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Računalniško podprta analiza cestnoprometne nezgode
Computer Supported Analysis of a Traffic Accident

IVAN PREBIL

Na temelju posnetega stanja prometne nezgode je predstavljen računalniško podprt potek vrednotenja trka dveh vozil. Pri izračunu v fazi trka sproščene deformacijske energije sta upoštevani energijsko ekvivalentni hitrosti. Ekvivalentni hitrosti rabita za oceno kinetičnih energij, ki dejansko ustrezata med fazo trka nastali deformacijski energiji.

Ključne besede: vozila cestna, nezgode cestnoprometne, analiza trka, vrednotenje poteka nezgode

Recorded data of a traffic accident are used to simulate on a computer the course of an accident involving two vehicles. The computation of the deformation energy released during the crash considers both energy equivalent speeds. The equivalent speeds are used to estimate the kinetic energy corresponding to the deformation energy during the crash.

Keywords: vehicle, traffic accidents, crash analysis, accident evaluation

0 UVOD

Za rekonstrukcijo poteka cestnoprometne nezgode imajo računalniško podprte metode, ki upoštevejo deformacijsko energijo - energijsko ekvivalentni hitrosti (EES), velik pomen, saj omogočajo zanesljivejše rešitve tudi v primeru centričnih trkov in trkov pod majhnim kotom nasproti vozečih vozil, ko postane čista teorija sunka manj zanesljiva. Določanje izgube hitrosti vozil v fazi trka dejansko temelji na zakonu o spremembi kinetične energije. Razlika kinetične energije sistema pred procesom trka in po njem naj bi bila enaka izgubi kinetične energije sistema v procesu trka. Izguba kinetične energije pomeni pretežno deformacijsko delo, zato smemo druge oblike energij (toplota, vibracije itn.) zanemariti.

Deformacijsko delo je za različne oblike trkov (centrični, čelno-centrični, čelno-ekscentrični, čelno-bočni itn.) in vrsto vozil v toge ovire eksperimentalno določeno (testi CRASH) in katalоško urejeno [1]. Na vozilih so testi o zanesljivosti izvedeni s testno hitrostjo (ETS), ki se pri dejanskih centričnih trkih od energijsko ekvivalentne hitrosti EES nekoliko razlikuje.

Ocenjena izguba hitrosti v fazi trka ima odločilen vpliv na izračunano hitrost vozila v fazi pred trkom ali po njem, zato je čim bolj natančna določitev te za rekonstrukcijo cestnoprometne nezgode zelo pomembna.

0 INTRODUCTION

Computer supported methods using deformation energy (Energy Equivalent Speed – EES) for the reconstruction of traffic accidents are gaining in importance, because their results are reliable even in cases of centric collisions, and collisions with a small angle between the vehicles, where the pure impulse theory proves to be less reliable. Determination of speed loss during the crash is based on the law of kinetic energy loss. The difference between the kinetic energy of the system before and after the crash should equal the loss of the system's kinetic energy during the crash. The kinetic energy loss consists mainly of deformation work, therefore we can omit the other energy forms (heat, vibration, etc.).

Deformation work during the collision of a vehicle with a stiff obstacle is determined experimentally (crash tests), for various types of vehicles, and collision configurations (head-on, head-on-centric, head-on-skewed, head-on-side, etc.) and can be obtained from catalogues [1]. Reliability tests on vehicles are done at Energy Test Speed (ETS), which differs slightly from the Energy Equivalent Speed (EES).

Computed speed before and after the crash depends directly on the estimated speed loss during the crash. Therefore the speed loss should be determined very accurately in order to correctly reconstruct the accident.

Osnovni pogoj testa CRASH, da se pri trku v togo oviro s hitrostjo približno 50 km/h pojavi pojemek okoli 80 g, v praksi pogosto ni izpolnjen. Zato se v zadnjem času vedno pogosteje preverjajo trki med vozili (katalog EVU). Na podlagi analize nastale poškodbe (oblika in velikost deformacij na vozilu - fotografije) lahko za enak tip vozila razberemo eksperimentalno določeno vrednost EES [3]. Druga možnost je vrednotenje ekvivalentne hitrosti po energijskem zakonu [2].

Izračun izgube hitrosti v fazi trka je po metodi EES manj primeren za vozila, ki glede trdnosti konstrukcije ne ustrezajo novim predpisom. Za tovrstna vozila je za enako stopnjo deformacije treba vložiti manj deformacijske energije. Ekvivalentna hitrost EES ne doseže dejanskih vrednosti, če v času trka prihaja do večjega relativnega drsenja med vozili. Med stičnima površinama - pločevinama - se pojavi trenje, ki pri izgubi sproščene energije ni upoštevano.

In praxis the basic requirement of a CRASH test (i.e. collision of a vehicle with a stiff obstacle at approximately 50 kph gives a deceleration of approximately 80g) is seldom fulfilled. Therefore the crash tests done lately are usually of the vehicle - to - vehicle type (EVU Catalogue). The analysis of the damage (shape and size of deformations on the vehicle – photographs) gives the experimentally derived EES speed value [3] that can be used on all vehicles of the same type. Another possibility is the evaluation of the equivalent speed, based on the energy law.

