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Neck injuries in frontal impacts: influence of crash pulse characteristics on injury risk

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Abstract

AIS1 neck injuries are the most frequent disabling injuries among car occupants in road traffic accidents. Although neck injury is mostly regarded as resulting from rear end collisions, almost one third of all neck injuries occur in frontal impacts. The injury mechanisms in both rear-end and frontal impacts are still not known, although different hypotheses exist. Since 1992, approx. 100 000 vehicles on the Swedish market have been equipped with crash recorders to measuring frontal impacts. This paper analyses the influence of different characteristics derived from the acceleration time history on the risk of short- and long-term disability to the neck in frontal impacts. The study includes injury outcomes from 187 restrained front seat occupants in 143 frontal collisions with an overlap exceeding 25%, where the crash pulses have been recorded using crash pulse recorders. The results show that the shape of the crash pulse influences the risk of long-term disability to the neck. The vehicle accelerations in the mid and last third of the crash pulse seem to be important. It is also shown how change of velocity and mean and peak accelerations influence the neck-injury risk. It is suggested that the risk of sustaining an AIS1 neck injury in frontal impacts could be reduced by using more effective pretensioners and more advanced belt-load limiters. These results may also have implications for neck injury mechanisms in rear-end impacts.

Keywords: Neck injuries; Crash pulse recorder; Crash recorder; Long-term consequences; Frontal impacts; Acceleration

1. Introduction

The number of fatalities and severe injuries among car occupants have been reduced in recent years (Vägverket, 1997; Elvik et al., 1997). One explanation is that the level of passive safety in new car models has increased dramatically (Larsson et al., 1998), especially concerning reduction of skull/brain injuries (Krafft et al., 1998a). There is, however, one injury that has increased substantially, both in terms of risk and in number. In England the incidence of neck injuries has been shown to have doubled over a 10-year period (Morris and Thomas, 1996). Krafft (1998) has shown that there is a 2.7 times higher risk of sustaining disability to the neck in cars launched at the end of the 1980's and in the beginning of the 1990's compared to those launched at the beginning of the 1980's. AIS1 neck injuries have become the major disability caused by collisions with modern vehicles. It has been shown that approx. 60% of the injuries causing disability in Sweden between 1990 and 95 were AIS1 neck injuries (Krafft, 1998).

Nygren (1984) found that 10% of the occupants in rear impacts and 5% of the occupants in frontal impacts that reported initial whiplash symptoms suffered permanent disability at least 1 year after the collision. In most research on AIS1 neck injuries, only the initial symptoms have been studied. It is, however, important to separate the analyses for initial and residual symptoms since there may be different injury types with different injury mechanisms. Spitzer et al. (1995) defined those patients with remaining symptoms more than 6 months after the crash as long-term consequences. Especially the long-term consequences may be the main problem regarding AIS1 neck injuries.

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Injuries to the neck are often regarded as a problem in rear-end impacts. However, 27% of the AIS1 neck injuries occur in frontal impacts (Galasko et al., 1993). The AIS1 neck injury mechanisms in different collision modes are still not known. Different hypotheses exist concerning injury mechanisms in rear-end impacts, covering both flexion (v Koch et al., 1995), extension (Mc Connell et al., 1995) and hyper-extension (States, 1979). In frontal collisions, Larder et al. (1995) found that no head contact with the interior of the vehicle compartment had been noticed and the forward flexion of the neck was assumed to be the injury-causing motion. Walz and Muser (1995) described the motion of the head relative the neck in a frontal collision with no head contact. For a restrained occupant in the initial phase of a collision a purely translational motion occurs (Ewing et al., 1975) forming an S-shape of the cervical spine. After that the cervical spine is forces into flexion (Walz and Muser, 1995). Walz and Muser suggested that neck injury may occur in such acceleration mechanisms.

Several technical solutions aimed to decrease the neck injury risk in rear-end impacts have been launched in the last few years (Wiklund and Larsson, 1998; Lundell et al., 1998; Sekizuka, 1998). The injury-preventive effect in these solutions have, however, not yet been validated.

