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The Minimal Collision Velocity for Whiplash

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Since the 1970s, an increasing number of whiplash injuries have been observed in Germany. At present, enormous sums of money, exceeding DM 1 billion each year, are being paid by the insurance companies alone for injury damages after whiplash traumas. In 1990, a comprehensive evaluation called Fahrzeugsiclerheit 90 (FS90) was carried out on 15% of all car–car accidents involving injury to occupants. It was found that half of these accidents were rear-end impacts, and in 94% of these impacts at least one of the occupants claimed to have suffered whiplash injury (4). Fig. 1 shows the statistical distribution of rear-end impacts in terms of the level of damage. Only accidents with injury victims are counted. Damage is classified into five classes, as detailed schematically in Figure 2. An interesting point to note is that in 65% of all rear-end impacts, the vehicles show only slight to moderate damage. An example of slight damage is shown in Figure 3; vehicles were placed in this class only when they suffered scratches and slight dents. An example of moderate damage can be seen in Figure 4; only vehicles with deformations up to a depth of about 10 cm were classified in this category.

The study also evaluated what percentage of the occupants claimed whiplash injury in accidents with the various levels of vehicle damage. This evaluation produced the astonishing result that rising severity of damage did not produce an increase in injuries, but a decrease instead. The highest level of injury claims was in vehicles with the slightest levels of damage.

Various studies showed that the biodynamic stresses arising in the cases of slight to moderate vehicle damage cannot be sufficient to cause injuries to the cervical spine (6,7,10,1,8,9,11). Higher stresses occur in normal, everyday movements, and especially in sports, and there is no question that these are tolerated by the cervical spine. Therefore, from a biomechanical point of view, it is not possible to explain the very high percentage of whiplash trauma with slight to moderate levels of vehicle damage. The insurance companies in Germany, Austria, and Switzerland are responding increasingly critically towards whiplash claims in the event of nonsevere rear-end impacts; more and more cases are being brought before the courts, and consequently the courts themselves have also become aware of the problems involved. In 1994, the issue of whiplash trauma was dealt with at a judges' conference, which adopted a recommendation that in cases of

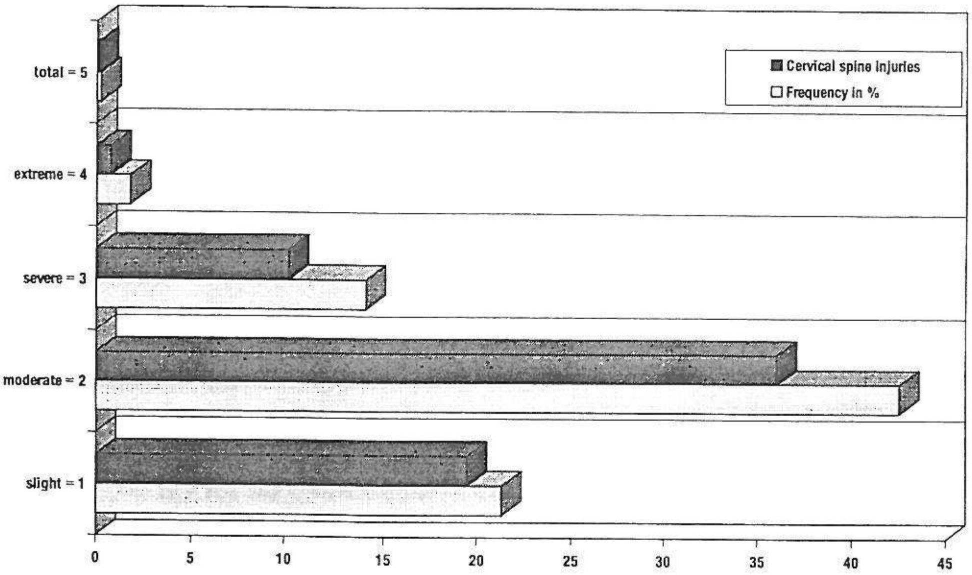


FIG. 1. Statistical evaluation of whiplash in Germany.

disputes, interdisciplinary technical and medical expertise should be obtained on the actual biomechanical stresses involved (2). In 1996, the subject was raised again in connection with claims for indemnification; the judges recommended that no damages should be paid for slight injuries, whereas the damages for severe injuries should be increased instead, and also that fraudulent exploitation of damages law should be combated more energetically (3).

As technical experts in the field of traffic accidents, we are being increasingly asked in court proceedings whether the stresses occurring in a vehicle were sufficient to cause injury to the cervical spine. As a matter of principle, the level of stress can be reconstructed by evaluating the vehicle damage. However, the question of what forces are exerted on the vehicle occupants for the various levels of vehicle deformation was poorly investigated. Therefore, since 1988, we have been carrying out crash tests with live test subjects at our crash test facility. The first systematic study was carried out in 1993 (6), and we are currently engaged in a second study in interdisciplinary cooperation with the Academy for Manual Medicine at the University of Münster.

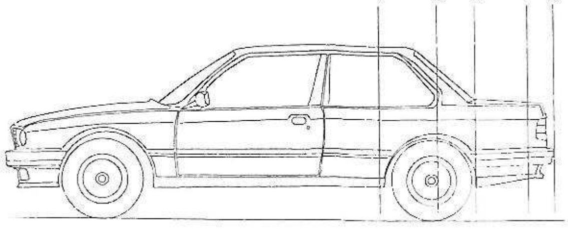


FIG. 2. Classification of rear-end deformation in FS 90 (*y*-axis in Fig. 1).

[redacted]

FIG. 3. Slight deformation in FS 90.

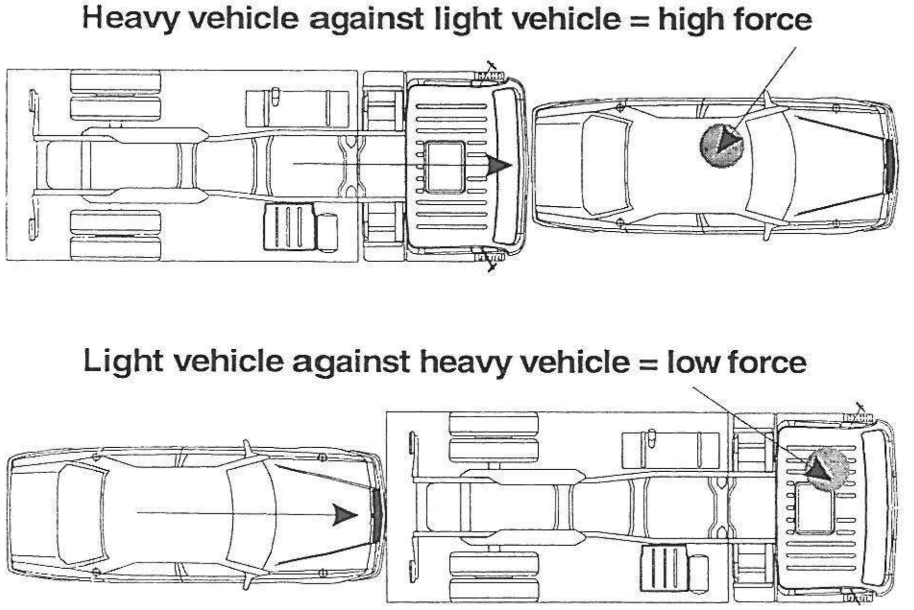
The results of the first study and the current status of the second study will be detailed here. To provide a general understanding of the technical and biomechanical factors involved, some explanations will first be given.

INTERDEPENDENCE BETWEEN VEHICLE DEFORMATION AND BIOMECHANICAL STRESS

It is fundamentally possible to infer the velocity of impact from the deformation of the vehicles. As the deformation intensity increases with the square of the impact velocity, this velocity can be stated with precision by evaluating the deformation. By now, a large number of crash tests have been carried out, which in normal cases allow impact velocities to be reliably determined from the deformation found. However, it is not only the impact velocities that determine the stresses exerted on the occupants. Other factors must also be taken into consideration:

The *weights of the vehicles* are very important. An extreme example of this is shown in Figure 5. If a heavy truck crashes into a normal car, the occupants of the target vehicle will be subject to high forces, even at a low impact velocity. Conversely, if a normal car crashes into a heavy truck, the force in the truck exerted by the same impact velocity will be slight.