The computation of speed loss during the crash, according to the EES method, is less suitable for vehicles that structurally do not correspond to the new regulations. In these vehicles less deformation energy is required to reach the same deformation. Equivalent speed does not reach realistic values if there is a large amount of relative slip between the vehicles during the crash. In this case some energy, that is not accounted for in the calculations, is used in friction between the contact surfaces – metal sheets.

1 IZHODIŠČA

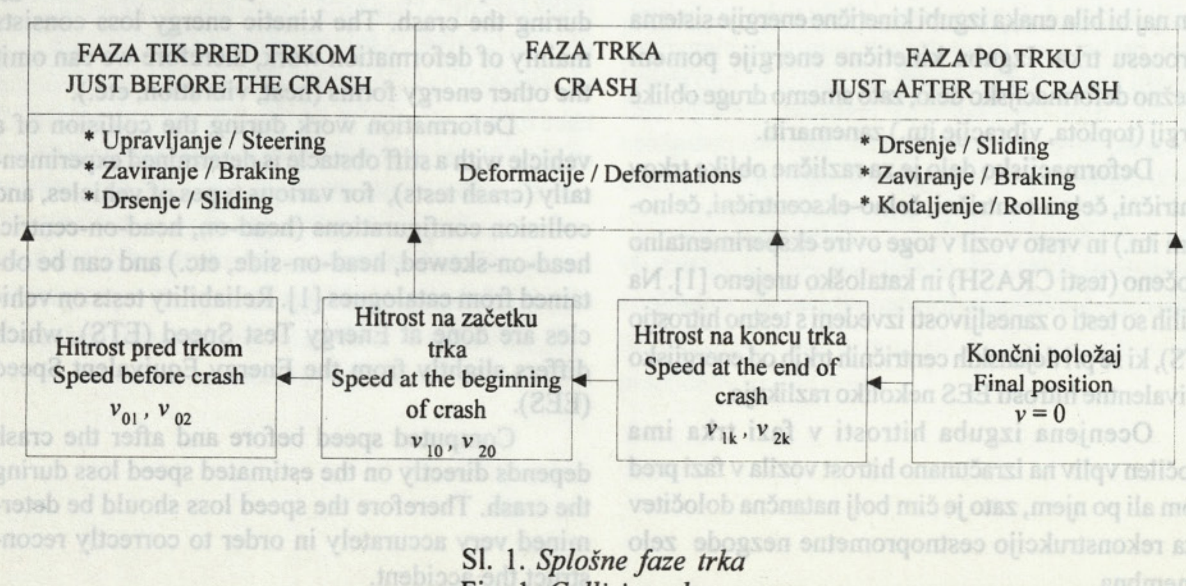
Pri analizi trka vozil obravnavamo tri splošne faze prometne nezgode: začetno fazo tik pred trkom, fazo trka ter sklepno fazo po trku (sl. 1).

Gibanje vozila v začetni in sklepni fazi trka je odvisno od tangencialnih, bočnih in normalnih reakcij vozišča na posamezna kolesa. Reakcije se pojavijo zaradi konstrukcijskih parametrov vozila, načina zaviranja, nagiba in stanja vozišča, vzpona itn. Potek omenjenih faz je razmeroma preprosto določljiv. V fazi trka prevladujejo predvsem učinki deformacijskih energij, ki so posledica lokalnih togosti vozila in velikosti nastalih deformacij.

1 BASICS

For the purpose of collision analysis we can define three phases: initial phase (just before the crash), actual crash, and final phase (just after the crash) (Fig. 1).

The vehicle motion in the initial and final phase is determined by the tangential, side, and normal forces – reactions of the driving surface on each wheel. These forces depend on vehicle design parameters, braking, state and inclination of driving surface, etc. The reconstruction of these two phases is relatively simple. During the actual crash the prevailing factors are the effects of the deformation energy, depending mainly on local stiffness, and the magnitude of the deformations.



Sl. 1. *Splošne faze trka*
Fig. 1. *Collision phases*

Pri računalniško podprti analizi prometne nezgode potrebujemo zanesljivo podatkovno bazo. Posamezni podatki so vezani na vrsto vozila (dimenzije, masa, lega težišča, zavorni sistem, moč motorja itn.), število in maso potnikov, tovor, mesto trčenja, točko stika udeležencev trka, smer vožnje - vstop v trk in izstop iz trka - vsaj za eno vozilo, končni legi vozil, stanje vozišča itn. Pri rekonstrukciji cestnoprometne nezgode moramo upoštevati ustrezen vrstni red dogodkov (sl. 2), ne glede, ali izberemo modul za računanje nazaj (faza po trku - faza trka - faza pred trkom) ali naprej (faza pred trkom - faza trka - faza po trku).