Several studies show that the neck injury risk is associated with seat-belt use (Otremski et al., 1989; Larder et al., 1995). Galasko et al. (1993) found an increase in neck injuries from 8–21% associated with an increase in belt wearing rates in the UK. In the studies mentioned above, it is unknown if the increase occurred in all impact directions.

Regarding impact severity, studies have shown a correlation between change of velocity and initial neck injury symptoms in rear impacts (Ryan et al., 1994; v Koch et al., 1995). However, Krafft (1998) found that given an initial neck injury, there was not a higher change of velocity in the struck cars leading to long-term consequences than those leading to short-term consequences. This indicates that the acceleration levels seemed to influence the disability risk to a higher extent. Also Olsson et al. (1990) found similar results. Results from real-life rear-end impacts where the crash pulse has been measured with a crash pulse recorder indicate that acceleration levels seem to better explain the neck injury risk than does change of velocity (Krafft et al., 1998b). In frontal impacts, little is known about how impact severity relates to neck injury risk. Norin et al. (1997) found that the neck injury risk increased very slowly with increased impact severity measured in Equivalent Barrier Speed, EBS. The link between neck injury risk in frontal impacts and impact severity parameters based on acceleration levels remains unknown, since such measurements require on-board measurement techniques, which would enable measurements of the crash pulse.

In analyses of injury risks in real-life collisions, it is important to determine adequate, valid and reliable impact severity parameters which influence the injury risk (Kullgren and Lie, 1998). The possibilities of using different impact severity parameters in retrospective reconstructions methods are limited. Most reconstruction methods use EES (Zeidler et al., 1985) or change of velocity to describe impact severity. Attempts have also been made to estimate mean acceleration (Peugeot-SA/Renault, 1991). However, other impact severity parameters may better relate to injury risk. A study by Kullgren (1998) showed that mean and peak accelerations separately better explain the overall injury risk than does change of velocity. Since the injury risk may depend on several parameters in the crash phases of an impact, it is important to have better reconstruction methods, where adequate severity parameters can be measured or reconstructed with accuracy.

The aim of this study was to show how the shape of the crash pulse influences short- and long-term AIS1 neck injuries based on results from real-life frontal impacts where the crash pulses were measured with crash pulse recorders. Another aim was to propose and recommend possible solutions aimed at decreasing the neck injury risk in frontal impacts.

2. Material/methods

Impact severity was measured with a crash recorder, called Crash Pulse Recorder (CPR), which measured the acceleration time history in the impact phase in one direction. Crash pulses were filtered at approximately 60 Hz. Change of velocity and mean and peak accelerations were calculated from the crash pulses. The CPR and the analysis of the recordings from the CPR have been described by Aldman et al. (1991) and Kullgren et al. (1995).

Since 1992, CPRs have been installed in approx. 100 000 vehicles, comprising four different car makes and 15 models. The car fleet has been monitored for 5 years, and every accident with a repair cost exceeding 7000 USD has been reported via a damage warranty insurance. The accident data collection system has previously been described by Kamrén et al. (1991). At the time this paper was written, approx. 400 accidents had been reported. This study includes 187 restrained front seat occupants in 143 frontal collisions with an overlap exceeding 25%. Belt use has been verified from inspections of the seat belt system. One hundred and thirty-three of the front seat passengers were male and 54 were female. In 24 of the collisions there was a deployed driver-side airbag and in two there was a deployed passenger-side airbag.

The injuries were classified according to the 1985 revision of the Abbreviated Injury Scale (AAAM, 1985). Only AIS1 neck injuries were considered in this study. The neck injuries were divided in short- and long-term consequences. The injury reports were collected directly after the accident, questionnaires were sent to the occupants. A follow-up after at least 6 months was also done by telephone interview. When the occupants recovered within 6 months the injuries were classified as short-term consequences. Occupants with remaining symptoms more often than once every second week, mainly pain, for more than 6 months were classified as long-term consequences. In Sweden it may take several years after an accident before a medical disability can be verified by a doctor. In three cases a medical disability was verified by a doctor and in seven cases it was recorded by telephone interviews.