FIG. 4. Moderate deformation in FS 90.



Heavy vehicle against light vehicle = high force

Light vehicle against heavy vehicle = low force

FIG. 5. Influencing factor: vehicle weights.

The level of stresses in the target vehicle is also influenced by the *degree of overlap*. The greater the degree of overlap, the higher the force (Fig. 6).

Another important factor is the *impact height*. In the case of rear-end collisions, the driver of the bullet vehicle usually has enough time to apply the brakes before impact occurs. This causes the vehicle to nose-dive (Fig. 7).As the bumpers of the two vehicles are at the same height when the vehicles are unbraked, nose-diving inevitably results in submarining of the bullet vehicle under the bumper of the target vehicle. According to measurements performed by us, the nose-dive depth is 10 to 15 cm (12). As a result, the direct contact, and therefore the exchange of forces, is between the headlamp plane and the rear bumper, and not, as in the case of unbraked impact, between the hard zones of the bumpers. In our view, most studies into the stress tolerance of the cervical spine (whiplash) do not take sufficient account of this factor. It is usually the case in rear-end collisions that the vehicles impact at different heights because of the nose-diving effect, and therefore tests that simulate bumper–bumper collisions are of little relevance to practical reality.

In principle, there are various possibilities for describing the forces occurring in vehicles. In practical terms, however, only a description of the acceleration phases over time and the change in velocity are useful. The acceleration phases over time is the more

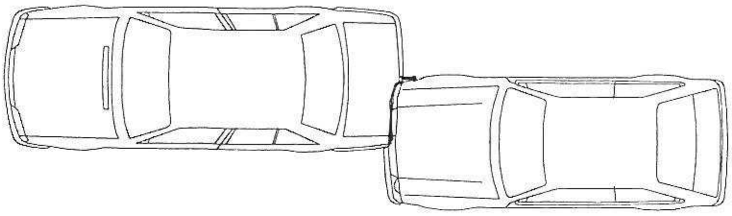


FIG. 6. Influencing factor: overlap.

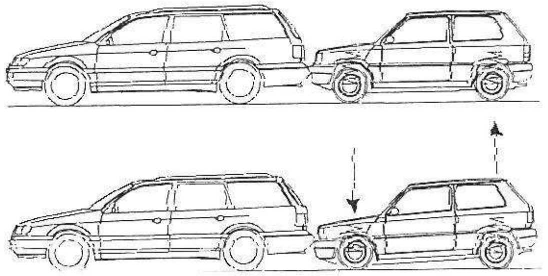
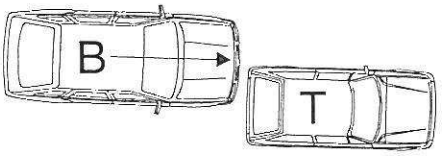


FIG. 7. Influencing factor: impact heights (**top**: unbraked impact; **bottom**, braked impact).

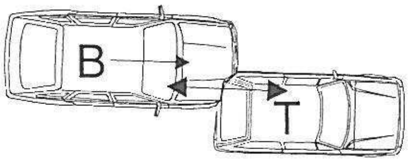
meaningful method, but it has the disadvantage of being abstract to people who are not technical experts. The change in velocity is much easier to imagine, but it does not take the duration of impact into account. In the case of longer-lasting collisions, the stresses are lower because of the longer impact duration in which the velocity change is produced; in the case of short impact duration, the velocity change is produced very quickly. Long and soft impacts occur when there is nose-diving and/or a small degree of overlap. Short and hard impacts occur in bumper–bumper contact with a greater degree of overlap. For practical purposes, a description using the velocity change ΔV (Fig. 8) is normally sufficient. Before impact, the bullet vehicle B is travelling at velocity V_B faster than the target vehicle T. During impact, about half of V_B is transmitted to T. This is only the case, however, if both vehicles are of approximately the same weight and the collision is not elastic. For a general consideration, though, this statement is adequate. After the collision, T continues to move with the velocity change ΔV. In the collision, this vehicle has undergone velocity change ΔV within a time of 1/10 to 2/10 s; the higher this velocity change is, the higher also is the biomechanical stress.

In the case of greater differences between the weights of the vehicles, the velocity change can be calculated according to the following formula (plastic impact):

Before collision:



During collision:



After collision:

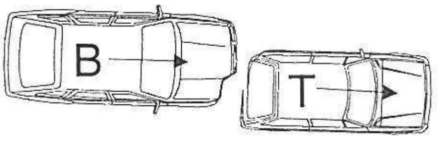


FIG. 8. Definition for change in velocity ΔV.

TABLE 1. *The same stress as produced by different velocity combinations*

Bullet vehicle (kph)	Target vehicle (kph)	Relative impact velocity (= biomechanical stress) (kph)
120	100	20
70	50	20
20	0	20
10 (forwards)	−10 (backwards)	20

$$\Delta V = [m_B/(m_T + m_B]v_B$$

The foregoing applies when both vehicles are in motion. In this case, the relative impact speed must be used for calculation. For example, the velocity combinations shown in Table 1 produce the same stresses.

Furthermore, the level of stress in the target vehicle is not significantly influenced by whether either of the drivers or both of them brake before, during, and after impact. It is not the case that higher velocity changes occur with an unbraked target vehicle; rather, the effect of the braking forces is negligible as compared to the impact forces.

The only significant influence of braking is the change in impact height. An uphill or downhill gradient at the site of the accident also has no significant influence.

As practice shows, most impacts are not plastic but partially elastic. This means that in the target vehicle slightly higher velocity changes occur in a magnitude of 60% of the relative impact velocity. Further details on this can be taken from the evaluation of the trials presented later, particularly in Figure 11.

METHODOLOGY

In the 1993 study (6), a total of 22 rear-end impacts were carried out at a ΔV of 6 kph to 12 kph. In 14 of the tests, live test subjects were located in the target vehicles; in the remaining tests, dummies were used. Recordings were made of the vehicle acceleration, the chest acceleration, and the head acceleration. Additionally, the muscle tone was recorded synchronously with the other data by means of surface electromyograms (EMGs).

Analysis of the kinematics was done by markers applied to the passenger compartment, the seat, and the body of the occupant. To prevent anticipation, some of the test persons were screened off acoustically. Additionally, the 1993 study also performed practical measurements at a bumper-car ride.

In the 1996 study (which is still continuing), the same basic instrumentation layout has been retained, but with significant improvements. The velocity change in the target vehicle has been considerably increased to a ΔV of 10 kph to 15 kph. It should be emphasized, however, that, as will be shown below, even at 15 kph the forces that occur are still comparable to those measured in bumper cars. Before the trials, all the test persons were informed of the possible risks. Most of them were technical or medical experts who also had a personal interest in the results of the trials. Comprehensive medical examinations took place 6 days before, 24 hours after, and 4 weeks after the trials. The test persons were subject to orthopedic/manual medical/neurologic examinations. On the same dates, a computer-controlled ultrasound examination of the motility of the cervical spine and spin tomography of the cervical spine with and without gadolinium-diethylene-triamine penta-acetic acid (DTPA) were performed.

All the crash tests were performed at the facility of Ingenieurbüro Schimmelpfennig + Becke. The medical examinations were carried out at the Academy for Manual Medicine and at Clemens Hospital in Münster. The Institute for Sports Medicine at the University of Münster was responsible for recording and evaluating the movement markers.

VEHICLES USED

In the 1993 study, no systematic selection of the test vehicles was made. All were fitted with normal European bumper systems, without energy-absorbing components. In the 1996 study, a systematic selection was made. The trials included five modern compact cars (Volkswagen Golf), five station wagons (Opel Kadett), and five limousines (Opel Rekord). Additionally, crash tests were carried out with two bumper cars of the type found at funfairs.

