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ABSTRACT

PC-CRASH is a windows©-based accident-reconstruction program which combines the simulation of pre-collision, collision, and post-collision dynamics for multiple vehicles in a graphical environment. This paper presents the trajectory and collision models on which PC-CRASH is based. PC-CRASH'S model for predicting the 3D kinematics of a vehicle's pre- and post-impact trajectory, which is based on a discrete- kinetic time forward simulation of vehicle dynamics rather than empirically-derived "spin-out coefficients", is described. The tire-force model (which accommodates ABS), steer angle, wheel braking, weight shift, and suspension effects are introduced and the program's method of handling pre-impact yaw, braking, acceleration and pre-impact steering is outlined. The momentum-based collision model, which relies on restitution rather than vehicle crush or stiffness coefficients, is defined and the program's method for dealing with secondary impacts, inter-vehicle friction, and impulse vectors with a vertical component is explained. The paper concludes with a simple reconstruction which demonstrates the various models and the program's built-in 3D animation capabilities

INTRODUCTION

The automotive industry uses several simulation models to learn about the driving behavior of their vehicles. These industrial vehicle dynamics simulation programs [1], [2], [3], [4].are optimized to predict the driving behavior under well defined initial and boundary conditions. As a result these models require many input parameters. For the reconstruction of a vehicle accident such detailed knowledge, especially regarding the suspension, the tires and the road conditions, is normally not available. In addition the steering, as well as the degree of braking is often not known. It is thus difficult to use these simulation models for the reconstruction of vehicle accidents.

Regarding collision models a similar problem exists. Several programs (mainly Finite Element based) exist, which allow the calculation of the deformations for well defined collision conditions. To get a good agreement with real impacts, they require a very detailed knowledge of the vehicle structure and a very powerful computer. Some 100,000 degrees of freedom are required to model one vehicle properly.

Several computer programs have been developed especially for the reconstruction of vehicle accidents. They allow the calculation of vehicle motion and collisions based on various physical models. [5], [6], [7], [8], [9], [10].

In PC-CRASH a kinetic time forward simulation of vehicle dynamics is combined with a momentum-based collision model. So the accidents can be reconstructed starting from the point of reaction to the end position for all involved cars simultaneously. The reconstruction is performed in an interactive graphical environment, which allows a sketch of the accident scene to underlay the reconstruction. For an effective presentation of the results, 3D animations can be created directly from the calculated results.

NOMENCLATURE

x_m	position of the center of gravity for the vehicle in the inertial system
ϕ_x, ϕ_y, ϕ_z	rotation angles of vehicle
α_r	current lateral slip angle.
$\alpha_{r\,max}$	maximal lateral slip angle. (the angle at which the maximal lateral tire force is reached for unbraked tires. When this value is exceeded the lateral tire force remains constant.)
μ_r	friction coefficient (valid for each wheel) for individual combinations tire - road.
$S_{r\,x''}$	instantaneous tire longitudinal force.

$S_{ry''}$	instantaneous tire lateral force.
$S_{rz''}$	instantaneous tire normal force.
S_{rz0}	static tire normal force.
F_{rB}	imposed brakeforce
F_A	wheelforce for acceleration
c_r	stiffness of the spring which can be given for each wheel individually.
c_{r2}	stiffness of the spring when the suspension is "bottoming out"
f_r	change of suspension travel compared to the static balance
$f_{r(max)}$	maximum suspension travel at which the suspension is "bottoming out"
d_r	damping constant, which can be defined individually for each wheel. Thereby it's possible to take into account e.g. the influence of a damaged shock absorber, for example.
γ_x	defines the angle between the gravity vector projected into the y-z plane and the z-plane
γ_y	defines the angle between the gravity vector projected into the x-z plane and the z-plane
F	external forces on vehicle
m_i	mass of vehicle i
L_m	angular momentum
M	external moments on vehicle
Θ_C	mass tensor of vehicle
I_{ix}...	mass moments of vehicle **i**
ε	coefficient of restitution
S_c	compression momentum
S_r	restitution momentum
S	total momentum
N,T	total momentum in direction n and t
N_c, T_c	compression momentum in direction n and t
n_i, t_i	position of impulse point for vehicle i in **n,t** coordinate system
v_{sit}	velocity of center of gravity before-impact in direction n and t for vehicle **i**
v'_{sit}	velocity of center of gravity after impact in direction n and t for vehicle **i**
v_{it}	velocity of impulse point before impact in direction n and t for vehicle **i**
V_t	relative velocity both impact vehicles at the impulse point

THE TRAJECTORY MODEL

PC-CRASH'S model for predicting the 3D kinematics of a vehicle's pre- and post-impact trajectory is based on a discrete- kinetic time forward simulation. The vehicle is defined as a stiff body which moves under the influence of external forces.