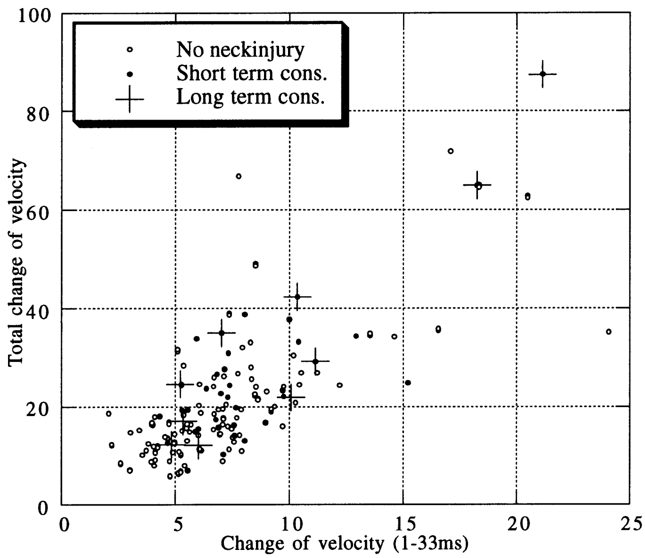

Fig. 1. Total ?V vs. ?V between 1 and 33 ms for the uninjured and the short- and long-term consequences to the neck.

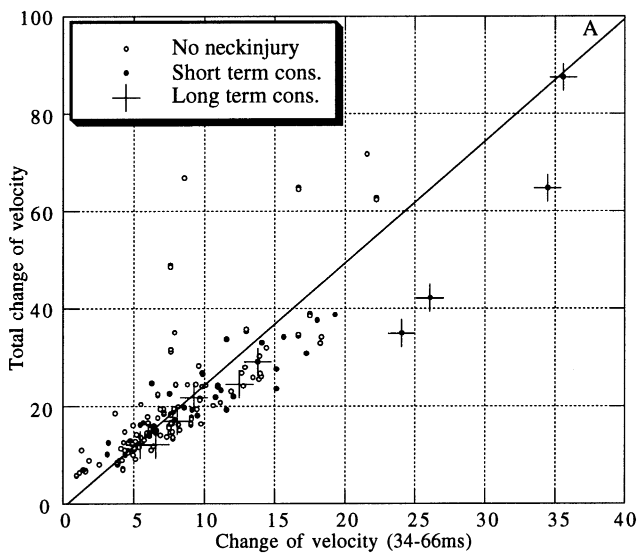

Fig. 2. Total ?V versus ?V between 34 and 66 ms for the uninjured and the short- and long-term consequences to the neck.

The crash pulses were divided into intervals of 33 ms, which is one third of a normal crash pulse. The change of velocity in each interval was used to show how the different parts of the pulse influence the AIS1 neck injury risk. The influence of the difference in change of velocity between the different 33 ms intervals of the crash pulse on injury risk was also studied. The parameters were plotted versus each other and the injuries regarding short- and long-term consequences were separated. This was done to illustrate how different impact severity parameters influence the injury risk and to determine whether the relation for short- and long-term consequences to impact severity differs. Mean values for the different impact severity parameters as well as the mean pulses were also calculated for uninjured, short- and long-term consequences. The crash pulses were based on the mean values for each 33 ms interval.

Data from four crash tests with eight involved vehicles were used to determine the moment of contact between the occupant and the seat belt in the crash phase of an impact. The tests were car-to-car tests with 50% overlap and with a test speed of 64 km/h for each vehicle. Two identical cars, except for the vehicle mass, were used in each test. To be able to obtain different changes of velocity for the involved vehicles, one of the vehicles in each test was approximately 300 kg heavier than the other. Four of the vehicles were modern cars with a stiff structure, while 4 were older models. The horizontal acceleration measurements in the chest of the Hybrid III dummy at the driver position were compared with the acceleration measurements in the vehicle, measured at the sill below the B-pillar. In one of the tests pretensioners together with airbags were used in both cars.