OCCUPANTS AND INSTRUMENTATION SETUP

In the 1993 study, only two different test subjects were used. These were both men, aged about 30, and neither complained of injury after the collisions. The trials were not subject to medical monitoring. The 1996 study includes women, and the trials are medically monitored. All volunteers are subject to only one rear-end collision. The test persons are chosen with a wide spread in terms of age, preexisting degenerative conditions, and physical constitution.

To prevent anticipation by the test persons, they are all completely screened off visually (by blindfold) and acoustically (Walkman with loud rock music). Most of the test subjects stated after the trials that they had been able to discern nothing of the further trial preparations, which took between 5 and 15 minutes. The EMG recordings of all the test subjects show typical rest potentials before the trials with no anticipation of the neck muscles.

The instrumentation applied to the test persons is shown in Figure 9. The test subject is already completely screened off at the time of recording. Accelerometers are installed

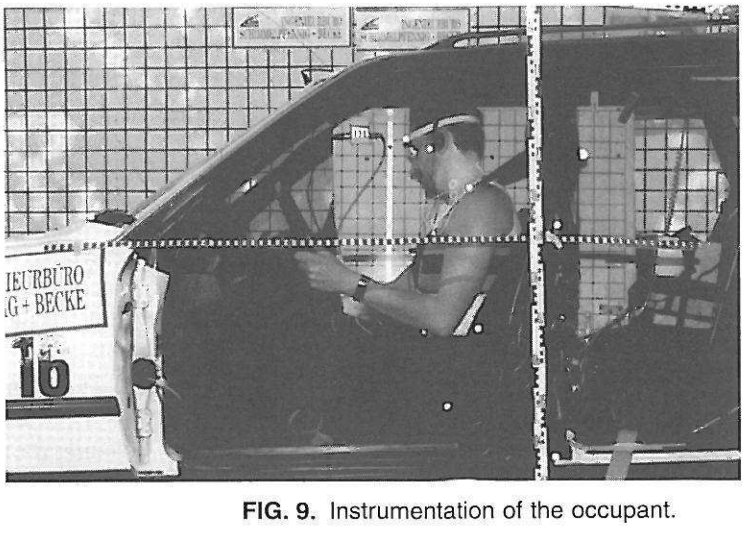


FIG. 9. Instrumentation of the occupant.

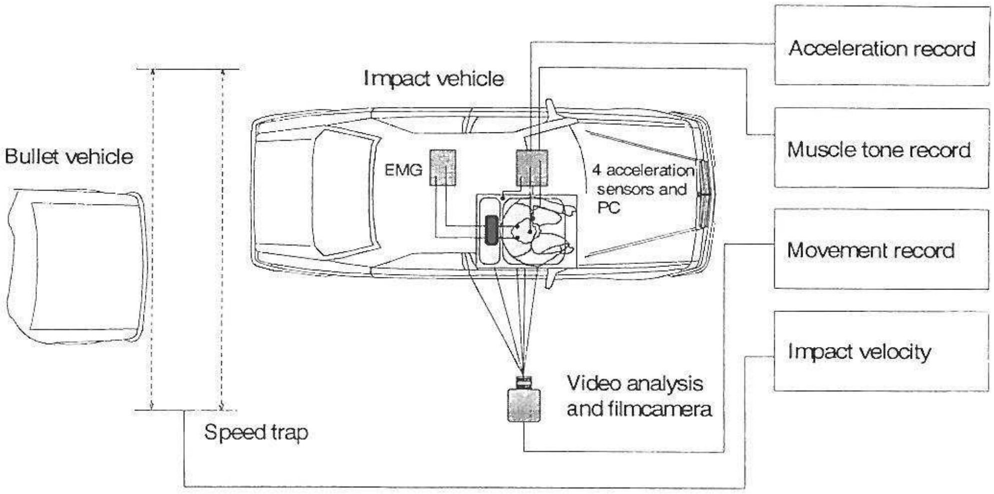


FIG. 10. Instrumentation layout for all tests.

in the vehicle's passenger compartment and on the chest and the head of the occupant. Additionally, movement markers are fitted at the shoulder, the center of gravity of the head, the forehead, and the hip of the test person. Other movement markers are located on the seat, the head restraint, and the "B" pillar. EMG signals are obtained from various neck muscles.

Figure 10 shows the schematic setup for the 1993 and 1996 studies. Besides passenger compartment acceleration, the kinematics of the occupant were also recorded in these rear-end impacts. The movement data were recorded by a video evaluation system and by additional biomechanical acceleration data. In addition to the kinematic data, the activity of the neck muscles was also recorded using surface EMGs.

For the 1996 study, the instrumentation setup was developed further, with accident data recorders (manufactured by Mannesmann-Kienzle, Villingen, Germany) being installed in both the bullet and the target vehicle. This enabled the acceleration effects to be recorded for the passenger compartment not only of the target vehicle but also of the bullet vehicle. For kinematic analysis, the screening frequency was increased from 50 to a good 700 Hz. Additionally, EMG signals were obtained from several neck muscles. The contact phase of the vehicle structures and the kinematics of the occupants were recorded using high-speed cameras.

VEHICLE MOVEMENTS

Table 2 lists the data of all persons and the most important data of all tests in the ongoing 1996 study. Figure 11 shows the impact velocity (V_I) and ΔV for all trials so far carried out in both studies. For the impact velocities of the vehicles, which in some cases differed significantly in weight, the weight influence has been eliminated. This allows a better comparison of the impact velocities. The x-axis shows the weight-adjusted impact velocities in the trials, the y-axis the velocity change ΔV. The line k = 0 stands for plastic collisions, whereby the velocity change ΔV is precisely half of the weight-adjusted impact velocity. The second line, k = 1, stands for elastic collisions. A virtually elastic impact takes place when, for example, two billiard balls strike each other. In vehicle col-

TABLE 2. *Data from all tests in the ongoing 1996 study*

Trial no.(yr)	Subject age	Height (m)	Weight (kg)	Sex	Overlap (%)	Time (s)	V_1 (kph)	ΔV_2 (kph)
I	36	1.84	76	M	75 l.	0.119	17.5	8.7
II	37	1.77	61	F	100	0.107	21	13.6
III	33	1.8	72	M	50 r.	0.108	18.5	9
IV	32	1.84	84	M	50 l.	0.105	18.5	9.4
V	48	1.74	82	M	100	0.106	19.5	11.4
VI	33	1.8	70	M	100	0.132	20.5	12.8
VII	30	1.85	78	M	100	0.13	19	12.7
VIII	30	1.89	80	M	85 r.	0.12	22.5	14.2
IX	28	1.75	63	M	50 l.	0.137	20	12.7
X	26	1.74	71	F	50 r.	0.128	22	13.3
XI	30	1.85	90	M	50 l.	0.119	25	12.6
XII	32	1.7	68	F	100	0.121	20.5	9.5
XIII	34	1.8	95	M	100	0.117	21	9.7
XIV	35	1.75	65	M	100	0.131	19.5	9.4
XV	36	1.81	72	F	50 r.	0.105	25	11
XVI	37	1.82	82	M	30 l.	0.169	27.5	13.3

V_1, impact velocity of bullet vehicle; ΔV_2, velocity change of the target vehicle.

lisions, however, elastic impacts are not observed. Figure 12 also shows that with rising collision velocity, the character of the impact becomes increasingly plastic.

The relevant impact times are stated in Figure 12. These are around 0.1 s; with greater intrusions, impact times of up to 0.16 s have also been observed. All the impacts are generally between 0.075 s and 0.16 s.

