8 g) corresponds to a more than twice as high average risk (from 8% to 18%).

In rear-end crashes the increase in both average change of velocity and mean acceleration between collisions with passenger cars and with trucks (9.8 km/h to 16.3 km/h and 3.7 g to 4.4 g) corresponds to a doubled average risk of whiplash injury with symptoms for more than one month (from 8% to 17% and from 7% to 13% respectively).

In frontal single-vehicle crashes the increase in average change of velocity between collisions with deformable (15.2 km/h) and with fixed objects (22.8 km/h) corresponds to an increased average risk of an MAIS2+ injury of four times (from 1% to 4%). The corresponding increase in average mean acceleration (from 4.5 g to 6.2 g) corresponds to an increased average risk of almost three times (from 3% to 8%).

Table 3. Frontal crashes with different collisions partners

	Average change of velocity, ΔV (km/h)	Average mean acc. (g)	Average peak acc. (g)	Average duration (ms)	n
Superminis	18,2 ± 3,8	5,5 ± 0,9	14,4 ± 3,4	93,2 ± 8,8	16
Small Family Cars	21,2 ± 3,3	6,7 ± 0,9	17,4 ± 2,5	91,9 ± 6,2	45
Large Family Cars	21,8 ± 3,3	6,0 ± 0,7	15,4 ± 2,4	99,0 ± 5,6	54
Executive Cars	24,1 ± 3,8	6,9 ± 0,9	17,4 ± 2,5	95,2 ± 4,8	89
Passenger Cars	21,3 ± 2,0	6,3 ± 0,5	16,1 ± 1,4	94,8 ± 2,1	204
LTV	28,6 ± 4,7	7,2 ± 1,3	15,8 ± 4,0	112,4 ± 14,6	12
Bus	24,9 ± 13,0	6,2 ± 2,4	16,71 ± 10,4	89,2 ± 16,0	10
Trucks	35,8 ± 14,3	8,8 ± 2,7	20,7 ± 7,5	109,1 ± 8,5	18
Bus and Trucks	30,3 ± 10,1	7,5 ± 1,9	18,7 ± 6,0	99,1 ± 7,7	28
LTV, Bus and Trucks	29,7 ± 7,1	7,4 ± 1,4	17,7 ± 4,3	103,6 ± 6,9	40
Total	24,9 ± 2,0	6,7 ± 0,5	16,8 ± 1,4	98,4 ± 2,7	244

Table 4. Rear-end crashes with different collisions partners

	Average change of velocity, ΔV (km/h)	Average mean acc. (g)	Average peak acc. (g)	Average duration (ms)	n
Superminis	9,8 ± 3,3	3,5 ± 0,9	8,5 ± 2,5	74,8 ± 13,8	8
Small Family Cars	9,7 ± 1,4	3,9 ± 0,4	8,7 ± 0,9	67,4 ± 5,1	53
Large Family Cars	8,6 ± 1,6	3,5 ± 0,4	7,5 ± 1,4	60,1 ± 8,9	30
Executive Cars	11,2 ± 1,8	3,8 ± 0,4	8,6 ± 0,9	78,9 ± 6,7	57
Passenger Cars	9,8 ± 0,7	3,7 ± 0,2	8,3 ± 0,4	70,3 ± 2,9	148
LTV	10,8 ± 1,9	3,8 ± 0,5	8,4 ± 1,4	79,1 ± 9,4	29
Trucks	16,3 ± 3,7	4,4 ± 0,6	9,2 ± 1,2	106,1 ± 18,0	12
LTV and Trucks	13,5 ± 4,3	4,1 ± 1,0	8,8 ± 2,6	92,6 ± 18,6	41
Total	11,1 ± 0,8	3,8 ± 0,2	8,5 ± 0,5	77,7 ± 3,4	189