3. Results

Out of 187 occupants in 143 collisions, 42 reported an AIS1 neck injury and 10 out of these 42 sustained long-term consequences.

Figs. 1, 2 and 3 show the relationship between the total change of velocity versus the change of velocity for three different time intervals, 1–33 ms, 34–66 ms and 67–99 ms, for uninjured and for short- and long-term consequences. Fig. 2 shows that the likelihood of sustaining long-term consequences to the neck were larger if the change of velocity in the mid part of the crash pulse was high. Fig. 3 shows that there was a high risk of long-term consequences if the part between 67 and 99 ms of the pulse had a small change of velocity. In Fig. 4 it is shown that a large change of velocity in

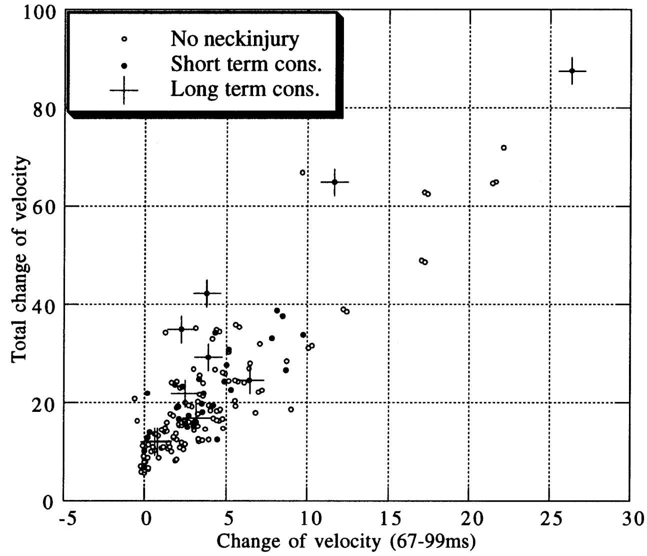

Fig. 3. Total ?V versus ?V between 67 and 99 ms for the uninjured and the short- and long-term consequences to the neck.

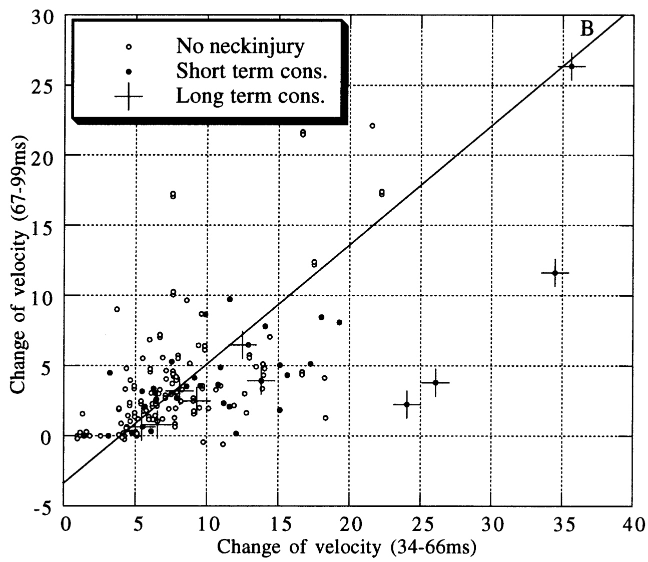

Fig. 4. ?V for part 2, 34-66 ms vs. ?V for part 3, 67–99 ms for the uninjured and the short- and long-term consequences to the neck.

the 2nd part of the pulse and a small change of velocity in the 3rd part of the pulse result in high neck injury risk. Fig. 5 illustrates how a large difference between the 2nd and 3rd part of the pulse results in a high risk of long-term consequences.

Line A in Fig. 2 splits the samples in the scattered graph into two halves. A 100% of the long-term consequences and 74% of the reported initial symptoms were below that line. A similar line has been drawn in Fig. 4, line B. A 100% of the long-term consequences and 71% of the reported initial symptoms were below that line. Also in Fig. 5 a similar line has been drawn, line C, where a 100% of the long-term consequences and 71% of the reported initial symptoms were to the right of that line.