BUMPER CAR MOVEMENTS

In funfair bumper car tests, a total of about 70 impact events were recorded and evaluated. Figure 13 shows that for bumper cars, the collision times for all individual impacts

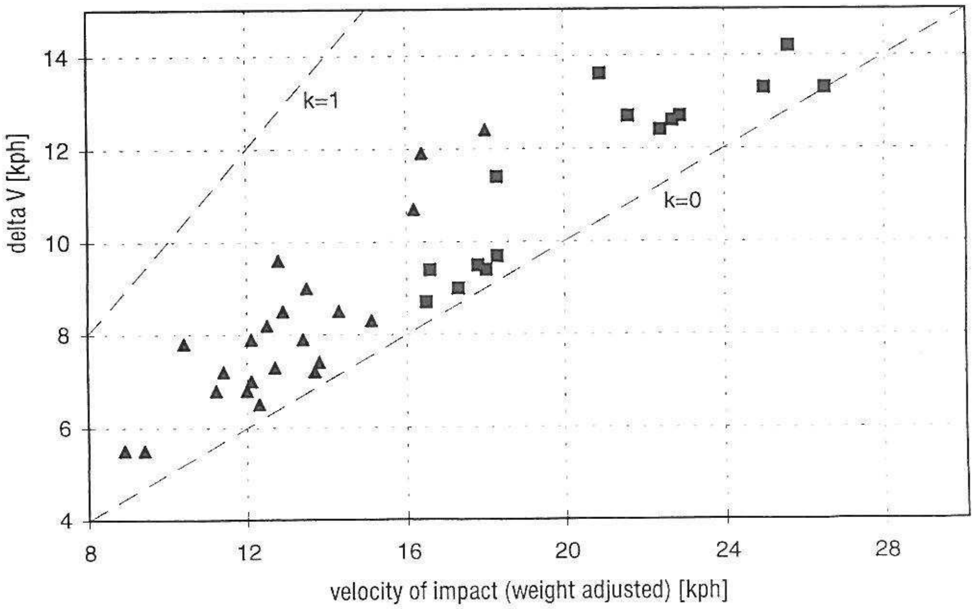


FIG. 11. Crash velocities (weight adjusted) and Δ V for all tests in the 1993 study (▲) and ongoing 1996 study (■).

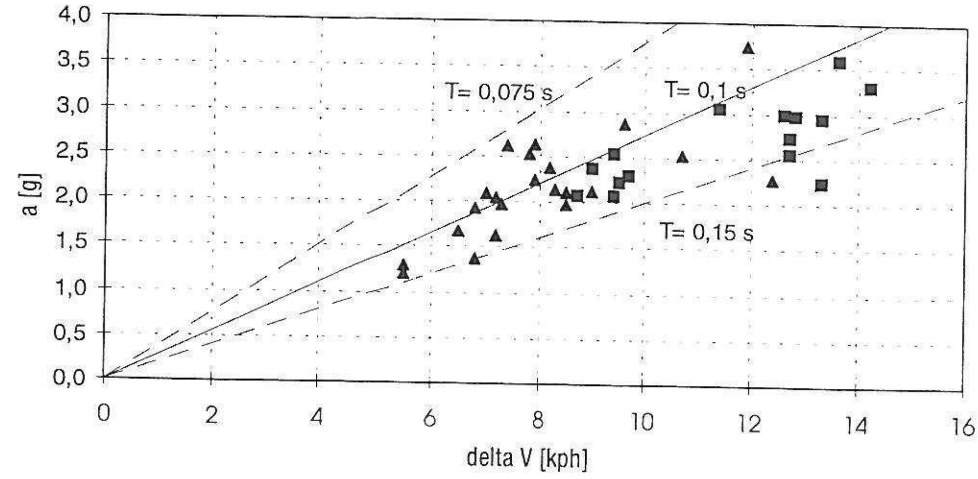


FIG. 12. Rear-end collision impact times, Δ *V*, and average acceleration in the 1993 study (▲) and ongoing 1996 study (■).

are in a range between 0.075 s and 0.15 s. Most of the values are grouped very densely around the mean impact time of 0.1 s (1/10 s). For bumper cars, Δ *V* values of approximately 4 kph to a maximum of 15 kph were found. This corresponds to mean vehicle passenger compartment accelerations of about 1*g* to 4*g*.

Figure 14 gives a direct comparison between vehicle and bumper car impacts. The vehicle acceleration shows typical high-frequency oscillations *(right)*. Because of the

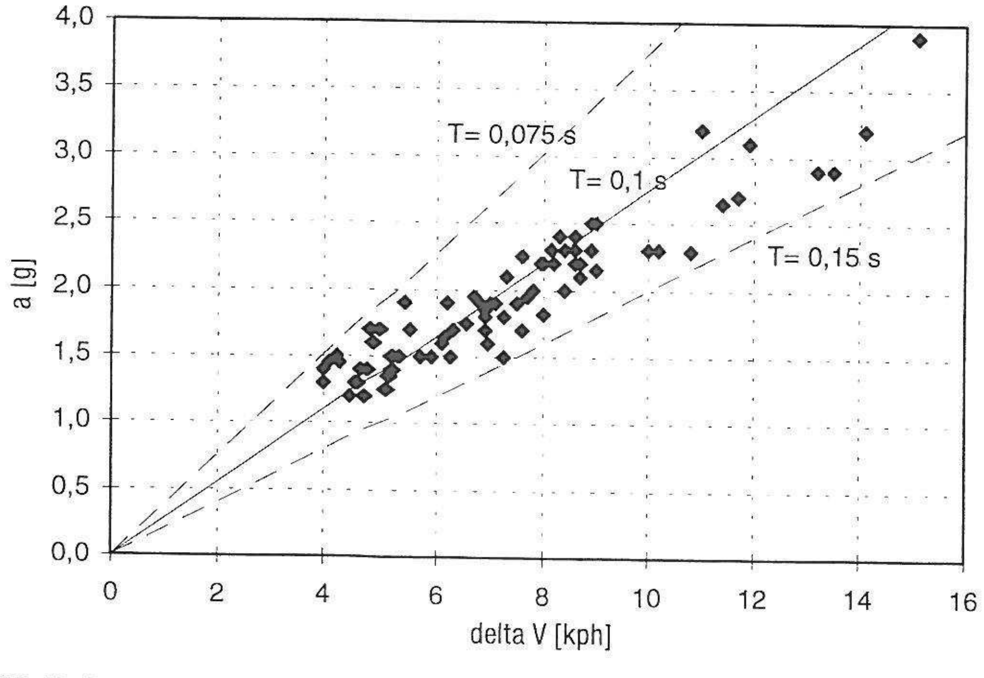


FIG. 13. Bumper car collision impact times, Δ *V*, and average acceleration for 70 impacts at a funfair.

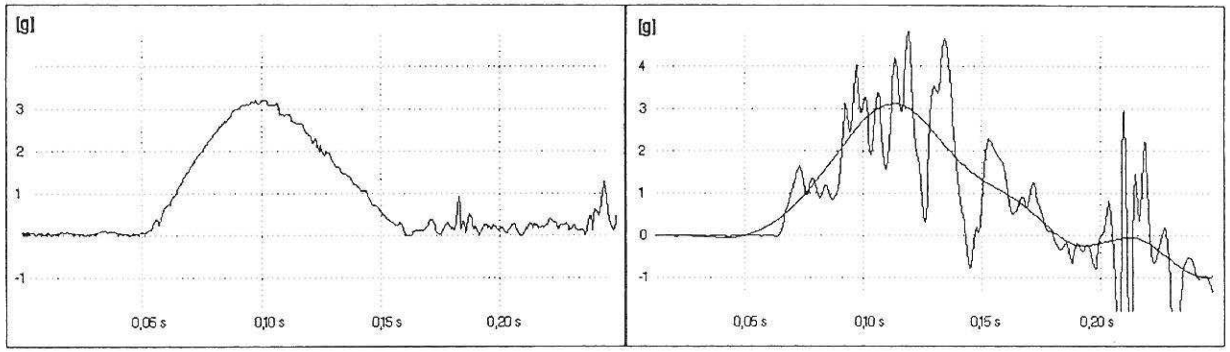


FIG. 14. Comparison of acceleration between bumper car collision *(left)* and vehicle collision *(right)*.