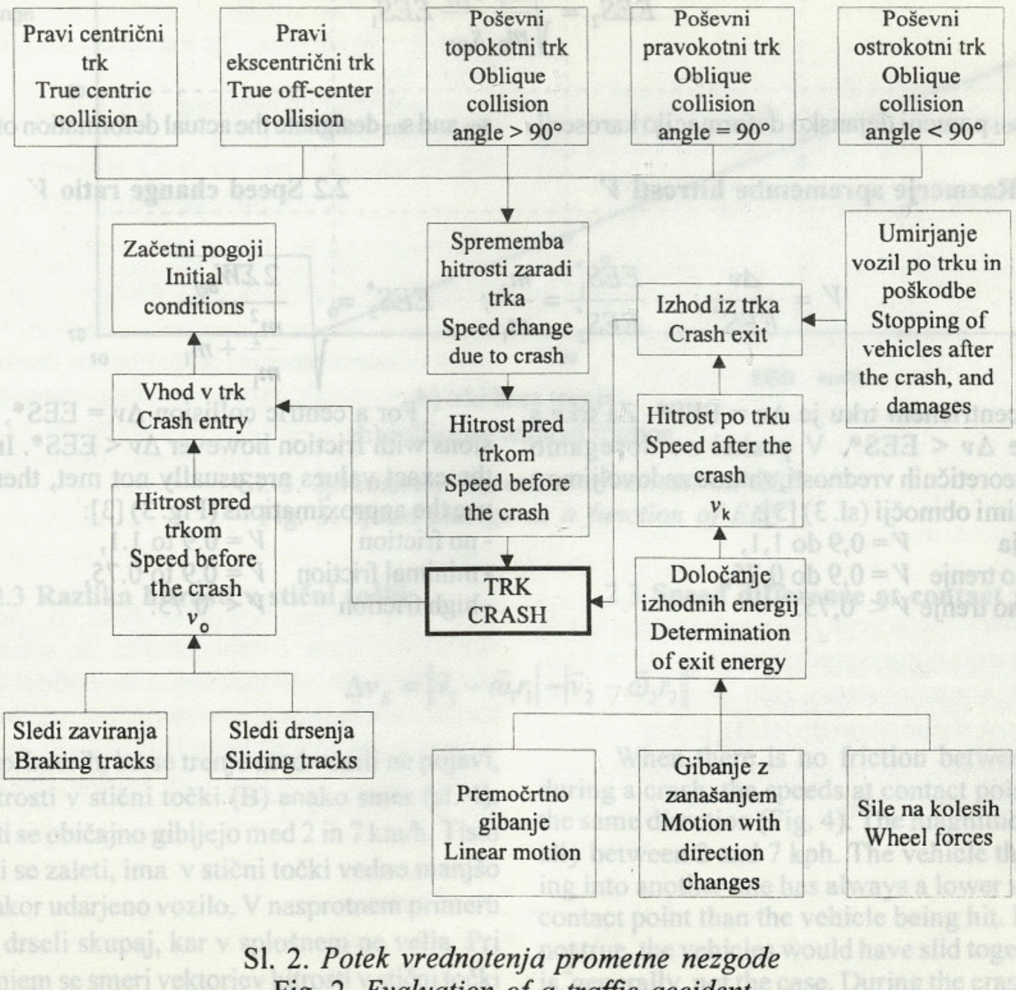
2 ZAKONITOSTI FIZIKALNIH METOD

Pri rekonstrukciji poteka cestnoprometne nezgode lahko uporabimo metodo sunka, zasuka ali energijsko metodo. Pravilno oceno realnega stanja dobimo z nadzornimi veličinami: udarno število k, torni koeficient μ, razmerje spremembe hitrosti V in razlika hitrosti stičišč Δv_B. Zanimajo nas predvsem izračunane vrednosti za ekvivalentni hitrosti, zato se omejimo na energijsko metodo.

For the computer analysis of a traffic accident, we need a reliable data base. The data contained in it describe the vehicle (dimensions, weight, position of the centre of gravity, braking system, motor power, etc.), number and weight of passengers, freight, location of collision, contact point of the parties in collision, initial and final direction of movement (at least for one vehicle), final positions of vehicles, state of driving surface, etc. For the reconstruction of a traffic accident we must take into account the appropriate sequence of events (Fig. 2), regardless of the computing module (computation forward: initial phase – crash – final phase, or computation backward: final phase - crash – initial phase).

2 PHYSICAL LAW APPLICATION

In the reconstruction of a traffic accident we can use the method of impulse, spin, or the energy method. The correct estimate of the actual state is derived through control values: Shock coefficient k, friction coefficient μ, speed change ratio V, and speed difference of contact points Δv_B. The most interesting are the computed values for equivalent speeds, therefore we are concentrating only on the energy method.



Sl. 2. *Potek vrednotenja prometne nezgode*
Fig. 2. *Evaluation of a traffic accident*

2.1 Energijska metoda

2.1 Energy method

Ekvivalentni hitrosti EES definiramo kot hitrosti, s katerimi izračunamo kinetični energiji, ki naj bi dejansko ustrezali med trkom nastali deformacijski energiji [1] in [2]:

Both equivalent speeds (EES) are defined as speeds used to compute the kinetic energies, that correspond to the actual deformation energy during the crash [1] and [2]:

$$E_{tran} + E_{rot} = E_{tran}' + E_{rot}' + E_{def} + E_{ost} \quad (1),$$

$$m_1 v_1^2 + m_2 v_2^2 + J_1 \omega_1^2 + J_2 \omega_2^2 = m_1 v_1'^2 + m_2 v_2'^2 + J_1 \omega_1'^2 + J_2 \omega_2'^2 + \frac{1}{2}(m_1 EES_1^2 + m_2 EES_2^2) \quad (2).$$

E_{ost} je v splošnem zanemarljivo majhna in obsega trenuten dvig vozila zaradi trka, drsenje koles pri izstopu iz trka ter zasučno energijo koles in pogonskega prenosa.

