# IMPLICATIONS OF VELOCITY CHANGE DELTA-V AND ENERGY EQUIVALENT SPEED EES FOR INJURY MECHANISM ASSESSMENT IN VARIOUS COLLISION CONFIGURATIONS

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## ABSTRACT

Technical tools to describe the crash severity of a vehicle are the delta-v of the center of gravity of the vehicle considered and the EES value of the deformation. In a collision without glance-off, such as a barrier impact with 100 % overlap, EES and delta-v are of similar values. If glance-off occurs in an impact with only partial overlap, the EES can be considerably higher than the delta-v, especially with high collision speeds. The theoretical background is standard knowledge for engineers dealing with accident reconstruction. However, scientists in the biomechanical and medical area are less aware of the difference of the two terms, sometimes using them as synonyms even in accident samples with all kinds of collision types. This can result in significant misinterpretations of the biomechanical and medical findings in their study. Mechanisms of severe injuries have to be divided into those with extensive intrusions, described by the EES, and into those without intrusion but high inertial loading, caused by a high delta-v. Several examples are shown where just „looking at the car photo“ leads to an enormous error in the judgement of the delta-v.

A large amount of instrumented crash tests has visualised the theoretical calculations in practice; more such tests will be carried out documenting the difference of collision speed, delta-v and EES in various collision angles and overlap values, also in pure side impacts. Moreover the test results have been be simulated by mathematical accident reconstruction tools.

## "SERIOUSNESS OF THE ACCIDENT", "CRASH SEVERITY", "SPEED"

In case reports as well as in scientific publications, terms like „seriousness of the collision" or „accident severity“ as a totality are used, often without clarifying what is meant. The technician is mainly referring to the estimated vehicle loading while the physician is concerned with the injury severity. Thus, the same term has different meanings and is used in a different way inducing misunderstandings. In medical documents, statements of „speed“ are usually based on the non-verifiable evidence of witnesses, concerned parties, auxiliary medical personnel, police officers, or even on inadmissible „estimates“ of the doctor based on the degree of injury. Moreover, it has to be admitted that most physicians are not aware of the fact that there are many types of „velocities“ and they do not know the difference between collision speed, energy equivalent speed and delta-v.

In order to overcome such shortcomings of a misleading general description of the „accident severity“, we propose to break down the whole complex into four different types of loading and individual circumstances:

- First, the dynamic loading of the vehicle during the collision, also called crash severity. It is measured by interior and exterior deformations, delta-v, EES, mean or maximal vehicle deceleration; these values have to be assessed by a technical expert.

- Second, the biomechanical loading of the occupant (for example, as estimated by occupant deceleration based on the type and way of use of head restraint and other restraint systems, the stiffness and the shape of the interior impact area, position and mechanical characteristics of the seat); this biomechanical assessment cannot be done by a clinician.

- Third, the circumstances of the injury itself (assessed by the morphology, medical examination, including objective signs of impairment); this is clearly the field of the clinician.

- And fourth, the degree of disability subjectively experienced by the patient; especially in problematic cases of neck pain and associated disorders a psychiatrist must be consulted.

A comprehensive judgement of the severity of an accident requires interdisciplinary knowledge and should be done in cooperation of medical and technical specialists. According to this general background it is to be mentioned, that the following explanations are focused only to the technical aspects.

## DEFINITION OF COLLISION INDUCED VELOCITY CHANGE AND ENERGY EQUIVALENT SPEED

Delta-v is defined as the change of velocity of the center of gravity of a vehicle in the fixed coordinate system during the contact phase, **Fig. 1**. It is usually different from the change of velocity calculated by integration of the vehicle deceleration components, e.g. in the vehicle coordinate system. In the special case where the vehicle movement remains parallel to its initial longitudinal axis during the collision and the velocity of the vehicle prior to the collision is known, delta-v can be calculated by integration of the vehicle deceleration in x-direction, **Fig. 2**.

The energy equivalent speed EES was first defined by BURG, MARTIN and ZEIDLER (1980) and proposed for general use. So it was a methodology of collision analysis developed in order to calculate delta-v and EES. The EES accident reconstruction method is founded on the physical principles of conservation of energy and momentum, including, in the case of a general planar motion, angular momentum, -Zeidler (1984).

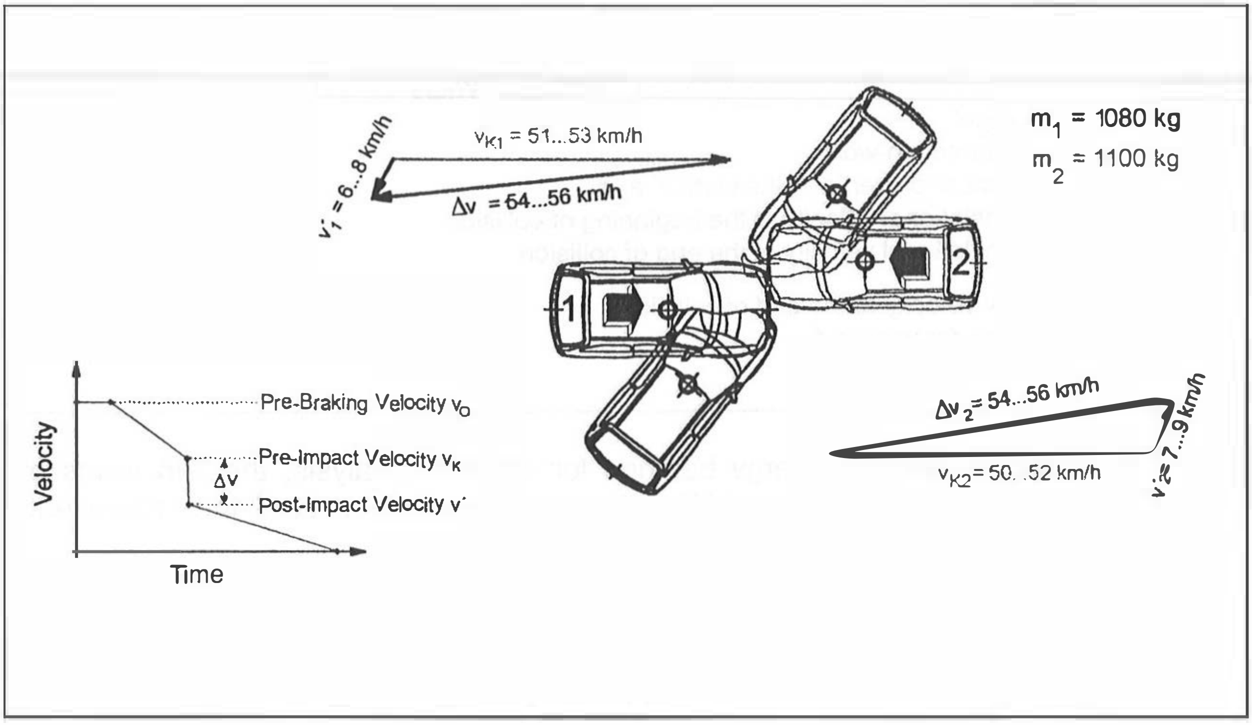



**Fig. 1** Collision related velocity change delta-v of the center of gravity of two vehicles in an experimental frontal crash test with 50% overlap, equal masses of the two vehicles.