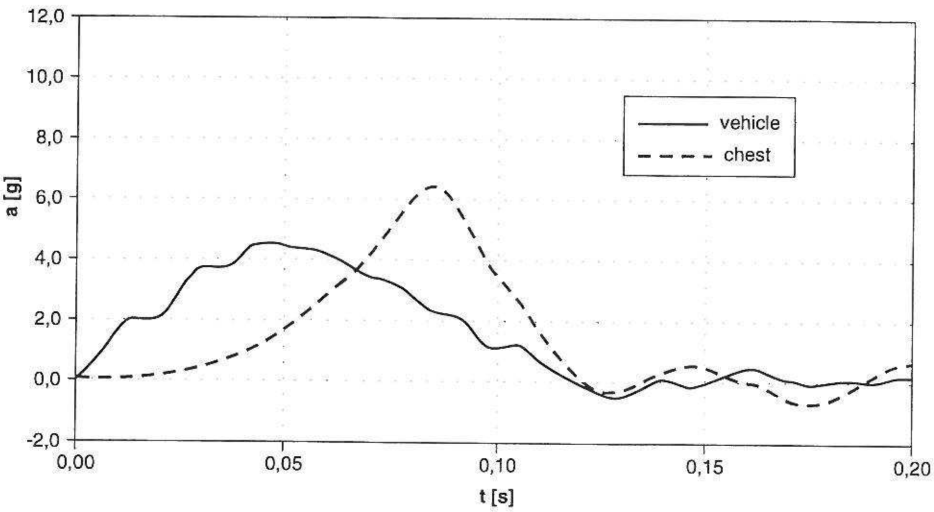


FIG. 15. Bumper car collision acceleration curves for car and chest in a trial.

mechanical inertia of the torso and body of the occupant, these oscillations are of no relevance for the biomechanical stress on the occupant. The digitally filtered signal that is also shown demonstrates that impacts between vehicles are highly comparable with impacts between bumper cars in respect to the time sequence of passenger compartment acceleration.

In the 1996 study, a test subject was used in the test vehicles at similar Δ *V* values in a bumper car collision and a car impact. The acceleration curves of the bumper car, motor car, and occupant's chest are very similar, whereas the head acceleration in the car is substantially higher. The explanation for this is that the head impacts on the head restraint in the car. In the bumper car, the head is not stopped; instead, its relative rearward movement is unrestrained. This results in a comparatively large angle between torso and head of the occupant. As an example, in Figure 15 the acceleration curves for car and chest of a rather hard bumper-car impact with a Δ *V* of 11 kph is shown. The peak acceleration of the bumper car went up to 4*g*. In this trial, we observed hyperextension of the cervical spine with a head–torso angle up to 80°! The volunteer in this test complained of no trouble.

OCCUPANT INJURIES AND SUBJECTIVE IMPRESSIONS

The test subjects in the 1993 did not complain of any trouble immediately after the crash or indeed at any time since then. It should further be noted in this context that because of the small number of test persons, each one was subjected to numerous impacts in the bumper car collisions and up to 50 impacts in the car crashes. As the test subjects were involved in both the bumper car and the motor vehicle impacts, they were able to give a subjective assessment of both types of impact. They stated unanimously that because of the unfavorable seat geometry and the absence of head restraints they found the bumper car impacts to be more unpleasant than the car collisions.

In the trials performed in the 1996 study to date, most of the occupants did not complain of pain after the test. Some test subjects stated immediately after the collision that they felt pain through contact of the head restraint with the back of the head. Two test subjects reported slight tension of the neck muscles in conjunction with slight restriction of movement, which, however, disappeared within the next few days.

OCCUPANT MOTION

In the following section, we take a closer look at the phases of motion of the vehicle occupants, produced by rear-end impacts. The aim is to obtain more detailed information on the injury mechanism. On the basis of motion analysis from the video recordings in the 1993 study, it was possible to determine the absolute and relative movements of the vehicle, of the seat and head restraint, and also of the occupant from the movement of the markers. In the example, impact velocity was 13.5 kph and ΔV was 7.5 kph. Figure 16 shows ten positions evaluated during the first 180 ms of a collision. The absolute movements of the passenger compartment, of the seat back and head restraint, and of the occupant were documented. Two markers each were attached to the head and chest. The motions shown for the head and chest could be calculated from the paths of movement. The absolute movements of the head restraint and seat back were also determined in the same way. Using this depiction, it was then possible to break occupant movement down into four constantly recurring movement phases in the case of rear-end impacts.

These movement phases are described in Figure 17. On the right, the lines of movement are shown in isolation (i.e., detached from the body of the test subject). If these individual pictures are superimposed on each other and the end points of the lines are joined, the result are the paths of movement as recorded by the video camera. The occupant movement can be split into four phases:

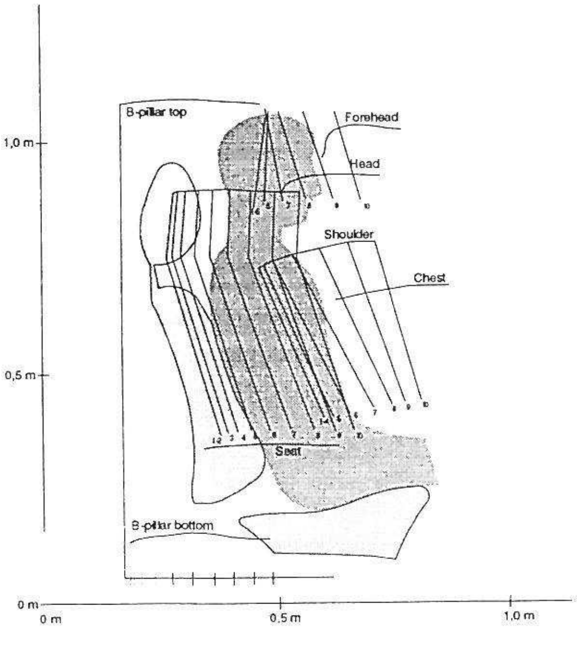


FIG. 16. Evaluation of the marker-movements.

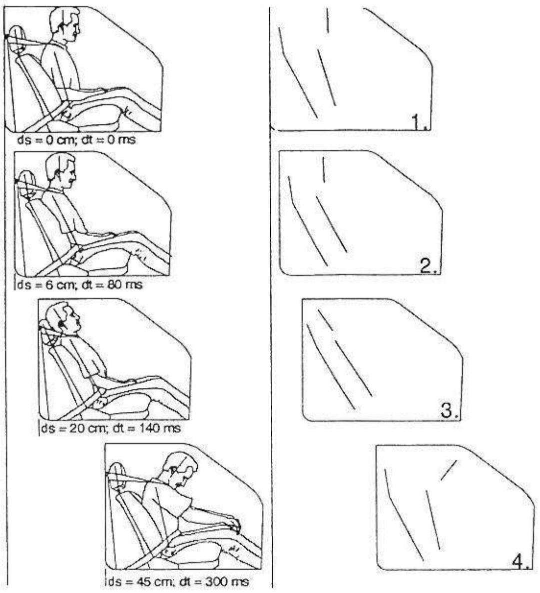


FIG. 17. Four phases of movement.

Phase 1

The characteristic of this phase is that the passenger compartment and the car seat move towards the occupant's torso, which is at rest. In this phase, therefore, there is as yet no movement of the occupant. The start of this phase is identical with the start of the impact, or the time of first contact between the two vehicles.

Phase 2

The second phase begins with the contact between the torso and the seat back. As the deformation margin of the seat back is consumed, the occupant's torso is more and more included in the general forward movement. Up to this time, the head has not moved at all. With the start of forward movement of the torso, the relative movement between the head and torso begins. At the start of the second phase, the passenger compartment has already moved forwards about 6 cm, without the body of the occupant participating in this movement at all. The second phase begins about 80 ms after first contact between the vehicles.