In all collisions above line A in Fig. 2, with a total change of velocity of more than 35 km/h, there was no reported neck injury. Above line A, 87% of the occupants did not report a neck injury, while below that line, 68% did not. Fig. 5 shows that if the difference between the 2nd and 3rd part of the pulse was less than 5 km/h, no injuries resulted in long-term consequences and only a few resulted in short-term consequences. To the left of line C, 87% of the occupants did not report a neck injury, while to the right of that line, 68% did so. To the left of line C there is a low risk for both short- and long-term consequences to the neck. These results indicate that if the change of velocity or mean acceleration of the 3rd part of the pulse is almost the same as for the 2nd part, or if the change of velocity in the 3rd part of the pulse is larger than in the 2nd, the risk of sustaining a neck injury leading to long-term consequences seems very low, even in more severe impacts with high mean acceleration and large change of velocity.

Table 1 shows mean values for total ?V and the ?V in each interval of the crash pulse as well as the difference between part 2 and 1 and between part 2 and 3. There is a significantly larger change of velocity for long-term consequences in part 2. This fact also entails that the differences between part 2 and 1 and between part 2 and 3 are significantly larger for long-term consequences. It is also shown that a high total ?V as well as high mean and peak accelerations result in high risks of sustaining long-term consequences to the neck. From Table 1 it can be calculated that of these three impact severity measures, the largest relative difference be-

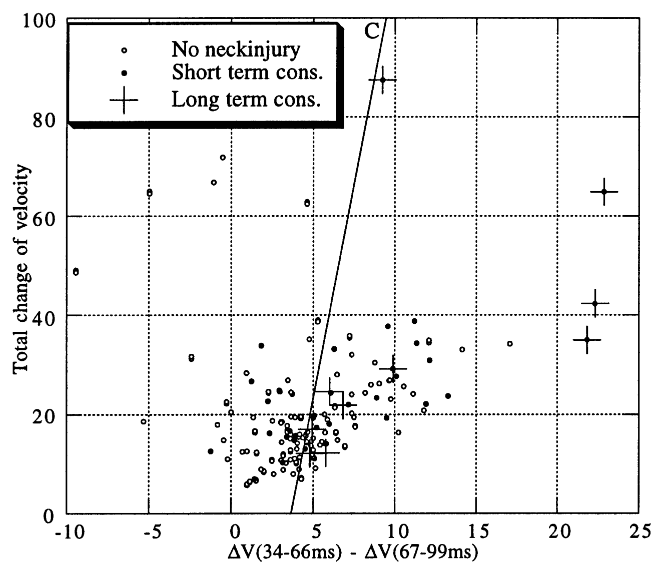

Fig. 5. Total ?V vs. the difference between ?V between 34 and 66 ms and ?V between 67 and 99 ms for the uninjured and the short- and long-term consequences to the neck.

Table 1
Mean values for different impact severity parameters for the uninjured and the short- and long-term consequences

	Mean DV (km/h)						Mean accelerations (g)	
	Part 1 (1–33 ms)	Part 2 (34–66 ms)	Part 3 (67–99 ms)	Difference (Part 2–Part 1)	Difference (Part 2–Part 3)	Total DV	Total mean acceleration	Total peak acceleration
No injury	7.3	8.6	4.1	1.3	4.5	21.5	5.7	15.3
Short-term	7.7	9.9	3.8	2.1	6.1	22.1	6.1	15.9
Long-term	9.9	17.6	6.1	7.6	11.4	34.6	9.0	27.5

Table 2
Crash test vehicles illustrating the moment of contact between the occupant and the seat belt

Vehicle	Test speed (km/h)	DV (km/h)	Vehicle mean acc (g)	Pretensioner/airbag	Belt contact at (ms)
1H	63.5	60	12.8	No	40
1L	63.5	70	14.0	No	30
2H	64.5	59	9.8	No	50
2L	64.5	70	10.8	No	35
3H	65.0	58	10.2	No	52
3L	65.0	71	11.7	No	33
4H	64.5	61	12.7	Yes	30
4L	64.5	73	14.6	Yes	17