Table 5. Single-vehicle crashes with different collisions partners

	Average change of velocity, ΔV (km/h)	Average acc. (g)	Average peak acc. (g)	Average duration (ms)	n
Deformable guard rail	16,1 ± 3,0	4,8 ± 0,9	12,8 ± 2,6	98,7 ± 14,6	23
Poles	16,3 ± 2,3	4,1 ± 0,6	10,4 ± 1,3	113,7 ± 15,2	26
Deformable object	15,2 ± 1,8	4,5 ± 0,5	12,7 ± 1,4	97,5 ± 10,5	49
Roadside	18,1 ± 2,6	5,0 ± 0,6	11,8 ± 1,5	98,1 ± 8,4	53
Tree	25,6 ± 6,8	7,1 ± 1,7	16,6 ± 3,9	98,1 ± 7,4	28
Other rigid objects	24,8 ± 5,0	6,5 ± 1,3	16,6 ± 3,5	106,3 ± 9,6	43
Fixed Objects	22,8 ± 2,5	6,2 ± 0,6	15,0 ± 1,6	100,9 ± 3,7	124
Total	19,8 ± 1,9	5,5 ± 0,5	14,1 ± 1,2	99,5 ± 4,0	173

DISCUSSION

In order to achieve the target for road casualty reductions it is important to know how crash severity should be limited to avoid injuries. The crash recorder data, achieved from studies of real-life crashes, gives a unique possibility to study these limits, especially regarding vehicle acceleration. Such limits may serve as guidelines in the design of a crashworthy road transport system.

Limitations

The data was limited to 29 car models of 4 car makes with on-board crash pulse recorders. The number of crashes was relatively low, especially regarding single-vehicle crashes and collisions with heavy vehicles. Also the number of impacts at high impact severity was relatively low. One of the inclusion criteria for frontal crashes was a repair cost of at least 5000 EUR. This limit excludes most of the crashes at a change of velocity, ΔV , below 10 km/h.

The average kerb weights of the cars with on-board crash pulse recorders were nearly the same for the collisions with vehicles of different size categories and roadside objects. The influence on the results by these differences could therefore be anticipated to be small.

In the crashes with deformable and fixed objects in the roadside area, the lateral distance between the object and roadway shoulder varied, which could have an influence on the velocity before impact.

The risk curves used for correlating average crash severity to injury risk, Ydenius and Kullgren (2006) and Krafft et al (2005), were based on mainly data from one car manufacturer. Therefore, it is not possible to generalise the results to the whole car fleet. Furthermore the risk curves do not reflect influence of intrusion on injury risk, but only parameters related to vehicle acceleration. However, in this study the objective was not to study influence of collision partner on intrusion.

The crash pulse recorder has a trigger level of approximately 3 g. In collisions with deformable objects the acceleration will be relatively low compared to collisions with rigid objects. The total change of velocity measured by the crash pulse recorder will therefore often be too low in these collisions. Information at the beginning and sometimes at the end of the crash pulse may be lost. The mean acceleration may because of that also be somewhat lower than the true value, but not to the same degree as for the change of velocity.

Vehicle types within the category LTVs could not be separately analysed due to the limited number of crashes available. It could be anticipated that the vehicle acceleration in collisions with these vehicle types; MPVs, SUVs and light trucks, will vary. Further research is necessary with more data.

Two-vehicle crashes

It was found that Small Family Cars cause higher acceleration than Large Family Cars in both frontal and rear-end crashes. These differences between the four passenger car categories could be explained by different stiffness of the frontal structure. Small Family Cars seem to be stiffer than Large Family Cars. The same relation has also been presented by Kullgren et al (2001). It could be a consequence of the improvement in frontal crash tests that require stiffer front ends. On the other

hand, Superminis were found to have lowest mean acceleration of all car categories. The stiffness property only has a small influence on the change of velocity. Instead the differences in change of velocity depend on the mass of the collision partners. Heavier collision partners result in higher change of velocity and thereby higher injury risk. Based on the average change of velocity, the corresponding injury risk was more than four times higher in a collision with a truck than in crashes with a passenger car. Such differences can also be seen in the Swedish national statistics on road traffic accidents. In 2004, collisions between trucks/buses and passenger cars accounted for 25 percent of all two-vehicle-crashes with severe injuries and 52 percent of all fatalities in Sweden (SIKA, 2005). The numbers are very high in comparison to the 10% proportion of trucks/buses registered in Sweden (SCB 2002).