Phase 3

When the passenger compartment has already moved forwards a distance of about 20 cm, and a time of about 140 ms from the start of the impact has elapsed, the approaching head restraint contacts with the back of the head. The start of this third phase is thus determined by the contact between the head restraint and the head. From this point on, the head follows the general forward movement, whereby, provided it is correctly positioned, the head restraint ensures that after the start of the third phase the relative angle between the torso and the head of the test subject cannot increase further.

Phase 4

The three primary movement phases are followed by the fourth phase, in which the low-energy secondary movement of the occupant in the form of a forward motion takes place (rebound). Because of the fact that the occupant follows the movement of the passenger compartment with his own time lag, he also reaches ΔV with only this time lag. He consequently moves forward relative to the passenger compartment and is finally restrained by the seat belt. In contrast to the primary movement (phases 1 to 3), however, this secondary movement is very low in energy and therefore certainly not liable to induce injuries.

For example, Figure 18 shows the acceleration curves recorded during an impact trial together with the EMG signal. In this figure, the first three of the four collision phases can be clearly seen. The acceleration of the passenger compartment, the chest, and the head were marked. The start of chest acceleration indicates the start of contact between the torso and the seat back, and the start of head acceleration marks the contact with the head restraint. In the periods between the start of the various accelerations, there is in each case the phase of relative movement between the passenger compartment and the torso, and the torso and head of the occupant. After passing the start point of head acceleration, which is shown as a broken line, the fourth and final phase of movement then begins, in which the test person moves forwards. In this context, it should be noted that for determining the relative movement between the head and the torso, only the time sequence of head acceleration is of interest. The maximal acceleration value, on the other hand, is only an indication for the strength of head impact with the head restraint. This impact therefore occurs during the phase of contact with the head restraint and is therefore not suitable for characterizing the relative movement between the head and torso.

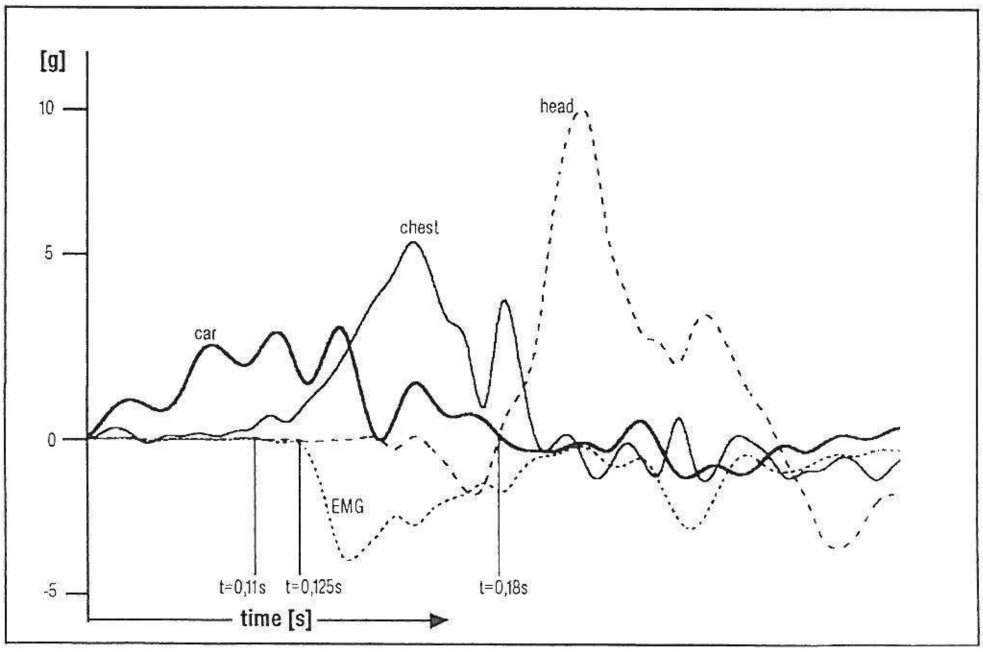


FIG. 18. Acceleration curves recorded during an impact trial together with the EMG signal.

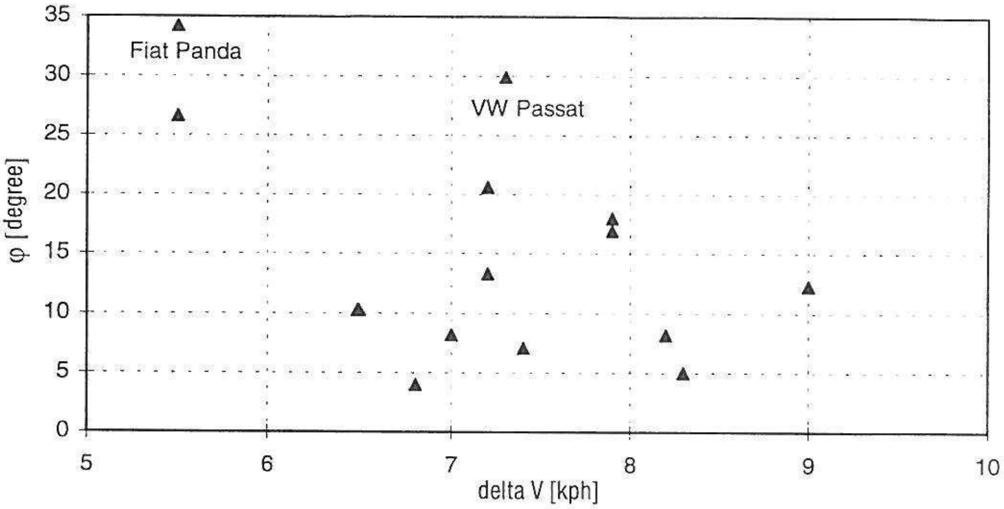


FIG. 19. Maximal angle of torso–head and change in velocity Δ *V* (1993 study only).

Figure 19 shows the maximal angle of movement between the head and body, as determined from motion analysis, in relation to Δ *V*. A uniform trend to the effect that the maximal angle increases with increasing Δ *V* cannot be found. Analysis of the occupant movement shows that the maximal relative angle is rather determined by the geometric factors of the seat construction. The greatest head–torso angle was found in impacts in the lower velocity range, with the test person located in a Fiat Panda. In this vehicle, the angle of the seat back could not be adjusted. A relatively large angle to the vertical was therefore predetermined. The so-called head restraint in this vehicle was integrated into the seat back and could not be adjusted in height, so it would be more accurate to speak of a neck roll than of a head restraint. The head is not supported at all; instead, rear hyperextension

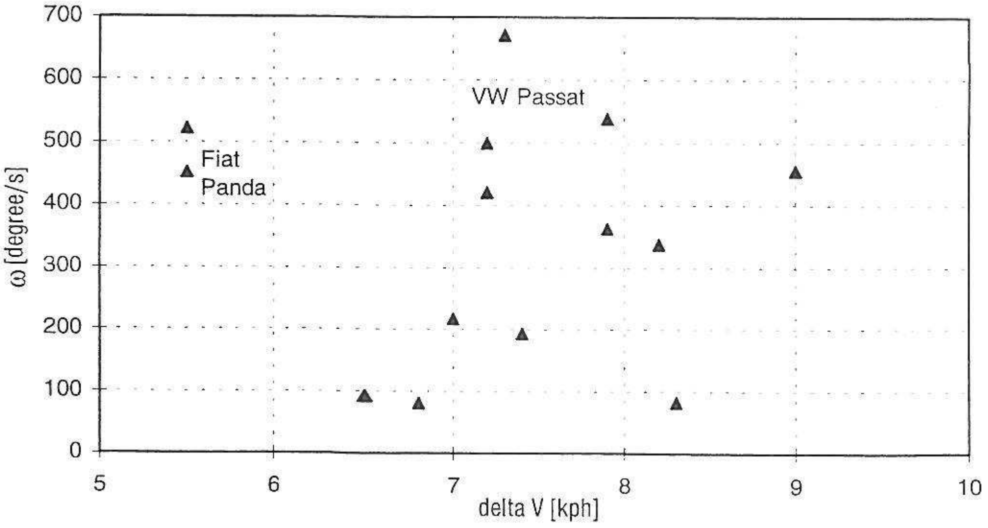


FIG. 20. Relative angle velocity over Δ *V* (1993 study only).

over the top of the head restraint is reinforced. Seat geometry of this type must be considered as promoting injury.