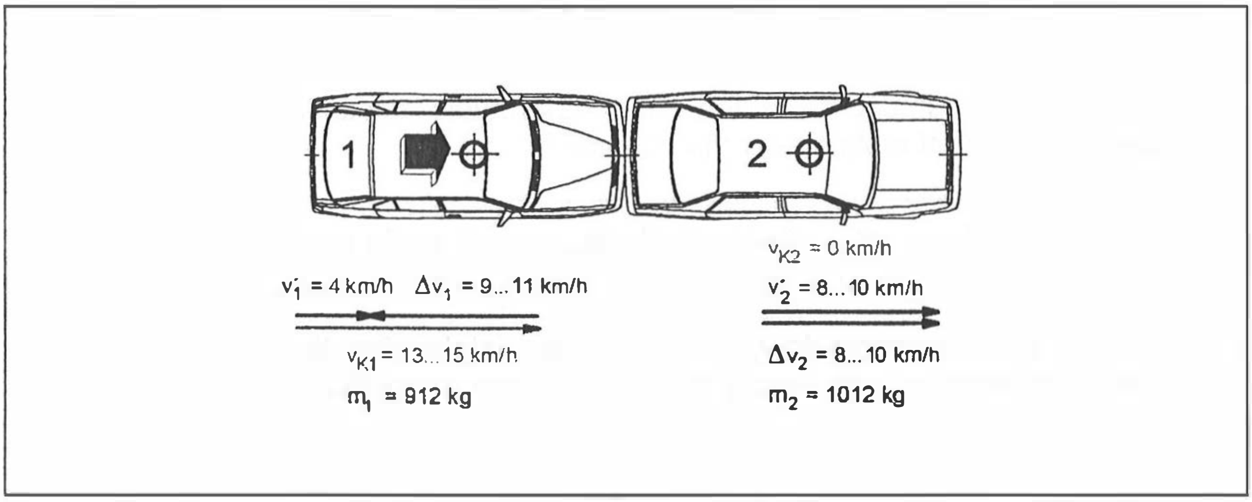



**Fig. 2** Collision related velocity change delta-v of the center of gravity of two vehicles in an experimental frontal crash test with 100% overlap in the special case of a one dimensional motion in x-direction in a experimental rear-end crash test.

Energy equivalent speed EES is a measure for the kinetic energy dissipated by the vehicle during the contact phase, i.e. the energy converted to thermal energy through deformation. The following energy balance can be formulated for a collision of two vehicles which are stable before the collision and spin out after the collision (simplified for planar motion).

$$\text{Kinetic energy before collision} = \text{Kinetic energy after collision} + \text{deformation-work}$$

$$\tfrac{1}{2} m_1 v_{K,1}^2 + \tfrac{1}{2} m_2 v_{K,2}^2 = \tfrac{1}{2} m_1 v_1'^2 + \tfrac{1}{2} m_2 v_2'^2 + \tfrac{1}{2} J_1 \dot{\Psi}_1'^2 + \tfrac{1}{2} J_2 \dot{\Psi}_2'^2 + W_{Def,1} + W_{Def,2}$$

**m :** weight
**$W_{Def}$ :** deformation-work
**J :** moment of inertia of the vertical axis
**$v_K$ :** translational velocity at the beginning of collision
**$v'$ :** translational velocity at the end of collision
**$\dot{\Psi}$ :** yaw velocity at the end of collision
**1 :** index for vehicle 1
**2 :** index for vehicle 2

In order to use this energy balance for collision analysis, the two terms of the deformation energy ($W_{Def,1}$ and $W_{Def,2}$) can be formulated as if they represented a kinetic energy,

$$\tfrac{1}{2} m_1 v_{K,1}^2 + \tfrac{1}{2} m_2 v_{K,2}^2 = \tfrac{1}{2} m_1 v_1'^2 + \tfrac{1}{2} m_2 v_2'^2 + \tfrac{1}{2} J_1 \dot{\Psi}_1'^2 + \tfrac{1}{2} J_2 \dot{\Psi}_2'^2$$
$$\tfrac{1}{2} m_1 EES_1^2 + \tfrac{1}{2} m_2 EES_2'^2$$

thereby yielding the classical definition of the energy equivalent speed EES:

$$W_{Def} = \tfrac{1}{2} m \, EES^2$$

$$EES = \sqrt{2 \cdot W_{DEF} / m}$$

If a vehicle impacts a fixed, non deformable obstacle, the energy balance including a spin-off motion after the collision is:

$$\tfrac{1}{2} m v_K^2 = \tfrac{1}{2} m v'^2 + \tfrac{1}{2} J \dot{\Psi}'^2 + W_{Def} = \tfrac{1}{2} m v'^2 + \tfrac{1}{2} J \dot{\Psi}'^2 + \tfrac{1}{2} m \, EES^2$$

If the vehicle comes to a full stop immediately after the collision (fully plastic impact), the entire kinetic energy is converted into deformation. In this simplified case the energy balance is:

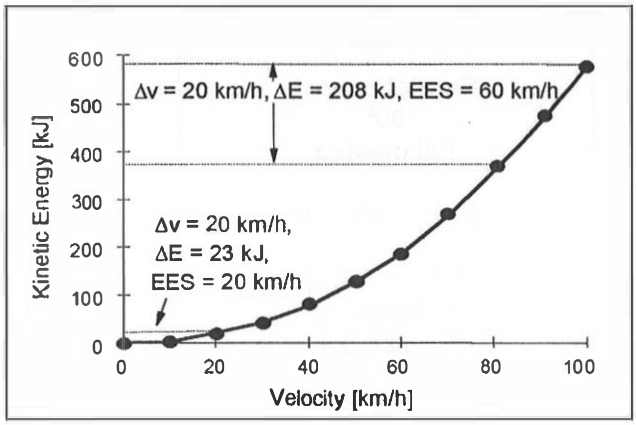
$$\tfrac{1}{2} m v_K^2 = W_{Def} = \tfrac{1}{2} m \, EES^2$$

$$v_K = EES$$

Using an illustrative interpretation of the EES formulae, the reconstructing engineer tries to derive the velocity at which the vehicle in question should be crashed against a fixed, non deformable object (with according geometric properties) in order to produce an identical deformation as observed in the vehicle. In a simplified approach, it is assumed that the kinetic energy is converted completely into deformation (no spin-off). Even for the experienced reconstructing engineer, the dimension of the deformation energy (kJ) is a rather abstract term; hence the formulation of the (thermal) deformation energy as a kinetic energy, leading to the dimension of the EES being km/h. On the other hand, this may also lead to confusion, since EES corresponds only in very special cases to an actual velocity of the vehicle before, after, or during the collision.