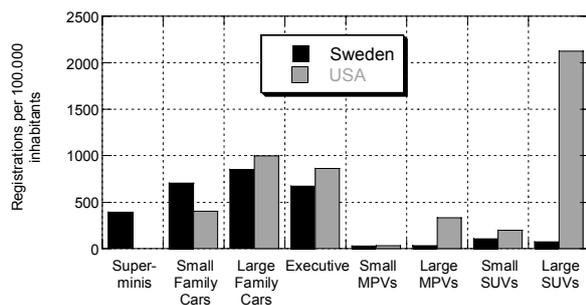


Fig. 6 - The 100 most sold passenger vehicles in Sweden versus US during 2005. (Source BIL Sweden and R. L. Polk Marketing Systems).

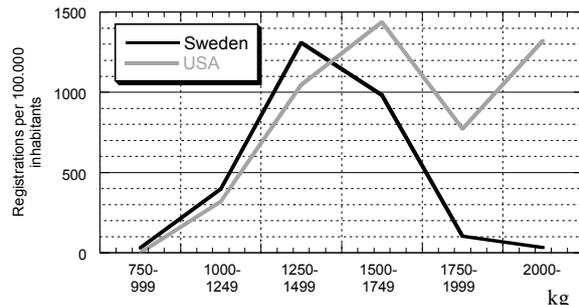


Fig. 7 - The 100 most sold passenger vehicles in Sweden versus US during 2005. (Source BIL Sweden and R. L. Polk Marketing Systems)

Both the US and the Swedish passenger car fleets include vehicles with a wide mass-range, but the proportion of heavy vehicle is larger in the US, see Fig. 6 and Fig. 7. In 2005 the new sold passenger vehicles in the US were dominated by large SUVs (43 %) and the average kerb weight of the new sold passenger vehicles in the US were 1750 kg compared to 1420 kg in Sweden. The average passenger vehicle in the US can be compared with the category LTVs included in this study. Because of the larger proportion of very heavy vehicles in the US, the problem of incompatibility is larger in the US compared to the situation in Sweden. Several studies in the US have analysed the risk of death in collisions between different types of vehicles (Acierno et al. 2004, O'Neill et al. 2004, Summers et al. 2003). Summer et al. (2003) showed that a large passenger car is twice as high aggressive than a small passenger car in a car-to-car crash. The death rate was significantly higher in cars colliding with LTVs than in car-to-car crashes. LTVs were more than three times as aggressive as average passenger cars in all two-vehicle crashes. The result in this study points in the same direction. Lund and Chapline (1999) showed that 700 lives per year in the US could be saved if the lightest cars (kerb weight >1,135 kg) and SUVs were replaced.

In Northern Europe large trucks and buses constitute the largest incompatibility problem since they account for 52 percent of all fatalities in two-vehicle crashes (SIKA 2005). To prevent head-on collisions with trucks guard rails as median barrier have been shown to be an effective technical solution (Elvik 1995). Such barriers are important to avoid collisions with trucks and other heavy vehicles. But also other solutions are needed to reduce the high acceleration levels in crashes between cars and heavy vehicles. For example re-designing front ends of trucks is needed to reduce the vehicle acceleration and thereby reduce the serious consequences in frontal crashes with cars, even on roads with low speed limits.

In rear-end crashes the size of the collision partner only seems to have minor influence of the mean acceleration. Krafft (1998) found a correlation between the kerb weights of the striking car and the injury outcome, but on the other hand there was a large difference in injury risk between car models with identical kerb weight. The findings indicate that there are other vehicle parameters or crash severity parameters that influence the risk of soft tissue injury in rear-end crashes. Previous studies,

based on real-life crashes, have found a correlation between mean acceleration and whiplash injuries. Most whiplash injuries leading to long-term disability occur between 3 and 6 g (Krafft et al., 2005). As seen in Fig. 5 the risk of whiplash injury increase rapidly above 4g and the mean acceleration should therefore be kept under this level. Therefore the small differences found in this study may have a large influence on the number of injured in rear-end crashes.