S preoblikovanjem energijskega zakona in upoštevanjem približnih enačb [2] dobimo za izračun ekvivalentnih hitrosti naslednja izraza:

E_{ost} is, generally, very small. It consists of the energy used for vehicle lift due to collision, sliding of tyres at the end of crash, and rotation energy of wheels and power transmission.

By rearranging the energy law equations and by use of approximation equations [2] we obtain the following equations for the computation of equivalent speeds:

$$EES_1 = \sqrt{\frac{2m_1}{1+\frac{s_{D2}}{s_{D1}}}\left(m_1(v_1^2 - v_1'^2) + m_2(v_2^2 - v_2'^2) + J_1(\omega_1^2 - \omega_1'^2) + J_2(\omega_2^2 - \omega_2'^2)\right)} \quad (3),$$

$$EES_2 = \sqrt{\frac{m_1}{m_2}\frac{s_{D2}}{s_{D2}}}\, EES_1 \quad (4),$$

kjer s_{D1} in s_{D2} pomeni dejansko deformacijo karoserij.

s_{D1} and s_{D2} designate the actual deformation of the body.

2.2 Razmerje spremembe hitrosti *V*

2.2 Speed change ratio *V*

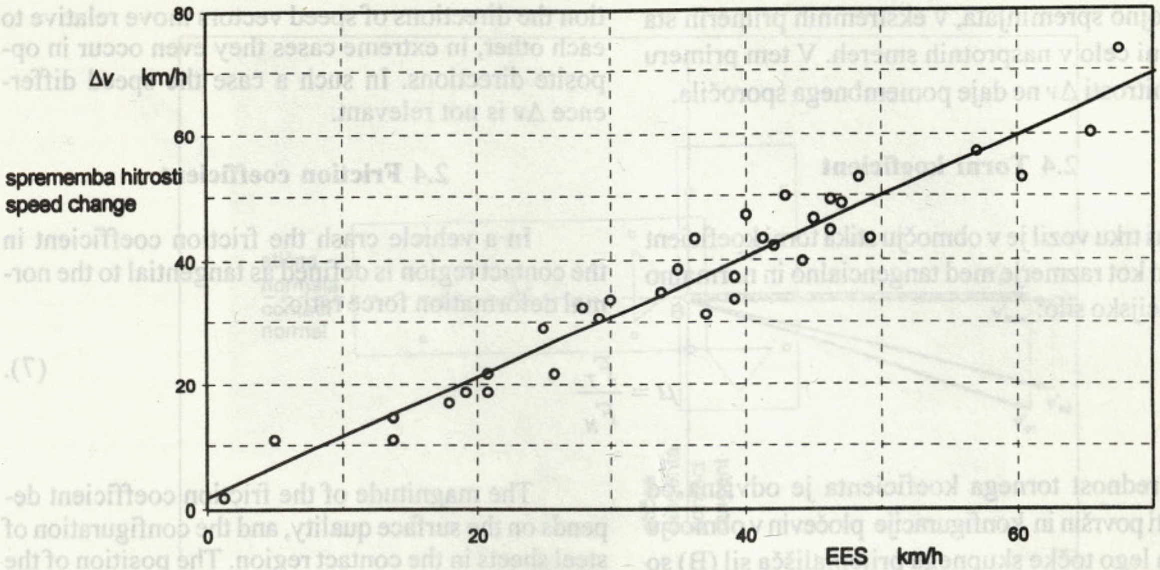
$$V = \frac{\Delta v}{EES^*}; \quad \frac{EES_1^*}{EES_2^*} = \frac{m_2}{m_1}; \quad EES_2^* = \sqrt{\frac{2\Sigma W_{def}}{\frac{m_2^2}{m_1} + m_1}} \quad (5).$$

Pri centričnem trku je Δv = EES*. Za trke s trenjem je Δv < EES*. V praksi ne dosegamo natančnih teoretičnih vrednosti, zato se zadovoljimo s priporočenimi območji (sl. 3) [3]:

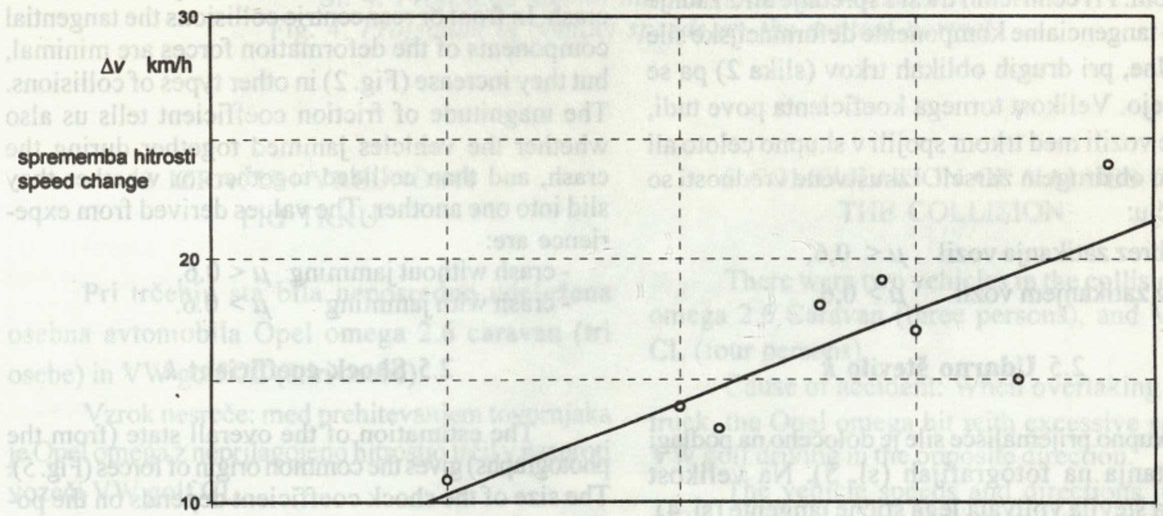
- brez trenja V = 0,9 do 1,1,
- minimalno trenje V = 0,9 do 0,75,
- poudarjeno trenje V < 0,75.

For a centric collision Δv = EES*, for collisions with friction however Δv < EES*. In practice the exact values are usually not met, therefore we use the approximations (Fig. 3) [3]:

- no friction V = 0.9 to 1.1,
- minimal friction V = 0.9 to 0.75,
- high friction V < 0.75.



a) trki s trenjem
a) collisions with friction



b) trki brez trenja
b) collisions without friction

Sl. 3. *Sprememba hitrosti v odvisnosti od EES*
Fig. 3. *Speed change as a function of EES*

2.3 Razlika hitrosti v stični točki

$$\Delta v_B = \left\| \vec{v}_1 - \vec{\omega}_1 r_1 \right| - \left| \vec{v}_2 - \vec{\omega}_2 r_2 \right\| \qquad (6).$$

V primerih, ko se trenje med vozili ne pojavi, imajo hitrosti v stični točki (B) enako smer (sl. 4). Vrednosti se običajno gibljejo med 2 in 7 km/h. Tisto vozilo, ki se zaleti, ima v stični točki vedno manjšo hitrost kakor udarjeno vozilo. V nasprotnem primeru bi vozili drseli skupaj, kar v splošnem ne velja. Pri trku s trenjem se smeri vektorjev hitrosti v stični točki

2.3 Speed difference at contact point

When there is no friction between vehicles during a crash, the speeds at contact point (B) have the same direction (Fig. 4). The magnitudes are usually between 2 and 7 kph. The vehicle that is crashing into another one has always a lower speed at the contact point than the vehicle being hit. If this were not true, the vehicles would have slid together, which is, generally, not the case. During the crash with fricmedsebojno spreminjata, v ekstremnih primerih sta usmerjeni celo v nasprotnih smereh. V tem primeru razlika hitrosti Δv ne daje pomembnega sporočila.

tion the directions of speed vectors move relative to each other, in extreme cases they even occur in opposite directions. In such a case the speed difference Δv is not relevant.

2.4 Torni koeficient

2.4 Friction coefficient

Pri trku vozil je v območju stika torni koeficient definiran kot razmerje med tangencialno in normalno deformacijsko silo:

In a vehicle crash the friction coefficient in the contact region is defined as tangential to the normal deformation force ratio:

$$\mu = \frac{F_T}{F_N} \quad (7).$$

Vrednost tornega koeficienta je odvisna od kakovosti površin in konfiguracije pločevin v območju stika. Za lego točke skupnega prijemališča sil (B) so pomembne predvsem razlike lokalne togosti, hrapavost površin in dejanska smer vozila neposredno pred trkom. Pri centričnih trkih s sprednje ali z zadnje strani so tangencialne komponente deformacijske sile minimalne, pri drugih oblikah trkov (slika 2) pa se povečujejo. Velikost tornega koeficienta pove tudi, ali sta se vozili med trkom spojili v skupno celoto ali sta drugo ob drugem zdrseli. Izkustvene vrednosti so v področju:

- trk brez zatikanja vozil $\mu < 0{,}6$,
- trk z zatikanjem vozil $\mu > 0{,}6$.

The magnitude of the friction coefficient depends on the surface quality, and the configuration of steel sheets in the contact region. The position of the common force origin is determined mainly by changes in local stiffness, surface roughness, and the actual direction of the vehicle movement just before the crash. In front or rear centric collisions the tangential components of the deformation forces are minimal, but they increase (Fig. 2) in other types of collisions. The magnitude of friction coefficient tells us also whether the vehicles jammed together during the crash, and than collided together, or whether they slid into one another. The values derived from experience are:

- crash without jamming $\mu < 0.6$,
- crash with jamming $\mu > 0.6$.