The relationship of velocity with kinetic energy is nonlinear. Therefore, a given delta-v on a high velocity level corresponds to a higher EES than the same delta-v in a lower velocity range, **Fig. 3**.

**Fig. 3** Kinetic energy vs. velocity of a car with a mass of 1500 kg. Delta-v and EES assume equal values only in the case where the car comes to a full stop (no rebound) during a collision.




Usually, the EES of the vehicle deformation is estimated based on the photographs of the damage, e.g. by matching the damage against experimental cases where the EES values are known.

## EES AND DELTA-V IN COLLISIONS AGAINST A FIXED OBJECT

We use EES catalogues depicting cars with a certain damage and the corresponding EES value determined by experimental crash tests for this purpose. In this first section, examples for an impact against a fixed, non deformable object or a fixed pole are shown. In this context it is important whether the vehicle came to a complete stop during the contact phase or if a glance-off occurred.

### Impacts without glance-off

An impact against a fixed object leads either to a full stop of the vehicle after the contact phase (fully plastic impact) or a rebound takes place (partially elastic impact). This scenario is observed usually in impacts with a full overlap against a fixed object, even with a high impact speed.

The crash tests shown in **Fig. 4** have been documented with high speed cameras. Film analysis revealed the trajectories and the velocities of a target on the roof corresponding to the center of gravity of the vehicle. Momentum and kinetic energy of the vehicles were calculated at the beginning and the end of the contact phase, **Fig. 5**.

**Fig. 6** shows the corresponding car damage to the vehicle front. Taking into account the tolerance values of the analysis, the collision speed was 28...30 km/h, the velocity change delta-v 31...35 km/h and the enery equivalent speed EES 28...30 km/h.