Irrespective of this, the maximum relative angle in all the trials was in a range that can also easily be reached with a slow, conscious movement. As the geometric arrangement of the seat in the area of head contact is independent of the speed of travel, an injury mechanism in the form of mechanical hyperextension through the extent of head displacement appears unlikely even for higher-impact velocities.

Figure 20 shows the maximal relative angle velocities measured between head and torso over Δ *V*. The maximal value is reached shortly before contact between the head and the head restraint (i.e., during the phase when movement between the head and torso is still unrestricted by external factors). What is conspicuous is that the rotation angle velocity of the head, in contrast to the relative angles, can achieve a considerable magnitude even at low impact velocities. The trials therefore indicate that with a correct geometric seat arrangement in the area of head contact, the injury-relevant parameter can lie only in the velocity of the relative movement between the head and torso.

BIOMECHANICAL ACCELERATION AND EMG SIGNAL

Figure 21 shows the time lag between the biomechanical signals in relation to the Δ *V* of the target vehicle. In this graph, the start of acceleration of the passenger compartment is defined as the zero point. It is evident here that with a normal seating position, the acceleration of the chest begins immediately after acceleration of the passenger compartment (irregularities begin to appear in the signals about 10 ms after the start of the impact), whereas acceleration of the head shows a time lag of about 110 ms relative to the acceleration of the passenger compartment. Within this period of time between the start of acceleration of the passenger compartment and the start of acceleration of the head, the head restraint travels a distance of about 20 cm. This distance also approxi-

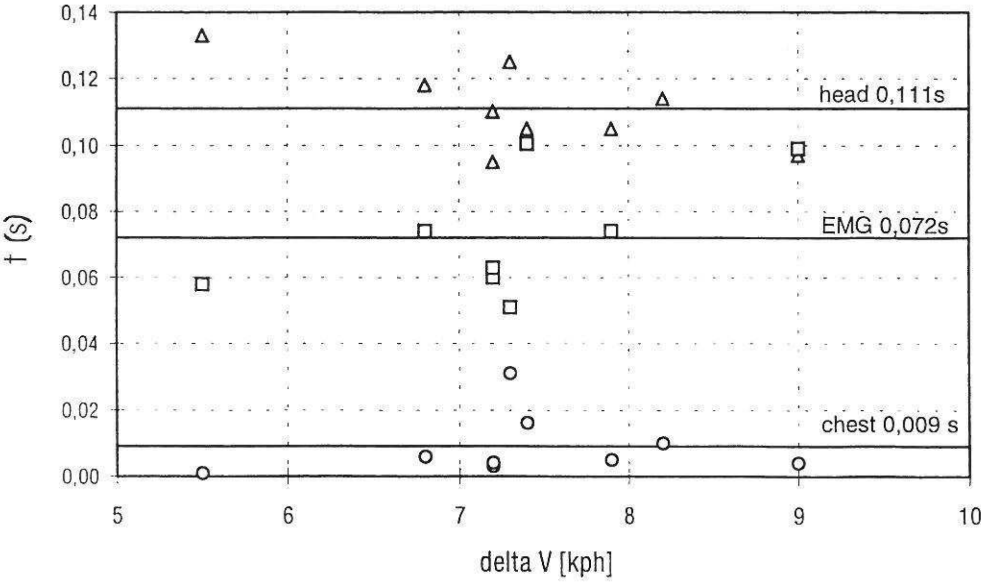


FIG. 21. Time lag between the biomechanical signals in relation to the Δ *V* (1993 study only).

mately corresponds to the distance between the head and the head restraint in normal circumstances. On the basis of this movement, a decreasing time lag between the acceleration of the passenger compartment and that of the head might be inferred at higher ΔV values. The measurement data, however, do not indicate such a relationship. The reaction time found for the neck muscles starts approximately 72 ms after the start of acceleration of the passenger compartment and 63 ms after the start of chest acceleration. Muscle activity therefore does not start until after the relative movement between the torso and head of the occupant, but on average almost 40 ms before the start of head acceleration. In view of the fact that in about half of the trials carried out in 1993 the test subject's attention was screened off, it can be concluded, despite the small number of trials, that this reaction must be a kind of reflex. As even in the case of conscious activity, the minimal reaction time to individual signals is 200 ms, the reaction time value we obtained of about 60 ms is plausible only for an unconscious reflex, and it is also in line with the reflex times for the neck muscles found by Foust (5).

EXAMPLE OF A TRIAL IMPACT

Figure 22 gives comparative pictures for the damage occurring in a real accident and that in a crash test carried out in the 1996 study. The aim was to determine the stresses on the occupant during the real accident, because the driver of the impacted Mercedes station wagon *(B)* claimed to have been severely injured. As the bottom pictures show, impact at a velocity of just under 28 kph produced comparable or somewhat more severe damage. ΔV in the impacted vehicle could therefore be determined at under about 13 kph.

Finally, Figure 23 documents the effect of nose-diving in this trial. The rigid structural parts in the area of the front bumper of the bullet Mercedes were subject to only little stress, whereas the higher body work sections were substantially deformed. The volunteer test person complained of no trouble after the trial, nor were any injuries found in the various medical examinations that were subsequently carried out.

For the same trial, Figure 24 shows the accelerations of the vehicle, chest, and head. The time lag between these accelerations is typical for rear-end collisions, for the increase of accelerations between vehicle, chest, and head, which depends on the distance between body and seat back and also on the seat construction. The lowest biomechanical stress occurs when there is no distance between seat and body and when the seat is rather stiff. After this test, we can say that the force level is similar to a slight bumper collision. We find no explanation for a severe whiplash.

RESULTS AND DISCUSSION

The question of whether a direct cause-and-effect relationship exists between an accident and an injury to the cervical spine can be answered only on the basis of a known ΔV of the vehicle concerned. In determining ΔV, the technical expert must, using the available photographs of damage, take into account the degree of overlap, and the differences in heights and the structural rigidity of the vehicle parts involved. Additionally, information on the vehicle weights is necessary.

To make statements with a high degree of statistical reliability, it is helpful to compare bumper car impacts at funfairs, whose forces are tolerated by the occupants without injury, with car–car collisions at ΔV values of the same magnitude. The occupants of bumper cars have very poor support, as the seats are of inadequate height and there are