The model uses two coordinate systems:

1. **A** fixed inertial system $\mathbf{x_i}$ is used as well as a coordinate system which is connected to the vehicle body $\mathbf{x_i'}$. The center of gravity of the vehicle defines the origin of the coordinate system $\mathbf{x_i'}$.
2. The coordinate directions of the vehicle's coordinate system are defined as follows: The longitudinal **axis (x'-axis)** is **defined** as an intersecting line between the longitudinal plane of symmetry of the vehicle and a plane parallel to the ground plane at the level of the center of gravity. The transverse axis (y'-axis) of the vehicle is defined normal to the plane of symmetry of the vehicle. The vertical axis **(z'-axis)** of the vehicle results fiom the orthogonality of the coordinate system. The coordinate directions are defined so that the **x'-axis** is positive towards the vehicle **front** and the 2'-axis is positive upward. The direction of the **y'**-axis results **from** the right hand coordinate system.

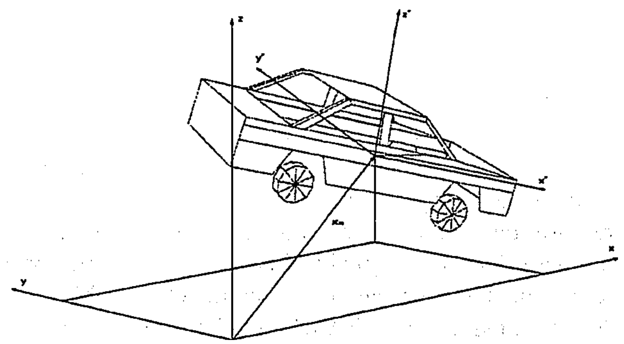

Figure 1: The Coordinate Systems

The vector $\mathbf{x_m}$ defines the position of the center of gravity for the vehicle in the inertial system. The rotation of the vehicle body is **defined** by the rotation matrix T, which can be seen as a combination of the following three rotations:

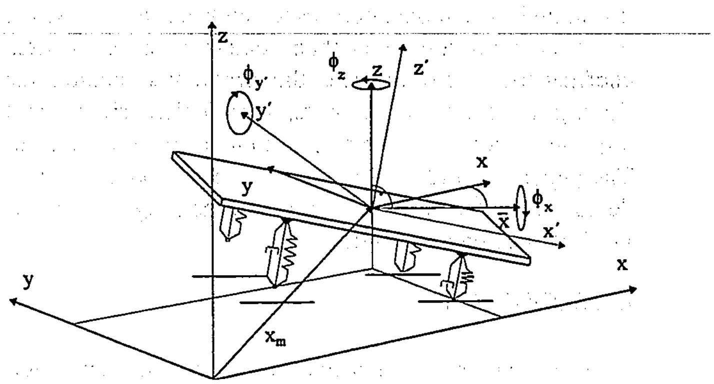

Figure 2: The **Vehicle** Model

The first rotation is about the z-axis (ϕ_z), the second about the rotated **x-axis(ϕ_x).** The third rotation is about the twice rotated y'-axis(@,,).

The following external forces influence the movement of a vehicle:

- tire forces (normal, lateral, and longitudinal forces)
- air resistance

- gravity
- trailer coupling forces (Can be handled by PC-CRASH but not discussed within this paper)

THE TIRE MODEL

Numerous tire models are described in literature. For most tire models the tire forces are split into the following three components:

- The tire normal force describes the component normal to the road surface at the idealized tire contact point.
- The direction of the tire lateral force results from a normal projection of the wheel axis on the road.
- The direction of the tire longitudinal force results from the orthogonality of the three components, as from the definition of a right hand coordinate system.

Thus an additional coordinate system is defined for each tire. It corresponds with the directions of the tire longitudinal force (x_r'' - direction), the lateral force (y_r'' - direction) and the normal force (z_r'' - direction).
Most tire models define the relation between tire lateral force (side tension and circumference force) and the slip (circumference slip and skew angle) for different parameters.

Figure 3 shows the measured relation between lateral and longitudinal tire force, with respect to the slip.

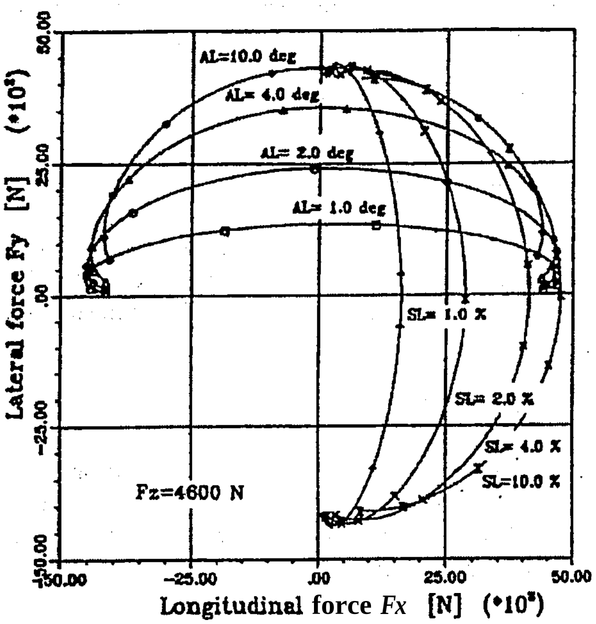

Figure 3: Measured Tire Forces (Provided by Semperit)