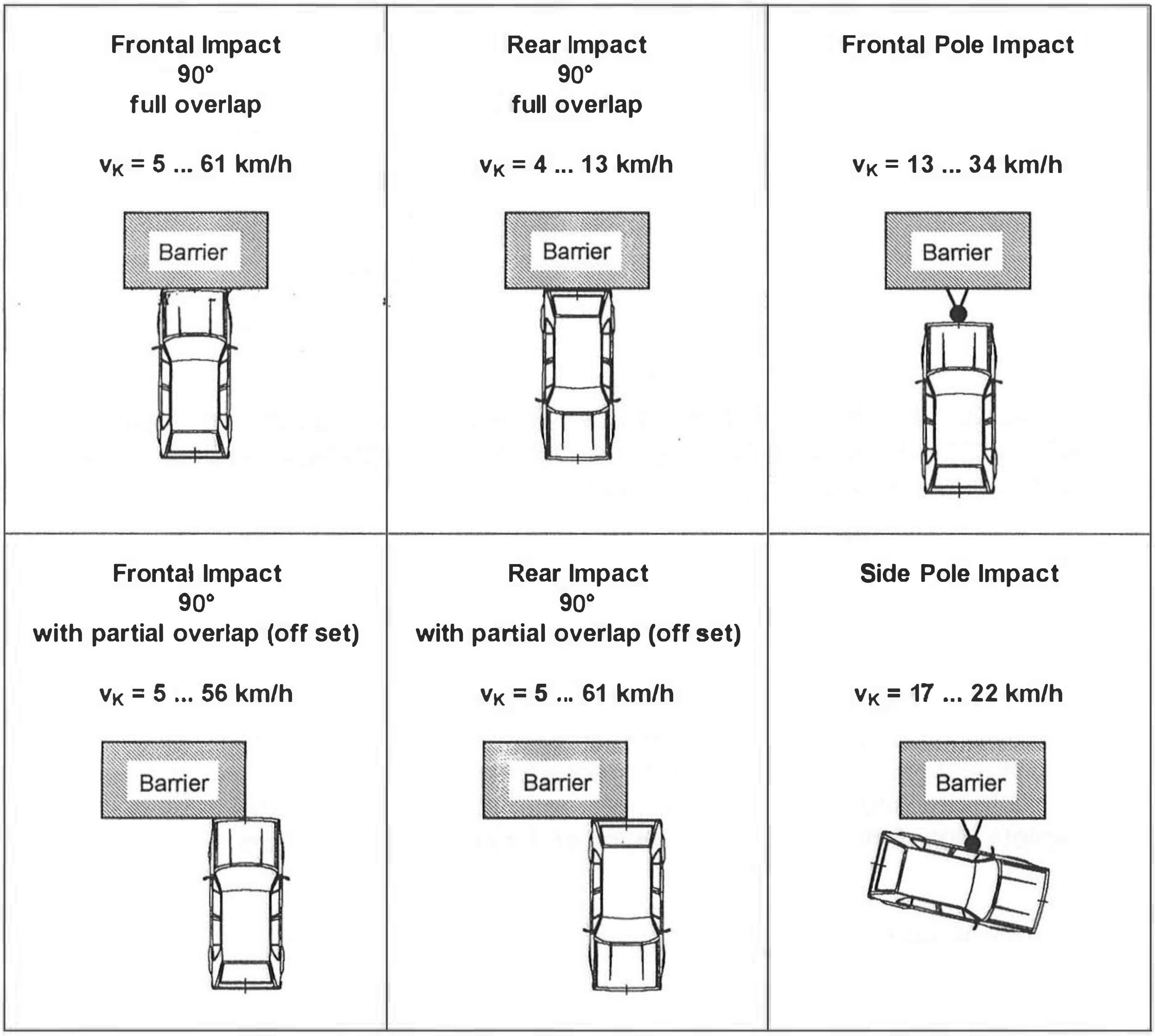



**Fig. 4** Overview of the crash tests performed, against fixed objects, no glance-off.

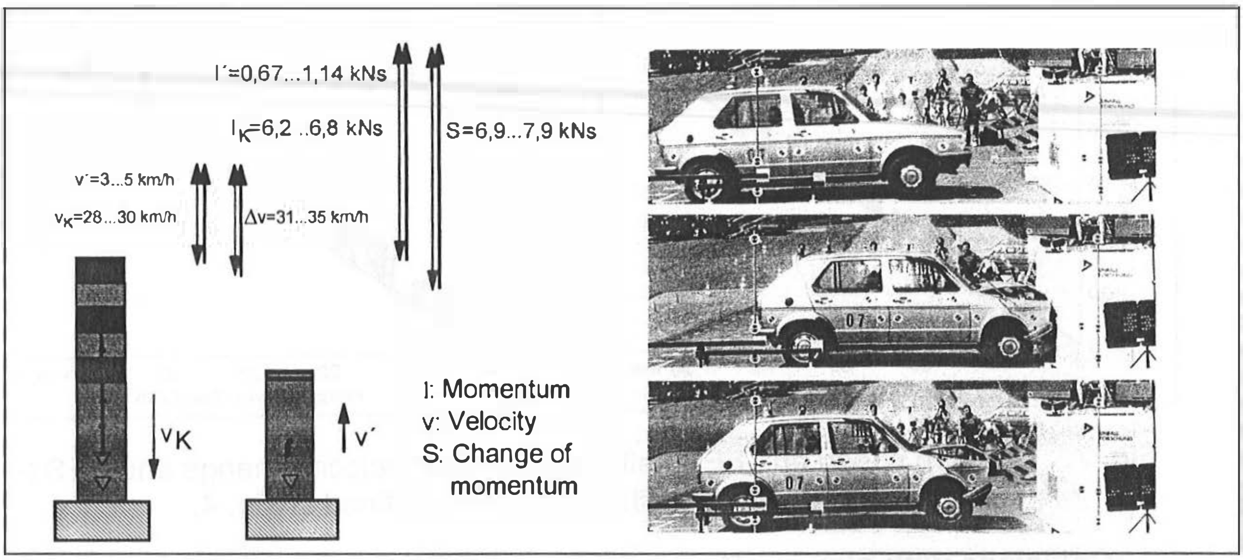
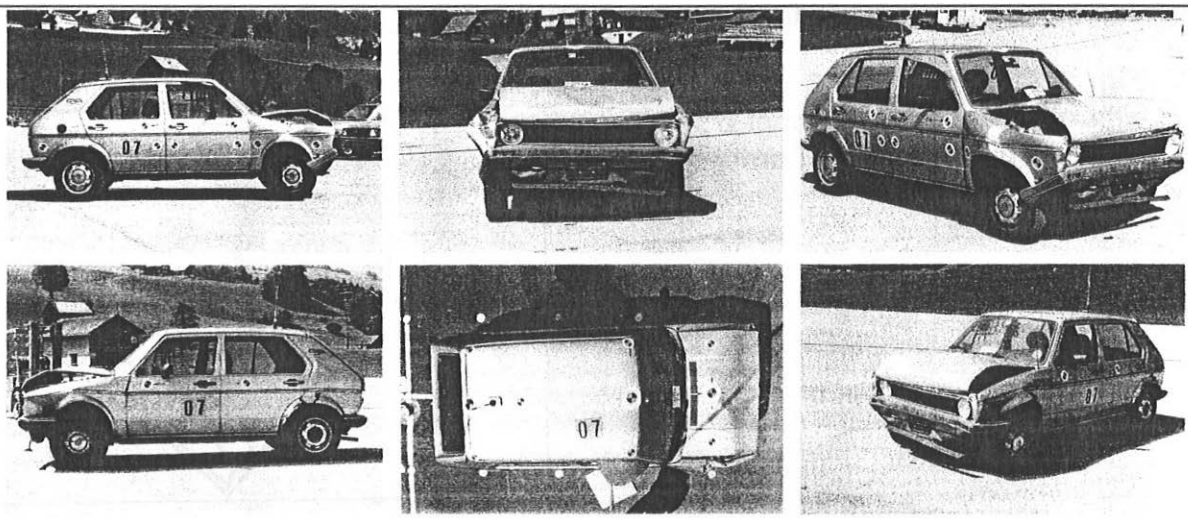



**Fig. 5** Example for the scenario top-left Fig. 4: Impact of a VW-Golf I with 29 km/h with full overlap against a fixed barrier. Delta-v 31...35 km/h, some elastic rebound.



$v_K$ = **28 ... 30 km/h** $\Delta v$ = **31 ... 35 km/h** **EES = 28 ... 30 km/h**

**Fig. 6** damage of the front of the VW-Golf I due to the crash test described in Fig. 5.

The mean EES values confirm the definition of EES, $v_K$ = EES (**Fig. 6**, left diagram). Accordingly, the delta-v values are somewhat higher, delta-v > EES and delta-v > $v_K$. The reason for this is the elasticity in the deformed structure which leads to a rebound at the end of the collision. Depending on the nonlinear relationship between speed and energy, the difference between delta-v and EES is clearly greater than the difference between EES and $v_K$. If the structures were completely plastic, EES would always be equal to delta-v and equal to $v_K$ in a collision without glance-off.

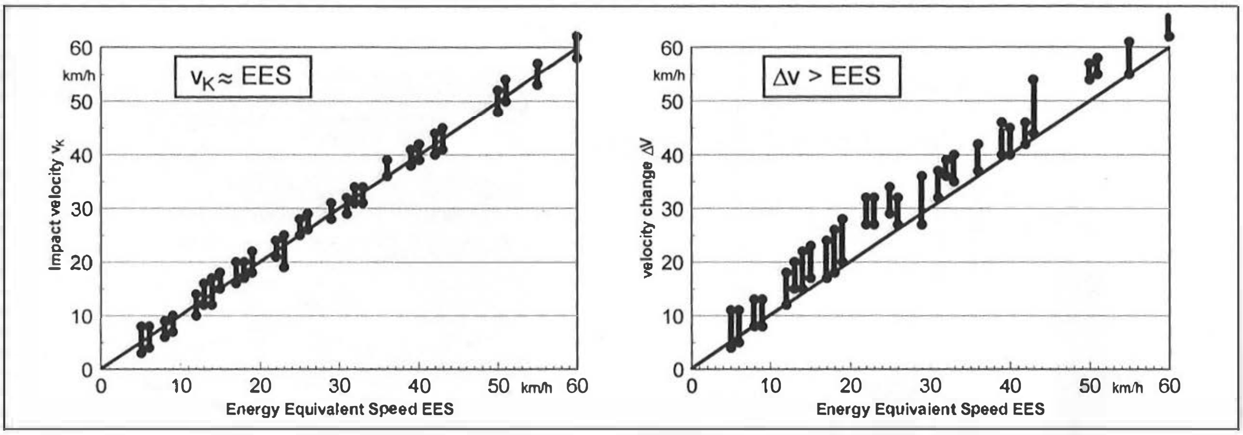
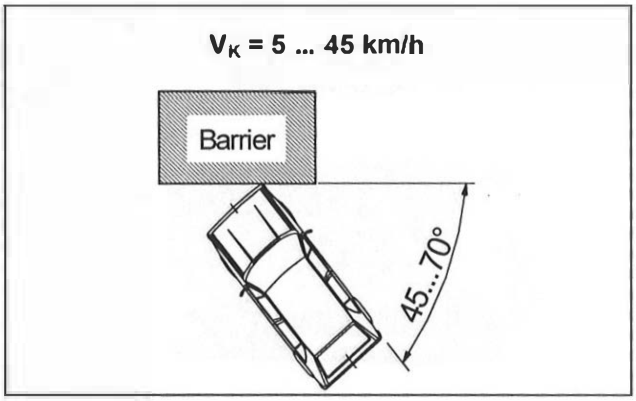



**Fig. 7.** Collision speed and EES (left diagram), and velocity change and EES (right diagram), resp., for the crash tests defined in Fig. 4.