2.5 Udarno število *k*

2.5 Shock coefficient *k*

Skupno prijemališče sile je določeno na podlagi ocene stanja na fotografijah (sl. 5). Na velikost udarnega števila vplivata lega stične tangente (sl. 4), ki jo določi izvedenec, in lastnost materialov v stiku. Odločilna je tudi stična hitrost, ki pomeni vektorsko vsoto preme in vrtilne frekvence vozila:

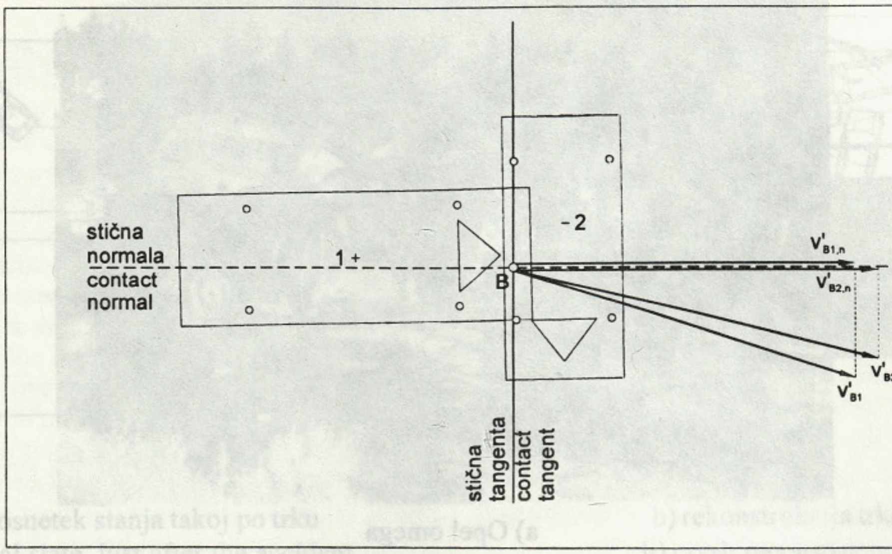
The estimation of the overall state (from the photographs) gives the common origin of forces (Fig. 5). The size of the shock coefficient depends on the position of the contact tangent (Fig. 4), determined by the expert, and the properties of the materials in contact. A decisive factor is also the speed, i.e. the vector sum of the translational and rotational speed of the vehicle:

$$\vec{v}_{B2} = \vec{v}_2 + \vec{\omega}_2 r_2 \quad (8).$$

Za izračun udarnega števila so pomembne le tiste komponente hitrosti pred trkom in po njem, ki so usmerjene v normalni smeri, zato jih v stični točki projiciramo na stično normalo (sl. 4). Udarno število doseže za različne razlike hitrosti pred trkom in po njem vrednosti med 0 in 1:

The computation of the shock coefficient considers only those components of the speed (before and after the crash) that are in the normal direction, therefore the speeds are projected on the contact normal at the contact point (Fig. 4). The shock coefficient ranges from 0 to 1 for various speeds before and after the crash:

$$k = \frac{\Delta v'_{B,n}}{\Delta v_{B,n}} = \frac{v_{B2,n} - v_{B1,n}}{v_{B1,n} - v_{B2,n}} \quad (9).$$



Sl. 4. *Projekcija stičnih hitrosti na stično normalo*
Fig. 4. *Projection of contact speeds on the contact normal*

3 IZRAČUN VREDNOSTI PRI TRKU

Pri trčenju sta bila neposredno udeležena osebna avtomobila Opel omega 2.6 caravan (tri osebe) in VW golf CL (štiri osebe).

Vzrok nesreče: med prehitevanjem tovornjaka je Opel omega z neprilagojeno hitrostjo trčil v nasproti vozeči VW golf CL.

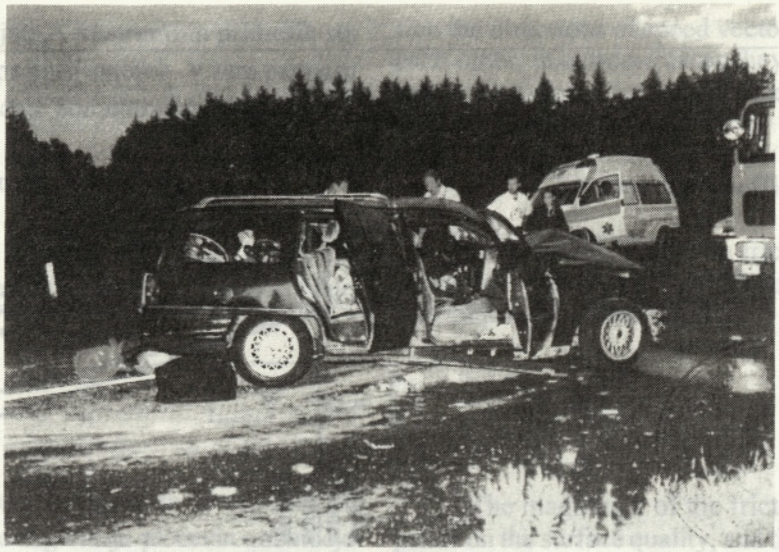
Hitrosti vozil in njuni smeri pri izstopu iz trka smo analizirali z uporabo programskega paketa za vozno dinamiko (CARAT). Pri izvajanju analize smo upoštevali podatke o vozilih (geometrijska oblika, moč motorja), začetno stanje vozil (lega trka; sl. 4), relativno stično točko vozil pri trku (sl. 5), končno stanje vozil (sl. 6a) itn. Potrebni so tudi podatki o smeri izstopa vozil iz trka, stanju vozišča, vrsti in učinkovitosti zavornega sistema, nosilnosti pnevmatik in prenosu sile na vozišče. Velikost deformacij smo ocenili na temelju poškodbe vozil (sl. 5), preostali parametri so bili določeni iz skice, izpovedi navzočih ali dokumentacije o nesreči.