When reconstructing a vehicle accident, the steering, braking or acceleration behavior as a result of driver inputs can only be estimated. However, it is important, that in the case of a sliding vehicle, the physical limits are predicted correctly. In addition it should be possible to see the influence of tire defects.

For this reason PC-CRASH uses a rather simple quasi-stationary tire model. The moment of inertia of the tire is neglected. The braking or acceleration forces F_B are identical to the tire longitudinal forces. PC-CRASH assures that the limits due to insufficient friction are not exceeded.

The tire model defines the relation between the lateral tire force and the lateral slip angle for a given tire longitudinal force.
The following linear relations are used:

$$S_{r\,y''} = \frac{\alpha_r}{\alpha_{r\,max}} \mu_r S_{r\,z''} \quad \text{for } \alpha_r \le \alpha_{r\,max} \qquad (1)$$

and

$$S_{r\,y''} = -\mathrm{sign}(\alpha_r)\mu_r S_{r\,z''} \quad \text{for } \alpha_r > \alpha_{r\,max} \qquad (2)$$

In any case, PC-CRASH assumes that the maximum tire force transferred in the road plane is independent of the tire's moving direction. So the resultant of $S_{rx''}$ and $S_{ry''}$ never exceeds $\mu_r S_{r\,z''}$. The maximum tire force in the road plane can be seen as a circle with the radius $\mu_r S_{r\,z''}$ (the "friction circle"). As can be seen in Fig. 3 this model corresponds well with the behavior of many modern tires. Fig. 3 also shows that only a minor difference of the friction coefficient for a rolling and a sliding tire can be seen. In PC-CRASH the friction coefficient for a rolling and a sliding tire are assumed to be identical.

So if the square root of the sum of $S_{r\,x''}^2$, defined as longitudinal tire-force by the user, and $S_{r\,y''}^2$ calculated from EQ (1) or EQ (2) exceeds $\mu_r S_{r\,z''}$

$$\sqrt{S_{r\,x''}^2 + S_{r\,y''}^2} > \mu_r S_{r\,z''} \qquad (3)$$

the magnitude of the wheel force components $S_{r\,x''}$ and $S_{r\,y''}$ depend on the direction of the wheel velocity, and

$$S_{r\,x''} = -\cos(\alpha_r)\,\mu_r S_{r\,z''} \qquad (4)$$

$$S_{r\,y''} = -\sin(\alpha_r)\,\mu_r S_{r\,z''} \qquad (5)$$

If the user defined brake force is larger than the tire longitudinal force calculated from EQ (4), the braked wheel locks and the components $S_{r\,x''}$ and $S_{r\,y''}$ can be calculated directly from EQ (4) and (5). Otherwise the wheel rotates and the two components are calculated from the following relations:
The tire longitudinal force corresponds to the brake force:

$$S_{r\,x''} = -F_{rB} \qquad (6)$$

The tire lateral force results from the following equation:

$$S_{r\,y''} = -\mathrm{sign}(\alpha_r)\sqrt{(\mu_r S_{r\,z''})^2 - F_{rB}^{\,2}} \tag{7}$$

The wheel forces for vehicles equipped with ABS are calculated from the following relation:
The lateral tire force is calculated from the actual lateral slip angle using the EQ (1) or (2):

And the longitudinal tire force is reduced to the following value:

$$S_{r\,x''} = -\sqrt{(\mu_r S_{r\,z})^2 - S_{r\,y}^{\,2}} \tag{8}$$

To take into account the fact that ABS never releases the brake completely, PC-CRASH uses the following assumption: The minimum value to which the brake force may be reduced is defined by:

$$S_{r\,x''\,min} = -0.1\,\mu_r\,S_{r\,z} \tag{9}$$

In this case the lateral tire force reduces to:

$$S_{r\,y''} = -\mathrm{sign}(\alpha_r)\sqrt{(\mu_r S_{r\,z})^2 - S_{r\,x''}^{\,2}} \tag{10}$$

The factor of 0.1 is purely an assumption which can vary for different vehicles.