Mismatching of car geometry influences crash incompatibility since energy absorbing structures will fail to engage in crashes between vehicles of different geometry. This can result in override and underride, and therefore larger occupant compartment intrusion (O'Neill et al., 2004). Override or underride in a rear-end collision may have a positive effect on the vehicle acceleration. This could be an explanation for the small differences in average mean acceleration for crashes with different vehicle categories found in this study.

Single-vehicle crashes

The average crash severity was found to be lower in single-vehicle crashes compared to two-vehicle crashes. In single-vehicle crashes the duration was longer than in two-vehicle crashes. It was also found in a previous study (Ydenius et al., 1999). Ydenius et al. (1999) found that the initial acceleration of the crash pulse seems to be lower in single-vehicle crashes than in two-vehicle crashes. The rate of deployed airbags was lower in single-vehicle crashes, which also indicate that the crash severity is lower in single-vehicle car crashes than in two-vehicle crashes. However, in this study the average mean acceleration of a two-vehicle crash was found to be similar as in collisions with rigid objects, such as trees. Trees were found to generate the highest crash severity, which also can explain why trees account for the majority of single-vehicle crashes with serious or fatal injury outcome in Europe (ETSC, 1998).

Results from this study indicate that collisions with poles lead to relatively low crash severity. Both crashes with deformable poles and rigid poles are included in this study. The average mean acceleration was 46% lower in collisions with poles compared to collisions with trees. A reason for this result may be that the pole relents or that the intrusion of the frontal vehicle structure was more favourable in collisions with poles than with trees. Durisek (2005) showed in crash test with poles that impacts that cause intrusion in the centre of the vehicle front give a lower acceleration until the object fully engage the engine than if it involved the frame rail. In collision with trees compared to poles the engagement of the engine may be more frequent and larger, and therefore the crash type will produce higher crash severity.

The result in this study with deformable and fixed object seems to agree with the result from the crash test with different types of guard rails. Steffan et al. (1998) and Ydenius et al. (2001 A) showed that deformable objects give a longer duration and thereby lower vehicle acceleration than a rigid barrier. Elvik (1995) showed, as early as 1995, the potential of preventing traffic casualties by using guard rails. The accident rate would increase with 30 % but the number of fatalities and personal injuries would be reduced by 20 % and 10 % respectively by using median barriers (Elvik 1995). He also found that using guard rails to protect the vehicle of running off the road would reduce the fatality rate with 45 % and personal injuries with 50 %. Probably the positive effect of using flexible guard rails like wire rope barriers is even higher.

The future road transport system must be more prepared for limiting the consequences of road crashes. The infrastructure plays an important role to avoid critical crashes or to design the road transport system based on the human tolerance to injuries. Good examples are separating lanes, advanced guard rails etc. This study illustrates the difference in crash severity depending on collision partner and indirectly it indicates the type of crash situations that are more critical than others. However, further studies with more data are necessary to better understand the relationship in the road transport system.

CONCLUSIONS

- Both average change of velocity and mean acceleration were lower in single-vehicle crashes compared with two-vehicle crashes.

- Both average change of velocity and mean acceleration were lower and average pulse duration was longer in collisions with deformable objects compared with collisions with fixed objects.
- In frontal two-vehicle crashes the average change of velocity in crashes with passenger cars was 21.3 km/h, while it was 35.8 km/h in collisions with trucks. The difference corresponded to an increased average risk of MAIS2+ injury with almost 5 times (from 3% to 14%). The corresponding values for average mean acceleration were 6.3 g and 8.8 g respectively, which corresponded to a doubled risk (from 8% to 18%).
- In rear-end crashes the average change of velocity in crashes with passenger cars was 9.8 km/h, while it was 16.3 km/h in collisions with trucks. The corresponding values for average mean acceleration were 3.7 g and 4.4 g respectively. The differences corresponded to a doubled average risk of whiplash injury with symptoms for more than one month.
- In frontal single-vehicle crashes the average mean acceleration in collisions with deformable objects was 4.5 g and in collisions with fixed objects 6.2 g. The increase corresponded to an increased average risk of an MAIS2+ injury of almost 3 times (from 3% to 8%).

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