3 COMPUTATION OF VALUES IN THE COLLISION

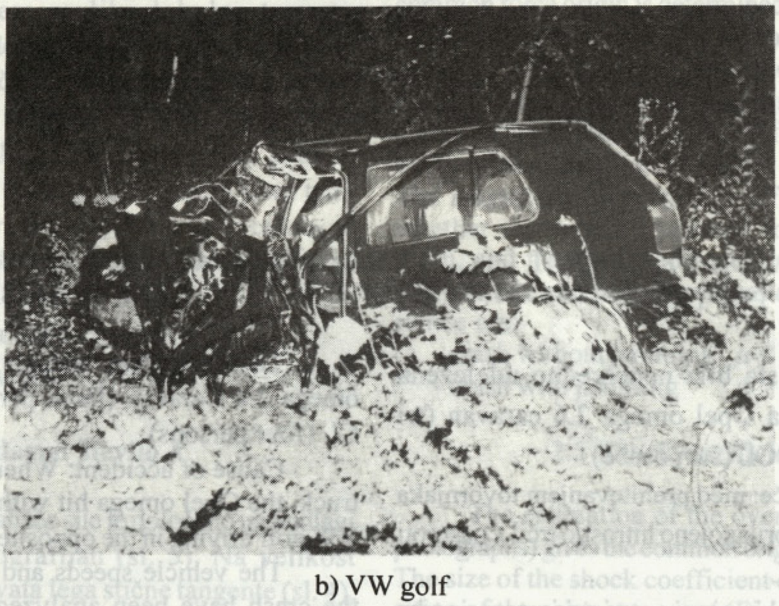
There were two vehicles in the collision: Opel omega 2.6 Caravan (three persons), and VW golf CL (four persons).

Cause of accident: When overtaking a trailer truck, the Opel omega hit with excessive speed the VW golf driving in the opposite direction.

The vehicle speeds and directions just after the crash have been analyzed using the CARAT (Computer Aided Reconstruction of Accidents in Traffic) software for driving dynamics computation. We considered the vehicle data (geometry, motor power), initial vehicle position (crash position, Fig. 4), relative contact point of vehicles in the crash (Fig. 5), final position of vehicles (Fig. 6a), etc. We also needed the data on vehicle direction just after the crash, state of driving surface, brake efficiency, carrying capacity of tyres, and force transfer from the tyres to the driving surface. The magnitude of deformations was determined from the vehicle damage (Fig. 5), the remaining parameters were determined from the sketch, witness statements, or accident documentation.



a) Opel omega



b) VW golf

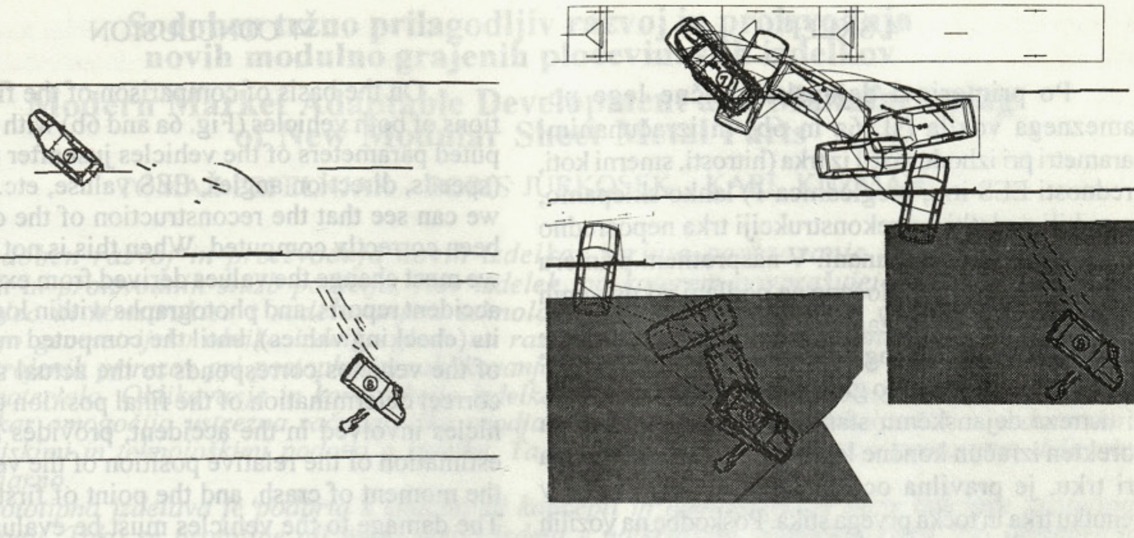
Sl. 5. *Poškodbe vozil*
Fig. 5. *Vehicle damage*

Poglavitni namen vrednotenja poteka nesreče je doseči čim večjo usklajenost gibanja vozil pri vstopu in izstopu iz trka in stanje vozil ob mirovanju z dejanskim stanjem, ki je bilo dokumentirano neposredno po nesreči. Tu mislimo predvsem na popolnost prekrivanja zavornih oziroma drsnih sledi (translatorno in rotacijsko gibanje) ter dejansko končno lego vozil in ne samo oddaljenost od predpostavljene točke trka (sl. 6).