### Collisions with glance-off

In an impact against a fixed non-deformable object a glance-off occurs already at a relatively low impact speed, if the impact angle is oblique. 13 such crash tests in a range of impact velocities between 5...45 km/h have been carried out, **Fig. 8**. An example to this is given in **Fig.9.**

**Fig. 8.** Setup of 13 crash tests with glance-off after impact against a fixed non-deformable barrier at an oblique angle.



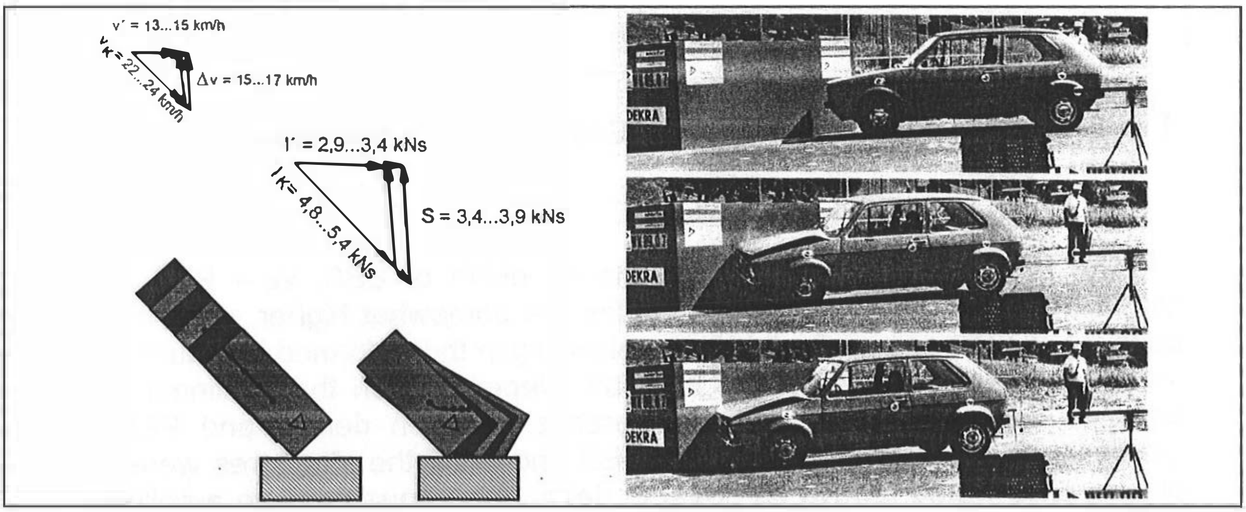
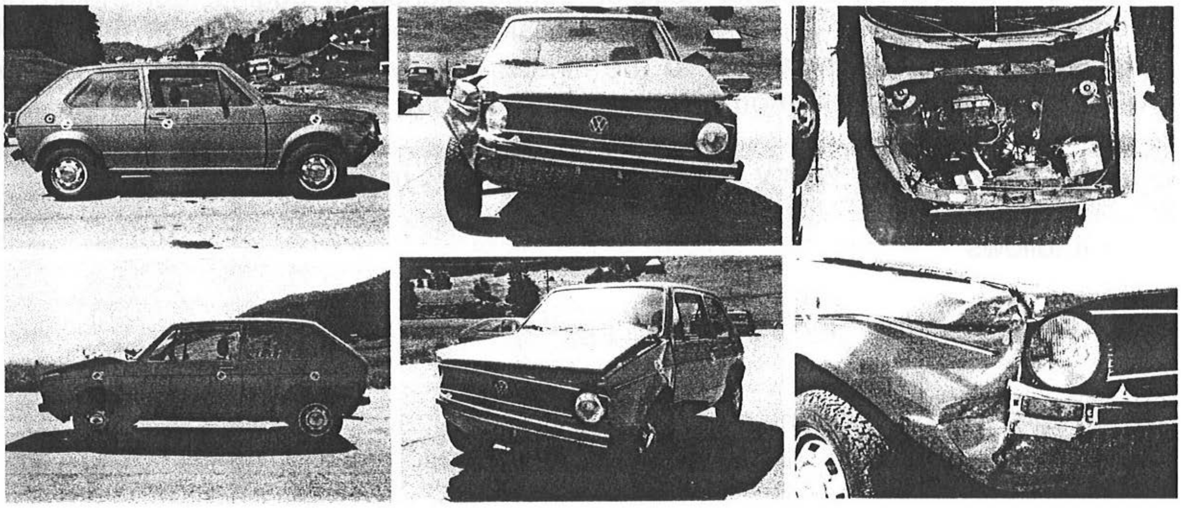




**Fig. 9.** One example with VW-Golf I at an impact speed of 23 km/h, crash setup according to Fig. 8.

The collision speed of the test in **Fig. 9** was 22...24 km/h, the velocity change delta-v 15...17 km/h and the EES 15...19 km/h. The damage of the car front is depicted in **Fig. 10**. All 13 crash tests under these circumstances yielded collision speeds vk > EES and delta-v ≅ EES, **Fig. 11**.



**$v_K$ = 22 ... 24 km/h** **$\Delta v$ = 15 ... 17 km/h** **EES = 15 ... 19 km/h**

**Fig. 10.** The damage of the VW-Golf I after the collision shown in Fig. 9.

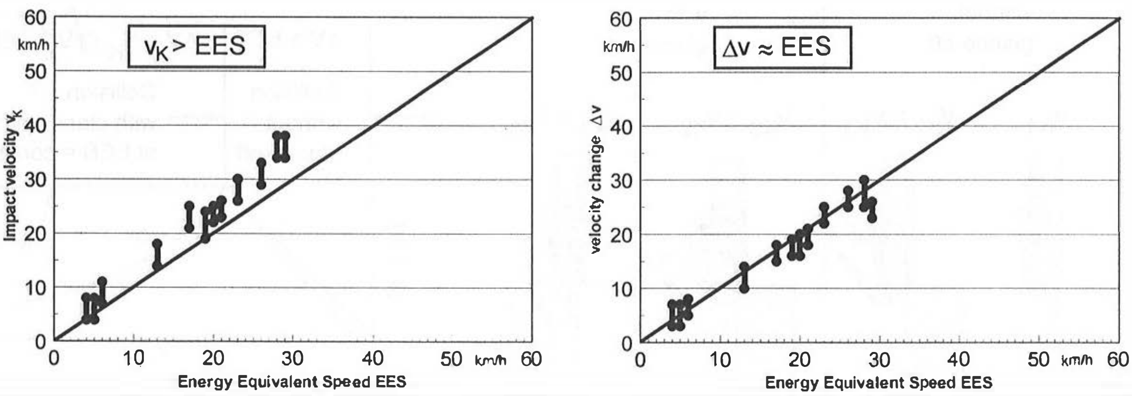



**Fig. 11.** Collision speed and EES (left diagram), and EES and velocity change (right diagramm), resp., of the crash tests explained in Fig. 8-10.