If the wheel is accelerated, the following situation arises:

$$S_{r\,x''} = F_A \tag{11}$$

The lateral tire force is calculated again from the lateral slip angle according to EQ (1) and EQ (2). But this force component is again limited by the available friction:

$$S_{r\,y''} = -\mathrm{sign}(\alpha_r)\sqrt{(\mu_r S_{r\,z})^2 - F_A^{\,2}} \tag{12}$$

Using EQ (1 - 12), the components of the tire forces can be calculated under all conditions.

SUSPENSION

In PC-CRASH the wheels and the suspensions are assumed to be free of mass. So the tire normal forces in direction (z') can be calculated directly from the suspension travel (spring characteristic) as well as its travel speed (shock absorber) by an algebraic equation. The force displacement characteristic of the spring is calculated from the following relation:

$$S_{r\,z'\,(spring)} = c_r f_r + S_{r\,z\,0} \tag{13}$$

The damping is calculated from the travel speed using the following relation:

$$S_{r\,z'\,(damping)} = d_r \dot{f}_r \tag{14}$$

Due to the fact, that for most accident reconstructions the damping rates of the involved vehicles are not known at all, the same damping rate for compression and rebound was used.

The total tire force in direction z' axis is given by the following equation:

$$S_{r\,z'\,(total)} = c_r f_r + S_{r\,z\,0} + d_r \dot{f}_r \tag{15}$$

For all vehicles the movement of the suspension is limited. This circumstance was taken into account in the following way:

$$f_r \geq f_{r\,max} \tag{16}$$

In a case where the tire normal force exceeds a certain limit, an increased spring stiffness is assumed, which is due to the suspension bottoming out, and the spring force is calculated from the following equation:

$$S_{r\,z'\,(spring)} = c_r f_{r\,max} + S_{rz0} + c_{r2}(f_r - f_{rmax}) \tag{17}$$

The value for $f_{r\,max}$ and the second, rigid spring constant c_{r2} must be defined. On the other hand certain wheels may lose contact with the road. So the condition:

$$S_{r\,z'} \geq 0 \tag{18}$$

must always be fulfilled.

The total tire normal forces can be calculated explicitly from the suspension stiffness and the damping forces. The necessary tire lateral and tire longitudinal forces are taken from the last time step.

$$S_{rz} = S_{r\,z'}\left(\cos(\phi_x)\cos(\phi_{y'})\right) \tag{19}$$

AIR RESISTANCE

As almost all accidents happen at speeds where air resistance can be ignored in comparison to the tire forces of a braked or accelerated vehicle, this influence is not taken into account within PC-CRASH.

GRAVITY FORCES

The stationary inertial system x, y, z is always chosen so that the x-axis and the y-axis coincide with the road plane. To take into account road slopes, the gravity vector may be rotated within the inertial system:

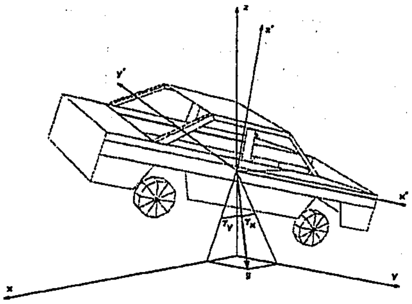

Figure 4: Gravity Force

The components of the gravity vector in the inertial system x, y, z are calculated as follows:

$$F_{g\,z} = -\frac{m\,g}{\sqrt{1+\tan^2(\gamma_x)+\tan^2(\gamma_y)}} \tag{20}$$

$$F_{g\,x} = -F_{g\,z}\tan(\gamma_y) \tag{21}$$

$$F_{g\,y} = -F_{g\,z}\tan(\gamma_x) \tag{22}$$

THE EQUATIONS OF MOVEMENT

After the **determination** of all external forces effecting the movement of the vehicle, the equations of movement for the vehicle body can be summarized as follows:
The balance of forces is determined from:

$$\mathbf{m\,\ddot{x}_m = \Sigma F} \tag{23}$$

The vehicle's accelerations can so be calculated from

$$\mathbf{x}_{\rightarrow} = \mathbf{\Sigma F/m} \tag{24}$$

respectively written in components:

$$\ddot{x}_m = \Sigma F_x/m \tag{25}$$

$$\ddot{y}_m = \Sigma F_y/m \tag{26}$$

$$z_m = \Sigma F_z/m \tag{27}$$

The conservation of the angular momentum results in:

$$\dot{\mathbf{L}}_{\mathbf{m}} = \Sigma\,\mathbf{M} \tag{28}$$

or:

$$\Theta_c \cdot \dot{\omega} + \omega \times \Theta_c \cdot \omega = \Sigma M \tag{29}$$

where Θ_c defines the inertia tensor for the vehicle along its center of gravity.