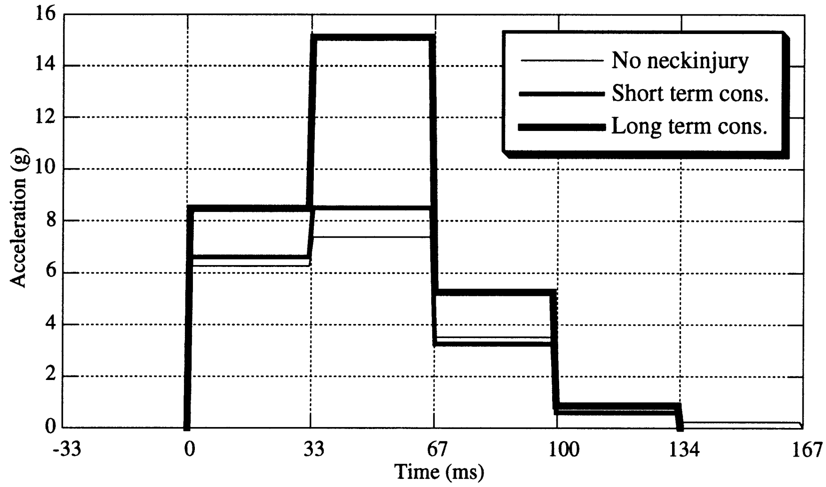

Fig. 6. Mean crash pulses for the occupants with no reported neck injury and for those with short- and long-term consequences.

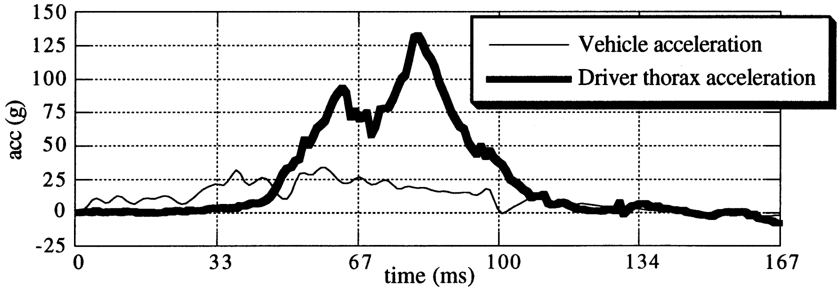

Fig. 7. Vehicle and driver thorax acceleration in vehicle 1L.

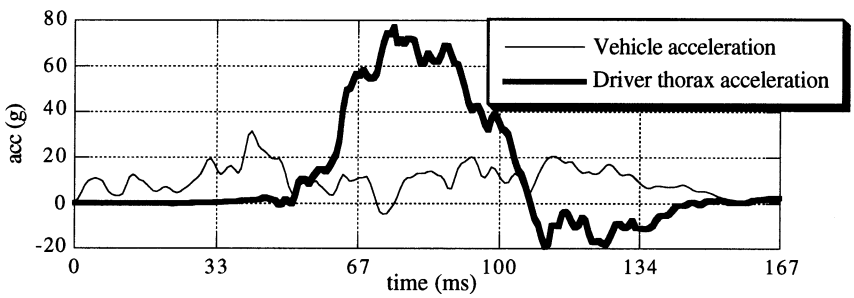

Fig. 8. Vehicle and driver thorax acceleration in vehicle 3H.

tween occupants sustaining long-term consequences and occupants that did not report a neck injury was obtained for the total mean acceleration. The mean total ?V for injuries resulting in long-term consequences was 34.6 km/h, ranging from 13 to 87 km/h. The figures from Table 1 have been used to draw the pulses in Fig. 5. In Fig. 5 there is substantial change in acceleration at 67 ms for occupants that sustained long-term consequences. There is also a slightly higher change for those that sustained short-term consequences than for those with no reported neck injury.