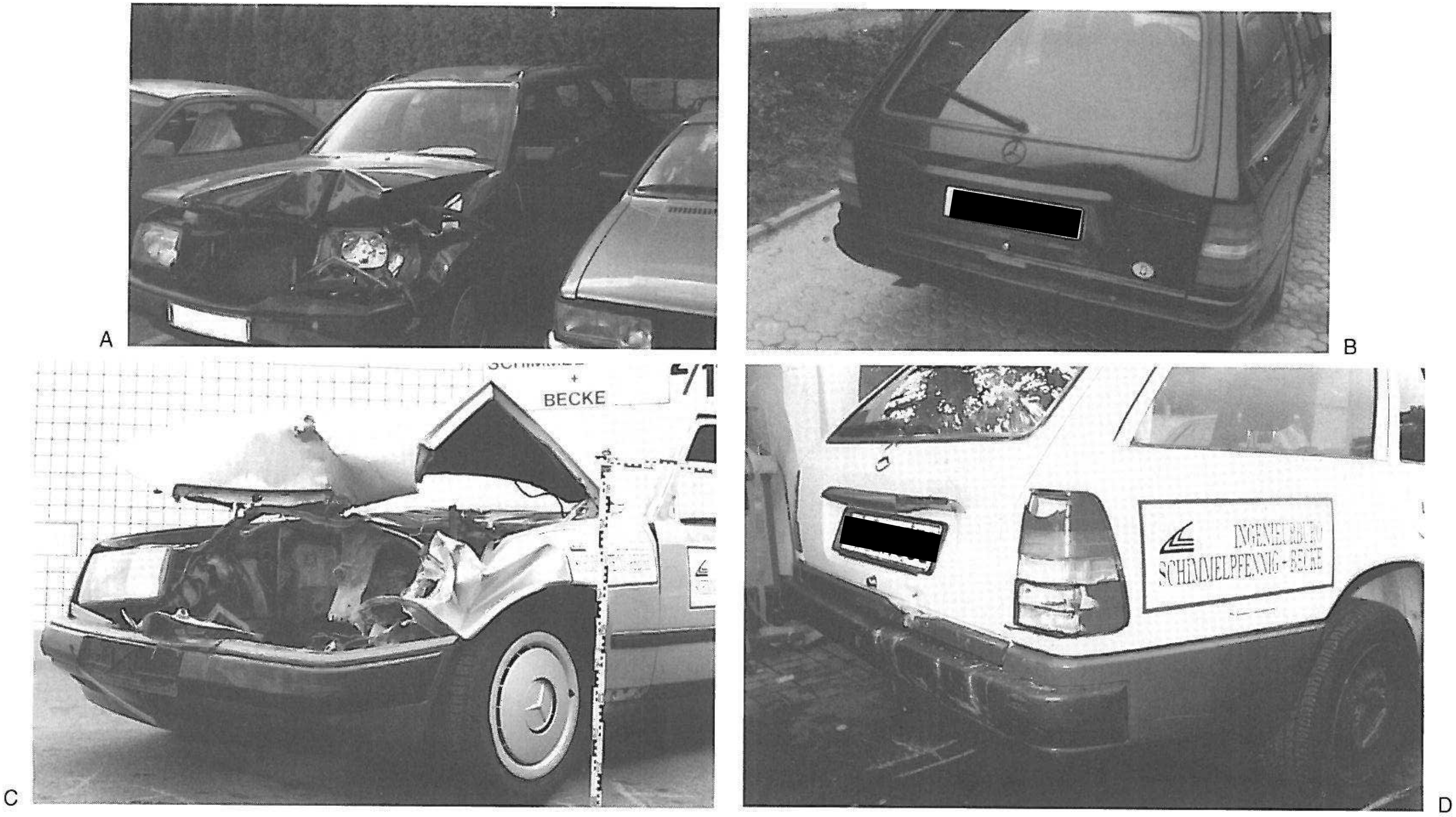


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FIG. 22. A,B: A rear-end accident between two station wagons. **C,D:** The trial we made to determine the impact speed.

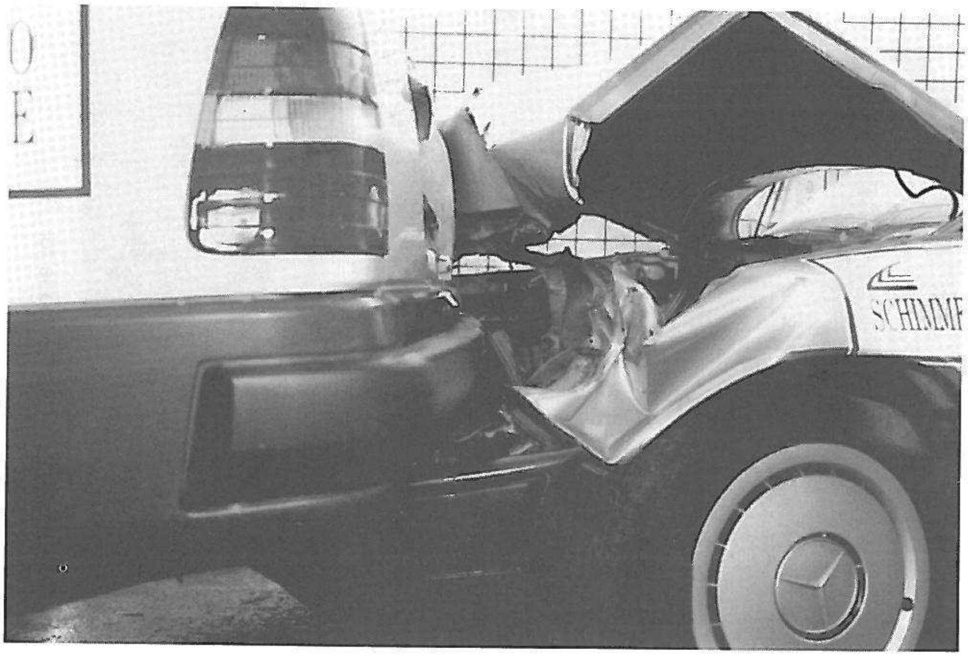

FIG. 23. The result of nose-diving in a rear-end impact.

no head restraints to prevent hyperextension of the cervical spine. Additionally, all possible directions of impact, body postures, and levels of muscle tension are observed in bumper car collisions (Fig. 25). We observed also that many older men and women, mostly with children but also alone, use bumper cars. Moreover, the occupants are in many cases taken completely by surprise by the impact and can therefore not adopt a protective posture.

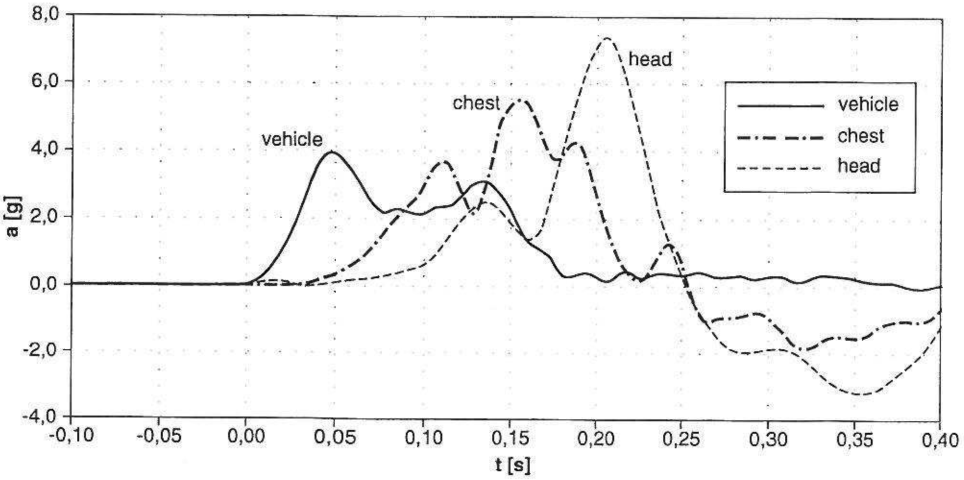

FIG. 24. Acceleration curves for car, chest, and head for the test shown in Figures 23 and 24.

FIG. 25. All kinds of impact directions and seating positions occur in bumper cars.

Despite these unfavorable circumstances, millions of bumper car collisions occur at funfairs every year, with symptoms being reported in only a statistically negligible number of cases, and indeed no such case being known to us in Germany. From this, it can be deduced that the forces occurring in bumper cars are tolerated by the cervical spine, even in the case of preexisting pathologic damages and major interpersonal differences. The assessment of injury causality requires an interdisciplinary (technical and medical) approach. On the basis of the knowledge acquired in the 1993 study, such interdisciplinary cooperation is essential at a ΔV greater than 10 kph, as, in addition to the technical collision parameters, factors related to the individual people involved must be taken into account.

However, on the basis of our 1993 study and our knowledge today, it can be stated that the limit of harmlessness for stresses arising from rear-end impacts lies around a ΔV of 10 kph. Taking the results of the initial part of the 1996 study into account, it appears probable that the injury threshold is much higher than a ΔV of 10 kph.

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