This tensor can be calculated in the vehicle related coordinate system:

$$\Theta_c = \begin{pmatrix} I_{x'} & -I_{x'y'} & -I_{x'z'} \\ -I_{x'y'} & I_{y'} & -I_{y'z'} \\ -I_{x'z'} & -I_{y'z'} & I_{z'} \end{pmatrix} \tag{30}$$

Due to the fact that the vehicle-related system was selected in a way, that the x'-z' plane defines a symmetry condition, it can be seen, that the y' axis is a so-called main axis. Due to this fact $I_{x'y'} = 0$ and $I_{y'z'} = 0$.

The moment of deviation $I_{x'z'}$ **will** not disappear completely for a vehicle. In PC-CRASH it is neglected. as for most cars the center of gravity lies approximately in the center of the vehicle and the mass distribution in longitudinal direction is rather symmetrical.
So the inertia tensor reduces to:

$$\Theta_c = \begin{pmatrix} I_{x'} & 0 & 0 \\ 0 & I_{y'} & 0 \\ 0 & 0 & I_{z'} \end{pmatrix} \tag{31}$$

So the system of differential equations is uncoupled and the individual equations can be solved independently.

$$I_{x'}\dot{\omega}_{x'} = \sum M_{x'} - I_{z'}\omega_{y'}\omega_{z'} + I_{y'}\omega_{y'}\omega_{z'} \tag{32}$$

$$I_{y'}\dot{\omega}_{y'} = \sum M_{y'} + I_{z'}\omega_{x'}\omega_{z'} - I_{x'}\omega_{x'}\omega_{z'} \tag{33}$$

$$I_{z'}\dot{\omega}_{z'} = \sum M_{z'} - I_{y'}\omega_{x'}\omega_{y'} + I_{x'}\omega_{x'}\omega_{y'} \tag{34}$$

THE INTEGRATION OF THE EQUATIONS OF MOTION

For the integration of these equations an explicit Euler method was chosen. This method works fine due to the fact, that all differential equations are of similar stiffness. The default integration time step is 5 ms which provides **an** accurate, stable and fast integration.

THE COLLISION MODEL

As pointed out before PC-CRASH uses a momentum based 2 or 3 dimensional collision model, which relies on restitution rather than vehicle crush or stiffness coefficients. This model assumes an exchange of the impact forces within an infinite small time step at a single point, herein called "impulse point". These models are also named classical Crash models. Instead of resolving the impact forces over time they only use their time integrals, also called momentum. The one which was described first by Kudlich & Slibar [11] **[12]contains** the means to calculate both, impacts with vehicles sliding along each other or full impacts.

THE CRASH MODEL - As defined by Kudlich & Slibar
As defined by Newton the impact can be divided into two phases: The "compression" phase and the "restitution" phase: At the end of the compression phase the velocities for both vehicles at the "impulse point" are identical in case of a full impact.

Due to a certain elasticity of the vehicle structures, the two vehicles will separate again. The "coefficient of restitution" is defined as ratio between restitution momentum and compression momentum.

$$1)\quad \varepsilon = \frac{S_R}{S_C} \tag{35}$$

The total exchanged momentum is calculated from

$$S = S_C + S_R = S_C * (1 + \varepsilon) \tag{36}$$

In a full impact the velocities of both vehicles at the impulse point must be identical at the end of the compression phase.

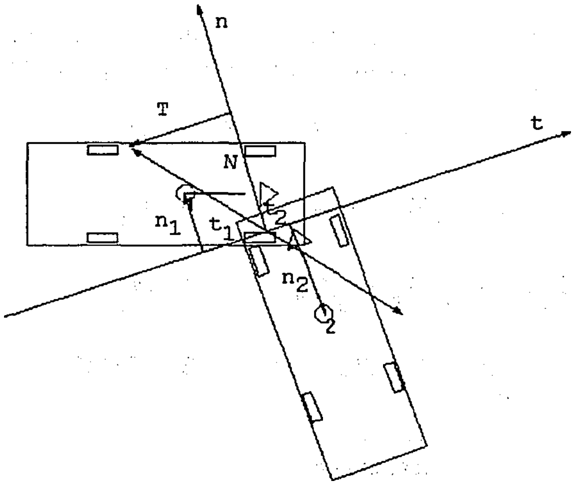

Figure 5: Impact Configuration

For simplicity, the impact model is only derived here in 2D. In PC-CRASH both models are available, a 2D and a 3D impact model. They are identical except that all velocities, the momentum and angular momentum is defined in 3D coordinates and all three components of the velocity and rotational velocity are taken into account.