The crash tests showed that in a frontal impact, when the car starts to decelerate, the occupant will keep on moving forward with the initial velocity until the occupant comes into contact with the seat belt. Table 2 shows that the occupants in the crash tests started to decelerate due to the seat belt at between 30 ms and 52 ms depending on the vehicle's acceleration Fig. 6. The acceleration levels were significantly lower for the older car models, where the compartments had severe intrusion. Vehicle 1H, 1L, 4H and 4L were of the same car model. In vehicle 4H and 4L pretensioners and airbags were used. The pretensioners decreased the time until the moment of belt contact by 10 ms for the vehicle with low mean acceleration and by 13 ms for the vehicle with high mean acceleration. The crash pulses from four of the tested vehicles are presented in Figs. 7–9 and Fig. 10.

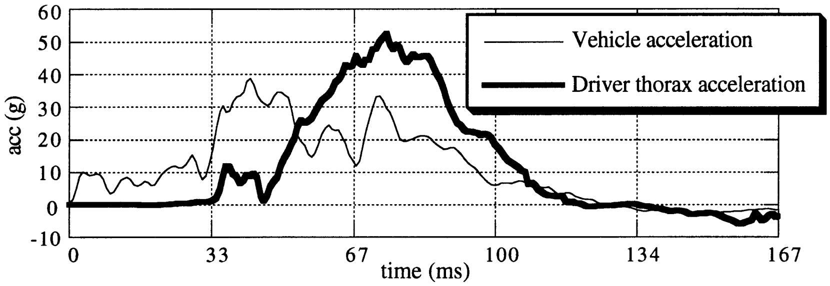

Fig. 9. Vehicle and driver thorax acceleration in vehicle 4H.

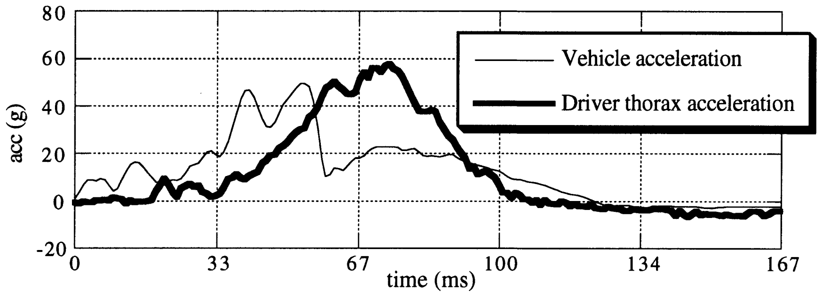

Fig. 10. Vehicle and driver thorax acceleration in vehicle 4L.

4. Discussion

The material used in this study is unique. The impact severity parameters were calculated based on measured crash pulses in real-life collisions and the injuries have been followed up during 5 years from the time of impact. This combination of valid and reliable impact severity measurements and medical information at different times after the collision made it possible to study relations which would otherwise be impossible to obtain.

The inclusion criterion for the collisions in this study was a repair-cost of 7000 USD. This may have influenced the number of reported neck injuries in the low severity impacts. The number of long-term consequences is, however, probably not influenced by this, since the average severity of impacts leading to long-term consequences was found to be higher than those causing short-term consequences. The proportions of both short-term and long-term consequences of all impacts are, though, influenced by the inclusion criterion.

It is difficult to objectively determine the diagnoses of AIS1 neck injuries. The question is often raised about the credibility of these injuries. This fact may have influenced the classification of short- and long-term consequences. Better significance could be expected if only disabilities verified from a doctor were used.

The results in this study indicate that in frontal impacts the shape of the crash pulse influences the neck injury risk, especially the risk of long-term consequences. A high mean acceleration between 34 and 66 ms and a low mean accelerations between 67 and 99 ms seem to increase the neck injury risk.

It is important to study the conditions under which the neck injury risk is low. The results indicate that if the mean acceleration level in the last part of the crash pulse is higher or equal to the level in the mid part of the pulse, the neck injury risk is likely to be low. If the mean acceleration in the third part of the pulse was higher than in the second part, only one occupant was reported to have sustained short-term consequences and no occupant sustained long-term consequences. These findings as well as those presented in the last paragraph imply that actions aimed at increasing the duration and at decreasing the mean acceleration in the mid part of the crash pulse are important in order to reduce the neck injury risk.