### Glance-off at higher collision velocities

In such a collision against a fixed object with a partial overlap a glance-off can be expected. Burg (1984) showed in a interesting theoretical experiment that at low and medium collision velocities no glance-off takes place: delta-v > EES (partially elastic impact), and delta-v = EES, resp., (fully plastic impact). This was shown in the crash tests in Fig. 5-7. At a higher collision speed, glance-off begins, depending on the degree of overlap. At an ever higher collision speed the damage of the car is not increasing any more and, due to the kinetic energy still inherent at the end of the contact phase, the glance-off speed rises. Therefore, the energy balance is :

$$E_{Kin} = \tfrac{1}{2}\, m\, v_K^{\,2} = \tfrac{1}{2}\, m\, v'^{2} + W_{Def} = \tfrac{1}{2}\, m\, v'^{2} + \tfrac{1}{2}\, m\, EES^{2}$$

it follows

$$v_K^{\,2} = v'^{2} + EES^{2} \text{ bzw. } v' = \sqrt{v_K^2 - EES^2}$$

Neglecting the movement in the y-direction (sideways), delta-v is calculated for a one dimensional motion according to the following formula:

$$\Delta v = v_K - v' = v_K - \sqrt{v_K^2 - EES^2}$$

As shown in **Fig. 12**, at a rising collision speed $v_K$ and a constant energy equivalent speed EES the velocity change delta-v decreases again and therefore the difference between EES and delta-v increases.

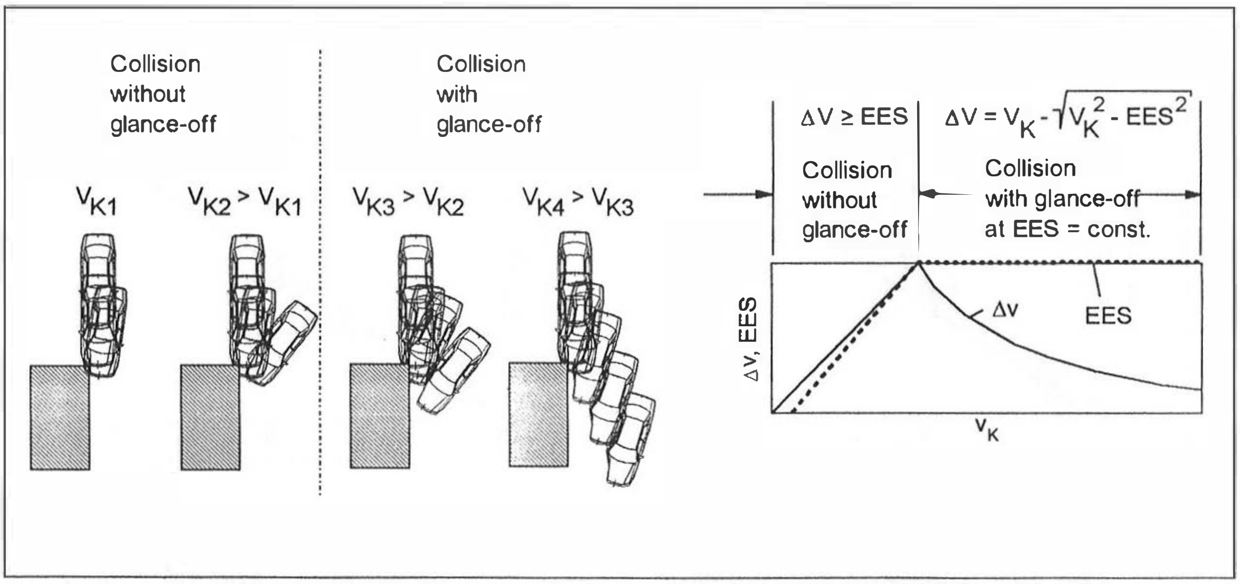



**Fig.12** Relationship between velocity change delta-v and energy equivalent speed EES in a frontal impact agaist a fixed non-deformable object with only a small overlap and rising impact speed (according to Burg, 1984).

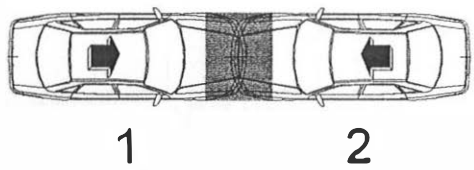
## EES AND DELTA-V IN IMPACTS AGAINST A MOVING BARRIER AND IN CAR TO CAR COLLISIONS

If the elastic part of an impact is ignored, the relationship of delta-v and EES in impacts against a moving barrier and in car to car collisions can be described by the principle of conservation of energy and momentum.

**Fig. 13** shows the case of a collision of two cars of equal mass with full overlap (according to Zeidler, 1992). In case of a frontal collision (fig.13, left), equal force-deformation characteristics of the two deforming car structures are supposed. For both cars the delta-v and EES values are equal, and for each car delta-v is equal to EES.

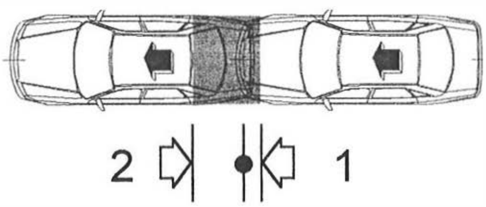
In case of the rear end collision (Fig.13, right) it is realistically supposed that the rear end of the struck car exhibits a softer structure than the front end of the impacting car. Therefore, the rear end dissipates more energy than the front end and its EES value is higher. Since the two masses are equal, the delta-v values for both cars are equal. For the struck car this results in the following statement: $EES_2$ > delta-$v_2$, and for the impacting car $EES_1$ < delta-$v_1$, resp..

$m_1 = m_2$
$v_{K,1} = 80$ km/h
$v_{K,2} = -20$ km/h
equal force-deformation characteristics of the deformable front structures




$v'_1 = v'_2 = ½ (v_{K,1} + v_{K,2}) = 30$ km/h
$\Delta v_1 = \Delta v_2 = 50$ km/h
$EES_1 = EES_2 = 50$ km/h
$\boldsymbol{\Delta v_1 = EES_1}$
$\boldsymbol{\Delta v_2 = EES_2}$

$m_1 = m_2$
$v_{K,1} = 80$ km/h
$v_{K,2} = 20$ km/h
Rear end of vehicle 2 softer than the front of vehicle 1




$v'_1 = v'_2 = ½ (v_{K,1} + v_{K,2}) = 50$ km/h
$\Delta v_1 = \Delta v_2 = 30$ km/h
$EES_1 = 25$ km/h; $EES_2 = 34$ km/h
$\boldsymbol{\Delta v_1 > EES_1}$
$\boldsymbol{\Delta v_2 < EES_2}$

**Fig.13** Fully plastic impact of two cars and relationship of EES and delta-v (according to Zeidler, 1992).

**Fig. 14** shows an example for car damages in experimental frontal-/rear-impacts: At nearly the same impact speed $v_K$ and velocity change delta-v, different EES-values are appearing on each vehicle.