As can be seen in Figure 5 a local coordinate system is defined which originates at the "impulse point". The components of the relative velocity for both vehicles at the impulse point can be calculated from:

$$V_{1t} = v_{s1t} + \omega_{1z} n_1 \tag{37}$$

$$V_{1n} = v_{s1n} + \omega_{1z} t_1 \tag{38}$$

where V_{1t} defines the velocity component of the impulse point for vehicle 1 in direction t and V_{1n} in direction n. So the components of the relative velocity for both vehicles at the impulse point can be calculated from:

$$V_t = V_{1t} - V_{2t} \tag{39}$$

$$V_n = V_{1n} - V_{2n} \tag{40}$$

In addition the balance of momentum can be formulated for both vehicles:

$$m_1 (v'_{s1t} - v_{s1t}) = T \tag{41}$$

$$m_1 (v'_{s1n} - v_{s1n}) = N \tag{42}$$

$$m_2 (v'_{s2t} - v_{s2t}) = -T \tag{43}$$

$$m_2 (v'_{s2n} - v_{s2n}) = -N \tag{44}$$

The balance of angular momentum can be formulated:

$$I_{1z} (\omega'_{1z} - \omega_{1z}) = T n_1 - N t_1 \tag{45}$$

$$I_{2z} (\omega'_{2z} - \omega_{2z}) = -T n_2 + N t_2 \tag{46}$$

When combining these equations the change of the relative velocity for both vehicles at the impulse point can be calculated from:

$$V'_t = V_t + c_1 T - c_3 N \tag{47}$$

$$V'_n = V_n - c_3 T + c_2 N \tag{48}$$

with

$$c_1 = \frac{1}{m_1} + \frac{1}{m_2} + \frac{n_1^2}{I_{1z}} + \frac{n_2^2}{I_{2z}} \tag{49}$$

$$c_2 = \frac{1}{m_1} + \frac{1}{m_2} + \frac{t_1^2}{I_{1z}} + \frac{t_2^2}{I_{2z}} \tag{50}$$

$$c_3 = \frac{t_1 n_1}{I_{1z}} + \frac{t_2 n_2}{I_{2z}} \tag{51}$$

To be able to solve these equations and to calculate the post-impact velocities and rotations two additional assumptions have to be made: These definitions vary for the two different kinds of impacts defined by Kudlich and Slibar.

THE FULL IMPACT - In case of a full impact two additional assumptions are made:

1. No relative movement between both vehicles can be found in the impulse point at the end of the compression phase.

$$T_c = \frac{V_n c_3 + V_t c_2}{c_3^2 - c_1 c_2} \tag{52}$$

$$N_c = \frac{V_n c_1 + V_t c_3}{c_3^2 - c_1 c_2} \tag{53}$$

2. The average between compression and restitution momentum is defined by the coefficient of restitution, which is defined according to EQ(35)
So the components of the total momentum can be calculated from:

$$T = T_c\,(1+\varepsilon) \tag{54}$$

$$N = N_c\,(1+\varepsilon) \tag{55}$$

These equations are sufficient to calculate all post-impact velocity conditions for both involved vehicles in case of a full impact.

THE SLIDING IMPACT - In certain collisions the two vehicles will never reach identical velocities in the impulse point during the impact. In such a case a contact plane has to be defined, along which the two vehicles slide. The impulse point must coincide with this plane. For such a situation the following two assumptions are made:

1. No relative movement between both vehicles can be found in the impulse point at the end of the compression phase in direction normal to the contact plane. So N_c can be calculated from EQ(53)

2. The direction of the momentum is limited by a friction (μ). This value defines the friction between the two impacting vehicles.

$$T = \mu\, N \tag{56}$$

3. The average between compression and restitution momentum is again defined by the "coefficient of restitution" according to EQ(35) and T and N can again be calculated from EQ(54) and (55)

Out of these relations the post impact velocity conditions for both involved vehicles can be calculated.

It is important for a good prediction of the collision phase to define the correct overlapping of the vehicle bodies when the forces are exchanged.

In PC-CRASH this position can be calculated easily: Crash tests show that the time from the first contact of the cars to the maximum engagement always lasts a time period of 45 to 60 milliseconds. So it is best to calculate this position by driving the cars from the point of first contact over the defined time distance with pre-impact velocity. At this point the impact calculation is performed. But it is also important to control the overlapping of both vehicle bodies on the computer screen in a manner consistent with the documented residual deformations.

Finally the position where the impact forces interact at maximum engagement must be defined by the user. When identifying this point on the screen the local stiffness of the vehicle body has to be taken into account by the expert. The motion of all cars to the rest position is calculated automatically.

The coefficient of restitution, which is an input parameter for PC-CRASH is easy to define. It usually lies in the range between 0.1 an **0.3.** The higher the deformations of the vehicles, the lower is the coefficient of restitution. Only for low approach velocities are values higher than 0.3 possible.

WORKING WITH PC-CRASH - A SAMPLE

The first step when simulating a new accident is the identification of all involved vehicles. Several databases containing all necessary data can be accessed directly from PC-CRASH and the vehicle data can be copied directly. The dimensions of the vehicles are then displayed on the screen. The correct loads of the vehicles can then be defined.

In a second step the involved cars can be moved to the collision position using the mouse. Here their correct overlapping must be taken into account.