Med računalniško podprto analizo poteka prometne nezgode lahko kot funkcijo časa ali poti zvezno spremljamo obremenitve koles, porazdelitev zavornih sil, bočne in obodne sile, hitrosti, pospeške, zasuke okoli vodoravne in pokončne osi itn., kar omogoča dodatno preverjanje ustreznosti končnega rezultata.

The basic goal of the accident evaluation is to reach the greatest possible accordance between vehicle movement before and after the crash, their position after the crash, and the actual state, documented just after the accident. The braking or sliding tracks (translational and rotational movement), and actual final position of vehicles (not only the distance from the assumed crash point (Fig. 6), should coincide.

During the computer supported analysis of an accident, we can record continuously the wheel forces, distribution of breaking forces, side and tangential forces, accelerations and rotation around the horizontal and vertical axes, etc. These data are used for additional checking of the final result.



a) posnetek stanja takoj po trku
a) actual state, just after the accident

b) rekonstrukcija trka
b) crash reconstruction

Sl. 6. *Primerjava lege vozil pri izstopu iz trka*
Fig. 6. *Comparison of the vehicle positions just after the crash*

Preglednica 1. *Rezultati računalniško podprte analize*
Table 1: *Results of the computer supported analysis*

		Vozilo 1 Vehicle 1	Vozilo 2 Vehicle 2
Faza pred trkom / Just before the crash:			
Hitrost trka / Crash speed	km/h	106,5	129,6
Smerni kot / Direction angle	°	175,0	0,0
Smerni kot vozila / Vehicle direction angle	°	-5,0	-5,0
Hitrost zasuka / Turning velocity	°/s	0,0	0,0
Faza Trka / Crash:			
Sprememba hitrosti / Speed change	km/h	87,0	113,8
Deformacija vozila / Vehicle deformation	m	1,50	1,30
Srednji pojemek / Mean deceleration	m/s²	194,5	384,0
Trajanje trka / Crash duration	s	0,12	0,12
Udarno pehanje / Shock	Ns	39814	39814
EES vrednost / EES value	km/h	106	113
Togost vzmeti / Spring stiffness	kN/m	373	482
Ročica sil pri trku / Force lever	m	1,46	1,23
Smerni kot / Direction angle	°	23,3	22,2
Faza po trku / Just after the crash:			
Hitrost na izteku / Speed after the crash	km/h	37,5	45,0
Smerni kot / Direction angle	°	150,9	-55,4
Hitrost zasuka / Turning velocity	°/s	408,1	394,2
Nadzorne vrednosti / Checking values:			
Številka udara / Crash number	-	-0,03	
Razlika hitrosti / Speed difference	km/h	7,1	
Torni koeficient / Friction coefficient		0,25	
Kot tangente stičišča / Angle of contact point tangent	°	90,2	
Razmerje spremembe hitrosti V /Speed change ratio V		0,91	

4 SKLEP

Po primerjavi dejanske končne lege posameznega vozila (sl. 6a in 6b) in izračunanimi parametri pri izhodu vozil iz trka (hitrosti, smerni koti, vrednosti EES itn., preglednica 1) lahko sklepamo, da so bili podatki pri rekonstrukciji trka neposredno po trku pravilno izračunani. V nasprotnem primeru moramo vrednosti, določene na podlagi izkustvenih enačb ali izbranih iz zapisa o nesreči in fotografij, prilagajati v okviru logičnih odstopkov (nadzorne vrednosti), da dosežemo gibanje posameznega vozila, ki ustreza dejanskemu stanju. Bistveni podatek za korekten izračun končne lege vozil, ki so sodelovala pri trku, je pravilna ocena dejanske lege vozil v trenutku trka in točka prvega stika. Poškodbe na vozilih moramo natančno oceniti in pri tem upoštevati čim bolj stvarno smer gibanja vozil pred trkom.

4 CONCLUSION

On the basis of comparison of the final positions of both vehicles (Fig. 6a and 6b) with the computed parameters of the vehicles just after the crash (speeds, direction angles, EES valuse, etc., Tab. 1) we can see that the reconstruction of the crash has been correctly computed. When this is not the case, we must change the values derived from experience, accident reports, and photographs within logical limits (checking values), until the computed movement of the vehicles corresponds to the actual state. For correct determination of the final position of the vehicles involved in the accident, provides a correct estimation of the relative position of the vehicles at the moment of crash, and the point of first contact. The damage to the vehicles must be evaluated precisely, taking into account the most probable direction of vehicle movement before the crash.

5 LITERATURA
5 REFERENCES

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[2] Burg, H.: Rechnerunterstützte Rekonstruktion von Pkw/Pkw- Unfällen. Dissertation TU Berlin 1984.

[3] EVU: EES-Katalogen, Allgemeine Unterlagen.

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