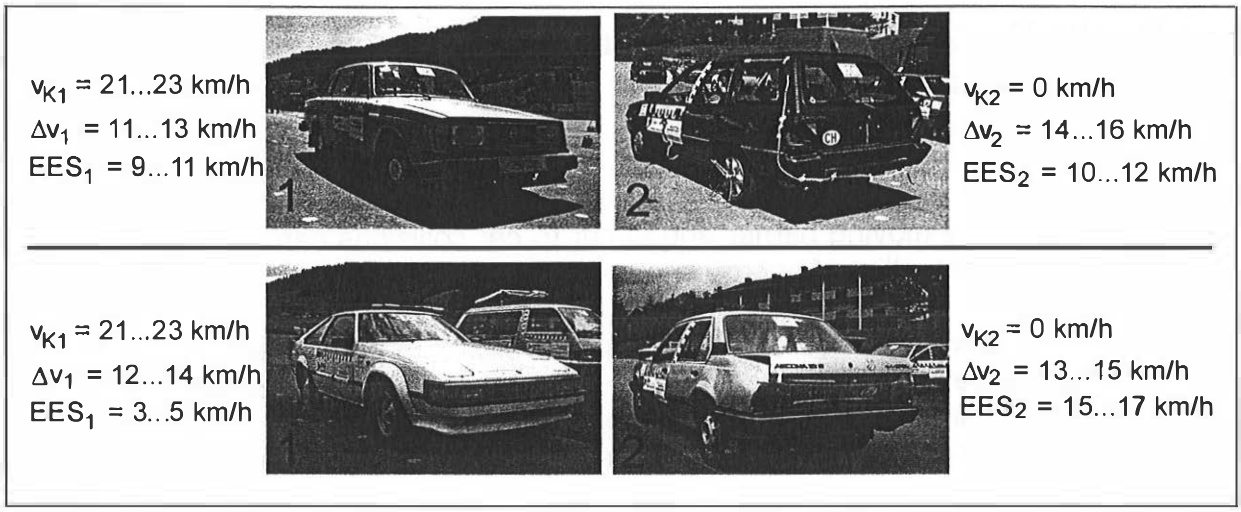
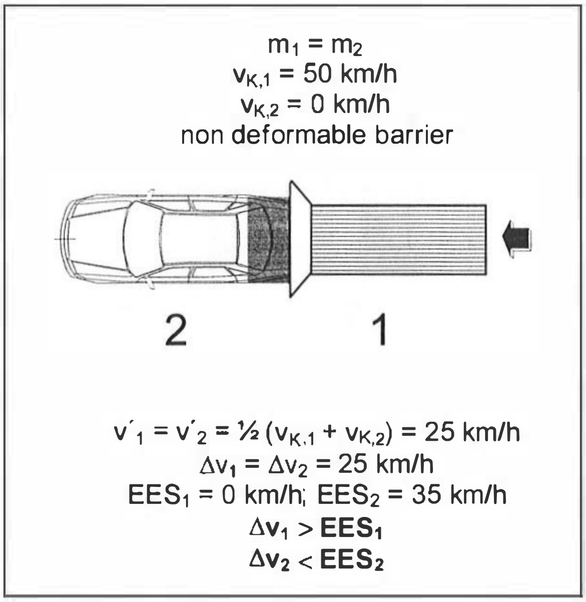



**Bild 14** Different EES-values at same impact speed $v_K$

In a similar way, the situation of a rear end impact of a non deformable moving sled can be described, **Fig. 15**. The values of the velocity change of car and moving barrier are equal (equal mass). The whole kinetic energy is dissipated by the car. Therefore, for the barrier delta-$v_1$ > $EES_1$ and for the car delta-$v_2$ < $EES_2$.

**Fig.15** Fully plastic impact of a moving, non-deformable barrier against the rear end of a car (according to Zeidler, 1992).



In a 90° impact of a Renault 5 with an impact speed of 51 km/h against the left side of a Nissan Micra, driving a velocity of 26 km/h (**Fig. 16**), the glance-off velocity of the Renault was 20...23 km/h, the velocity change delta-v 30...32 km/h and the EES 28...30 km/h.

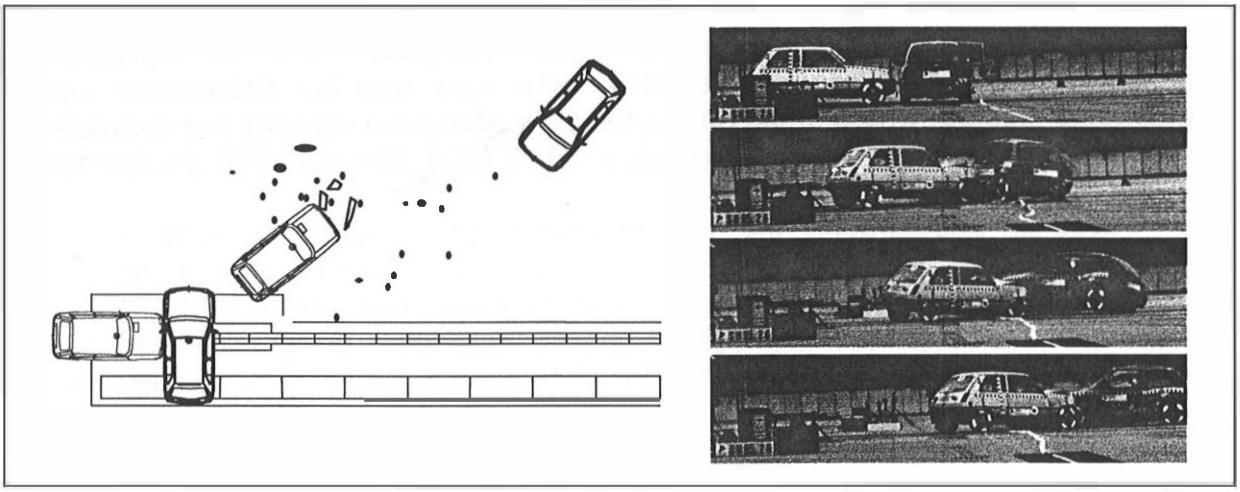


**Fig. 16** 90° impact between two economy-vehicles with velocities of 51 km/h (R5) and 26 km/h (Nissan Micra).

The corresponding values for the Nissan were: glance-off velocity 31...33 km/h, velocity change 23...25 km/h and EES 24...26 km/h. The car damage and the set up of the crash test is depicted in **Fig. 17**.