To define the friction conditions and the driver's actions, sequences can be specified. The different steering, brake and acceleration actions can be defined by listing the actions in a so called sequence window. The values for the individual actions can then be given. The validity of one sequence can be limited by definition of a time interval or a travel distance of the vehicle's center of gravity. The brake or acceleration forces can be given for every wheel independently.

Changes of the available friction can be defined by identifying the individual areas with the mouse on the screen and specification of the corresponding friction coefficient and slope.

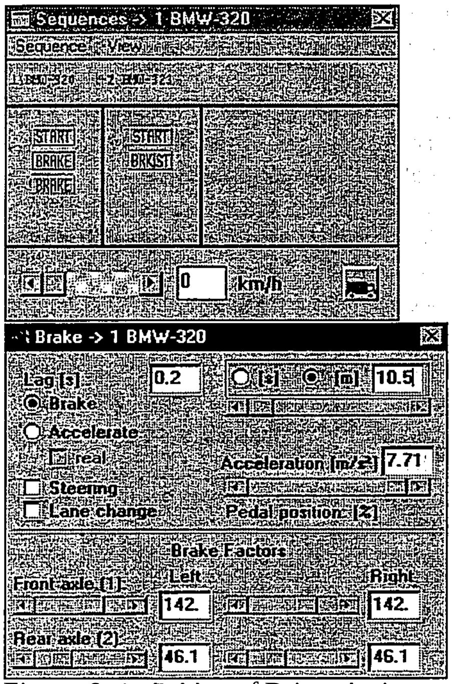

Figure *6:* Definition of Driver Actions

After these definitions have been given, the impact can be calculated and the post-impact movement will be be simulated automatically. The movement of the involved vehicles including their wheel traces can be seen on the screen. It can then be compared to a previously created DXFdrawing of the scene. As an alternative a scanned Bitmap can be underlayed. The pre-impact velocities can be varied as well as all other impact parameters until the tire traces match those on the drawing or Bitmap. The stability of the solution and the influence of the individual parameters can be seen immediately. On an Intel© Pentium 90 processor the simulation of one set of parameters including display of the results typically takes less than 1 second of computational time.

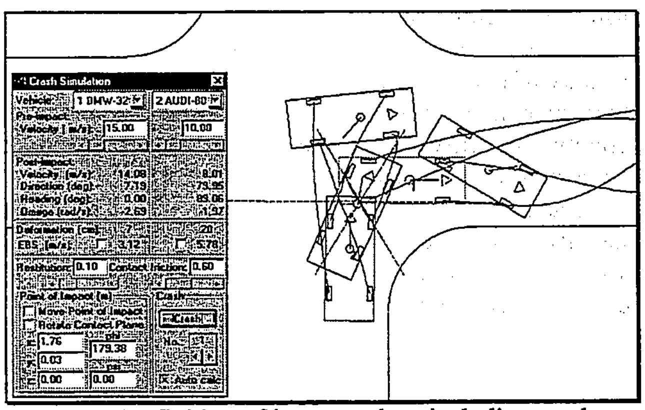

Figure 7: Definition of impact values including results

The following figures show the movement of two vehicles after a 90 degree impact in steps of 100 ms. The pre impact velocity for the vehicle hit at the front was 10 m/s and for the vehicle hit at the rear it was 15 m/s. A dry asphalt surfaced road was assumed. Both cars were fully braked during the post impact phase.