The crash tests showed that the dummy came into contact with the seat belt at between 30 and 52 ms after the crash depending on the vehicle acceleration in the early phase of the impact. Table 1 shows that the average change of velocity for the occupants sustaining long-term consequences was 34.6 km/h. Since the average change of velocity and the average mean acceleration in the real-life collisions were lower compared to those measured in the crash tests, it could be expected that the average time for belt contact occurred later in the real-life collisions, approximately between 30 and 70 ms. This occurred in the same time interval as that in which a large difference in change of velocity between the mid and last part of the crash pulse was found to act negatively for the neck injury risk.

It was shown that ?V in the 1st part of the pulse does not seem to influence the risk of long-term consequences to the neck. However, ?V in the 1st part of the pulse as well as ?V in the 2nd part affect the relative velocity between the occupant and the seat belt. This indicates that this relative velocity is not the main factor to influence the risk of long-term consequences to the neck. The main factor influencing this risk seems to be the deceleration during the phase when seat belt contact has occurred and the occupant is decelerated. This finding in turn indicates that the main injury mechanism for AIS1 neck injuries in frontal collisions is in the flexion mode, possibly when the head is rapidly rotated. The neck injury can also occur in the initial phase after seat belt contact. This injury mechanisms have also been mentioned by Walz and Muser (1995), while Larder et al. (1995) found that neck injuries may occur in the flexion mode. Similar symptoms have been found for neck injuries in both frontal and rear impacts (Jonsson et al., 1994; Minton et al., 1998), while the injury mechanisms in the two impact directions have not. In rear impacts different possible injury mechanisms have been presented including flexion (v Koch et al., 1995), extension (Mc Connell et al., 1995) and hyper-extension (States, 1979). The injury mechanisms for long-term consequences may, however, be found in both impact types. In rear end impacts, a high rebound velocity resulting in a similar situation as in a frontal impact may occur. It is hoped that the results from this study may help to develop better injury criteria for neck injuries in both frontal and rear impacts.

A possible way to decrease the neck injury risk could be to use more effective pretensioners, acting very early on in the crash phase or even before the time at impact, possibly triggered by braking or by presensing of a crash. It may also be beneficial to use more advanced belt load limiters, which could reduce the loads when the occupants are decelerated by the seat belt. The belt load limiter could act progressively with a very low level in the initial phase, followed by an increased level to hinder head contacts in severe impacts. It could also be used in combination with an airbag. The belt-load limiter could also act actively and adjust the belt-loads according to the shape of the crash phase.

Further studies have to be undertaken to evaluate the neck injury risks in which narrower time intervals are used and where the time for belt contact is estimated in each collision. This information would be helpful when designing injury-reducing systems. The timing of such systems seems important to be able to tune it according to the trajectory of the occupants. Mathematical simulations would be a helpful tool to study how the shape of the crash pulse influences the simulated dummy measurements. Crash pulse data from this study could be used as input in the simulations. It would also be of interest to relate the findings in this study to the Neck Injury Criterion, NIC, developed for predictions of AIS1 neck injuries in rear impacts (Boström et al., 1996). NIC addresses the relative acceleration between head and torso in the early phase of a rear impact when the head has a translational motion. If the AIS1 neck injury in frontal impacts occurs when the head has a translational motion, NIC may relate to neck injury risk in frontal impacts.

5. Conclusions

It is important to do separate analyses for short- and long-term consequences of AIS1 neck injuries.

A large difference in mean acceleration or change of velocity between the mid and the last part of the crash pulse seems to be negative for AIS1 neck injury risk.

The deceleration of the occupant directly after belt contact seems to explain the risk of sustaining long-term consequences to the neck.

Possible ways to decrease neck injury risk could be to use more effective pretensioners acting very early on in the crash phase or even before the time of impact and to use more advanced belt-load limiters, which would reduce the loads when the occupants are decelerated by the seat belt. The belt-load limiter could act progressively with a very low level in the initial phase, followed by an increased level to avoid head contacts in severe impacts.

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