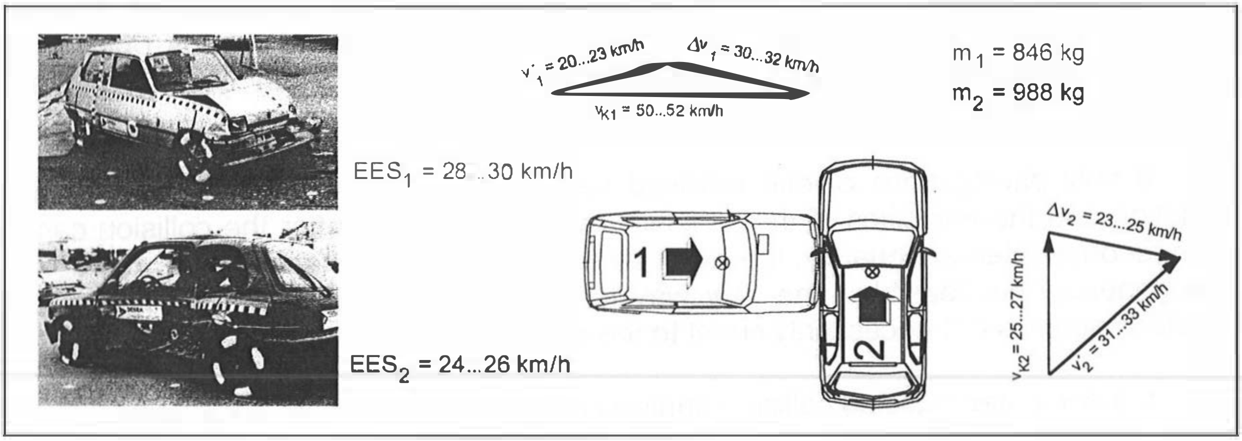



**Fig. 17** Despite lower EES values the Nissan shows a more extended damage than the Renault 5. This is due to the soft structure of the door area of the Nissan and the stiff front structure of the Renault 5.

## Discussion

The examples show that, in general, there is no direct relationship between the velocity change delta-v and the energy equivalent speed EES of a vehicle in a collision. The type of collision (with or without glance-off, collision speed, mass ratio and force) as well as deformation characteristics of the deformed structures of the vehicles involved decide whether EES is greater, equal or smaller than delta-v. If photographs of the vehicle deformation and a „damage catalogue" with known EES values are available, the corresponding EES value can be estimated. If the vehicle deformation is either photographed in a orthogonal view or corresponding measurements are available, the EES value can also be determined using a geometric method, where areas on the top view of a given vehicles are characterised by their energy absorption capabilities (Campbell 1974, Sharper 1979, Zeidler 1992).

Based on photographs, the starting point of the accident reconstruction is the EES value. It can be determined individually for each vehicle involved. In general, the assumption that EES is equal to delta-v leads to misjudgements. If the EES values are known the corresponding delta-v can be calculated using a collision analysis taking into account the physical principles of conservation of energy and momentum.

In order to apply the principle of energy conservation it is necessary to know the EES values of the deformation of each vehicle involved. The application of the principle of momentum conservation requires that the directions of motion of both vehicles prior and after the collision and the spin-off velocities after the collision are known. The latter are determined by analysing the tire marks, e.g.. In the context of an accident reconstruction, the combined application of the principles of conservation of energy and momentum reveal a system of equations which requires only the values of three of the four velocity directions (Burg et. al. 1980, Burg, Rau 1982).

If the velocity vectors of the vehicles before and after the impact can be determined on the basis of an adequate skid mark documentation, the principles of energy and puls conservation lead to a overdetermined system of equations. This fact can be used in order to verify the results. By using additional means of classical accident analysis (Burg 1984), misjudgements of the EES can be detected and improved interactively.

If only photographs of one involved vehicle are available, or if the direction of motion and the velocities of the vehicles involved prior and after the collision cannot be reconstructed adequately, the exact determination of the change of velocity delta-v is generally not feasible. The only way to ascertain the crash severity is the EES (which again is not necessarily equal to the delta-v).

If a computer assisted collision analysis is performed carefully, EES values can be determined within a range of $\pm$ 2...3 km/h. If only photographs are available, the estimation is less precise. It can be assumed that an experienced expert is able to assess the EES values based on photographs in a range of $\pm$ 5 km/h, if the amount of deformation is not excessive. The quality of the photographs is important; moreover, geometry and structure of the deformed areas of the vehicle have to be analyzed carefully.

Predominantly in frontal impacts EES values can be determined reliably if the crush zone has absorbed energy in a controlled way. For EES values above 50...60 km/h the frontal deformation zone has bottomed out and additional structural components in the area of the passenger compartment and the undercarriage begin to absorb energy, the amount of which is, however, difficult to determine based only on photographs. Moreover, deformation of these stiffer vehicle structures occurs at very high force levels with only minor changes of the vehicle length. Therefore, at these high EES values the actual values of EES and delta-v are relatively uncertain if only photographs are available.

Similar uncertainties also appear in the lower velocity range for the photograph-based assessment of EES values. Contemporary vehicles with reversibly deformable front and rear bumpers show permanent exterior deformation only at EES values above 10...15 km/h. In cases with minor velocity changes, it is necessary to inspect the potentially deformed structures of the vehicle underneath the soft skin of the „bumper", too.

In addition, it has to be stressed that the advantages of a crash recorder can help analyzing accidents in a more accurate way (Barth et. al. 1994). The UDS (Accident Data Recorder, "Unfalldatenspeicher") provides the possibility of recording the linear and rotational velocity and acceleration time histories of the vehicle in a vehicle related planar (x-y) coordinate system. With these data the motion of the vehicle can be reconstructed and an accurate collision analysis can be performed, including the calculation of the velocity change. Based on these data for an impact against a stiff obstacle the "loss of kinetic energy" during the collision, and - taking into account the vehicle mass - the energy equivalent speed EES can be assessed.

## CONCLUSION

In a simplified approach it can be stated that the velocity change is greater than the energy equivalent speed EES if a stiff vehicle structure and a full overlap are involved, the impact takes place at a low velocity change and no glance-off takes place.

In an analog manner it can be concluded that the velocity change of a vehicle is smaller than the EES if soft vehicle structures and only a small overlap as well as high velocity changes are involved and glance-off occurs.

As a general statement it has to stressed that important misjudgements take place if in an accident sample with different collision circumstances such as overlap, glance-off and structure stiffness the EES is errorneously thought to be equal than the velocity change delta-v.

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