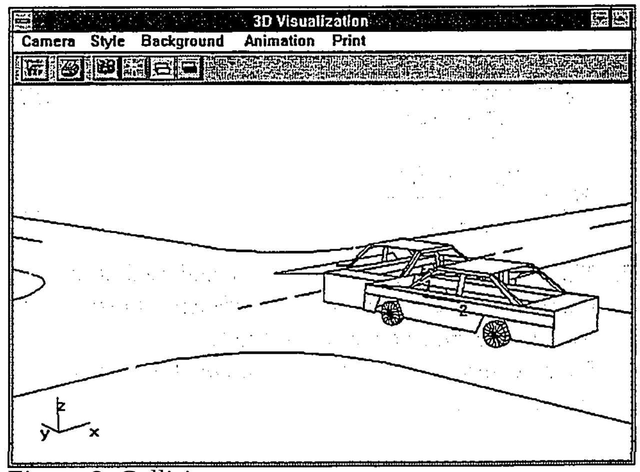

Figure **8:** Collision

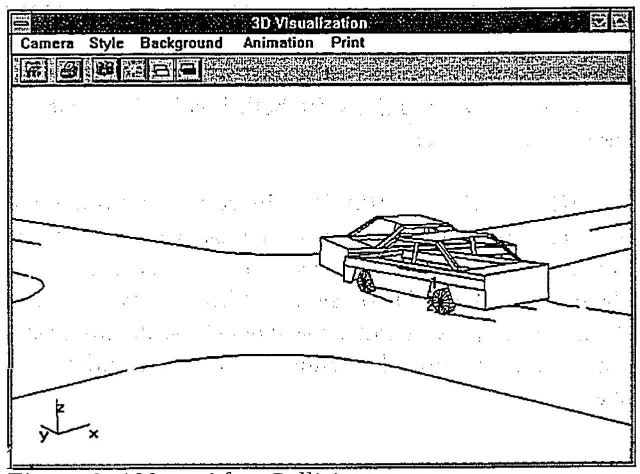

Figure 9: 100 ms After Collision

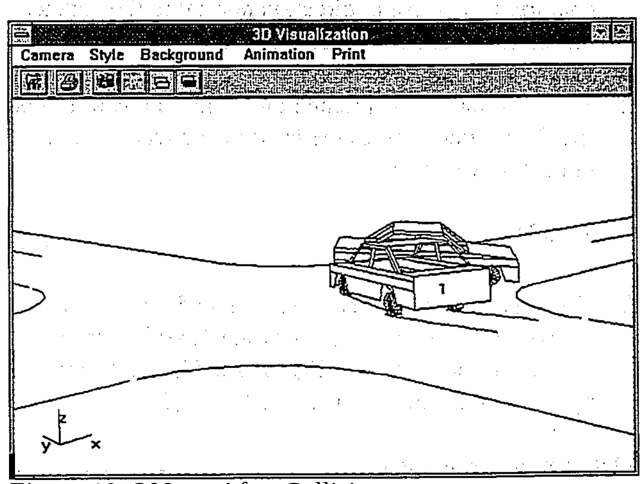

Figure 10: 200 ms After Collision

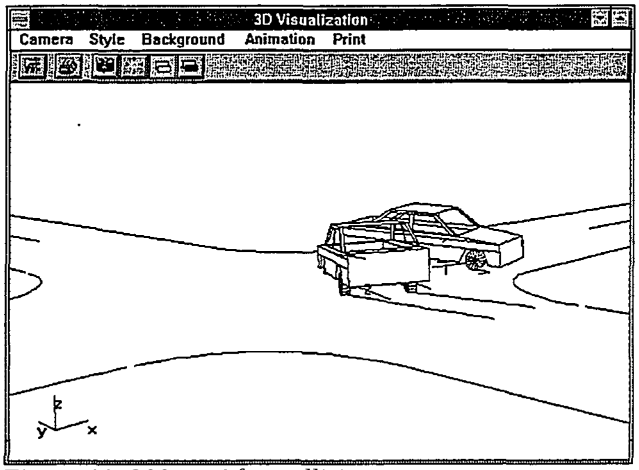

Figure **11:** 300 ms After collision

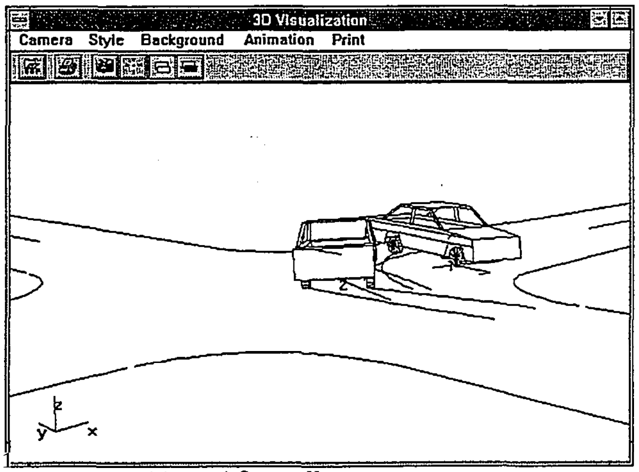

Figure **12:** 400 ms After collision

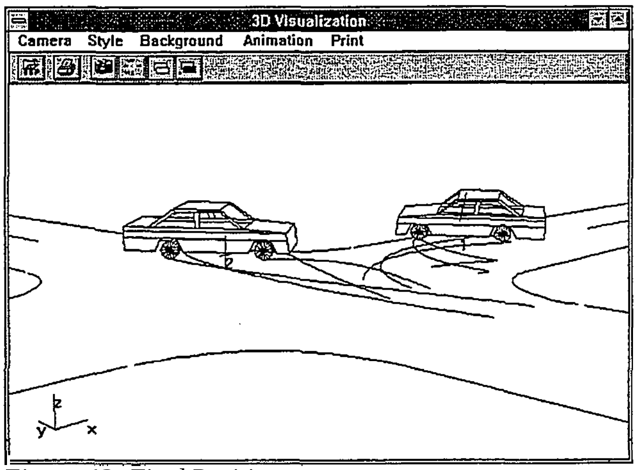

Figure **13:** Final Position

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