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COMPUTER BASED ROAD ACCIDENT RECONSTRUCTION EXPERIENCES

ABSTRACT

Since road accident analyses and reconstructions are increasingly based on specific computer software for simulation of vehicle driving dynamics and collision dynamics, and for simulation of a set of trial runs from which the model that best describes a real event can be selected, the paper presents an overview of some computer software and methods available to accident reconstruction experts. Besides being time-saving, when properly used such computer software can provide more authentic and more trustworthy accident reconstruction, therefore practical experiences while using computer software tools for road accident reconstruction obtained in the Transport Safety Laboratory at the Faculty for Maritime Studies and Transport of the University of Ljubljana are presented and discussed. This paper addresses also software technology for extracting maximum information from the accident photo-documentation to support accident reconstruction based on the simulation software, as well as the field work of reconstruction experts or police on the road accident scene defined by this technology.

KEY WORDS

road accident, investigation, reconstruction, simulation, safety

1. INTRODUCTION

The road accident reconstruction has been defined as the effort to determine from whatever information available how the accident happened at one or several points in time [12, 6]. As scientific work under established practical conditions, an accident reconstruction is based upon a set of analyses considering: collision, injury, accident and injury avoidance, and accident causation. To perform a majority of analyses needed for the accident reconstruction computer software tools are nowadays available to the reconstruction experts.

The foremost computer software intended for simulations of automobile collisions (SMAC - *Simulation Model of Automobile Collision*) was developed at the aeronautical laboratory Calspan at the Cornell University in 1974. As a preprocessor of the SMAC program another program (CRASH - *Calspan Reconstruction of Accidents Speeds on Highway*) was also designed in the same laboratory and was later developed as a standalone program CRASH3 [4]. While SMAC is intended for collision simulations, which include vehicle motion before, during and after the collision, CRASH calculates the speed change (delta *v*) of vehicles during the collision and for their estimated motion after the collision from known damage and positions of the vehicles before and after the collision. With the appearance of personal computers, the use of simulation programs became everyday practice for road-accident reconstruction experts. In 1986 commercial versions EDSMAC and EDCRASH appeared [14], and in 1994 the software named m-smac [15] and later on in 1996 the programs WinSMAC and WinCRASH became available [13]. In the mid-nineties the programs such as CARAT - *Computer Aided Reconstruction of Accidents in Traffic* and PC-Crash [9] were developed in Europe. Unlike SMAC and CRASH, these two programs are based on the model of impulsive collision.

The reliability, accuracy and trustworthiness of an accident reconstruction depend on the quality and quantity of the data available from which to make an evaluation. Reliable input data has to be provided for successful analysis performed by computer software tools for collision simulations as well.

By the time an accident reconstruction expert is sought the only available data consists of the police report, the police sketch of the accident scenario, minutes of the statements in court, and photographs of the scene with record of the skid marks, vehicle damage, and involved vehicles still on their positions at rest.

Namely, by the time a reconstruction expert investigates the scene of an accident, the vehicles had been moved from the scene, usually already repaired, the skid marks on the scene of an accident have faded and the debris has been washed away.

The data required for accident reconstruction are usually available only in the photographs taken by the police on the day of the accident and can be extracted from them. The first computer programs intended for photogrammetric analyses of accident scenes were developed in the mid-eighties [2]. Nowadays, excellent special software such as PC-Rect [7] and commercial of the shelf software is available for processing photos of the accident scene. The use of such software enables reconstruction expert to create an accident scene diagram to scale which includes the location and the length of skid marks, vehicle positions at rest, and impact location from an accident photo-documentation. Furthermore, a digital model of a vehicle damage sustained in an accident can be extracted from a photograph with the use of off–the–shelf software such as PhotoModeler [8].

The imbued purpose of this article is to describe some relevant computer software tools for accident simulation and reconstruction, to provide pros and contras for their usage, and their limitations are also discussed. Everyday experiences of a reconstruction expert namely show that when one particular computer software is relied upon the exclusion of others or when accident reconstructions relies solely upon simulation, erroneous conclusions can be drawn. It has to be stressed that the presented article is not an advertisement; the intention of its authors is to provide their practical experience while using computer software tools for road accident reconstruction gained in the Transport Safety Laboratory at the Faculty for Maritime Studies and Transport of the University of Ljubljana.

2. PRIMARY RECONSTRUCTION TOOLS – TRAJECTORY AND COLLISION SIMULATIONS

The calculation of vehicle motions in the accident reconstruction software is based on assumptions that a vehicle is a rigid body on elastic suspensions or simply suspensions are ignored. The motion of vehicle is defined by the forces acting on the vehicle tires. For the sake of definiteness, we provide the basic equations for two-dimensional vehicle motion simulation on a horizontal ground with air resistance neglected [1].

The basic vehicle geometry data and its position on the plane are shown in Figure 1. When the position of the center of gravity of the vehicle is not known the 50:50 distribution between front and rear axes are assumed.

The differential equations which describe the vehicle motion are:

$$\begin{aligned}
\frac{dX_0}{dt} &= v_x \cos\psi - v_y \sin\psi \\
\frac{dY_0}{dt} &= v_x \sin\psi - v_y \cos\psi \\
\frac{d\psi}{dt} &= \omega \\
\frac{dv_x}{dt} &= \frac{1}{m}\left(\sum F_x\right) + \omega v_y \\
\frac{dv_y}{dt} &= \frac{1}{m}\left(\sum F_y\right) - \omega v_x \\
\frac{d\omega}{dt} &= \frac{1}{J_z}\sum M_z
\end{aligned} \tag{1}$$

where m is the total vehicle mass including mass of the passengers, J_z is the inertial yaw moment of the vehicle around its center of gravity, v_x and v_y are components of the velocity of vehicle's center of gravity expressed in its own coordinate system, ω is the angular velocity of the vehicle, ΣF_x and ΣF_y are forces in the direction of vehicle coordinate axes and ΣM_z is sum of yawing torques around the center of gravity of the vehicle. The system of equations (1) is integrated with the Runge-Kutta method with fixed increment or even with low order Euler method. The vehicle inertial moment can be calculated simply by the assumption that the vehicle is a homogenous plate $J_z = (l^2 + w^2)m/12$ [7] or using the empirical formula $J_z = 0.1269 \times m \times w \times l$ [9].

In order to calculate the wheel forces, the vertical load on a particular wheel has to be calculated first.

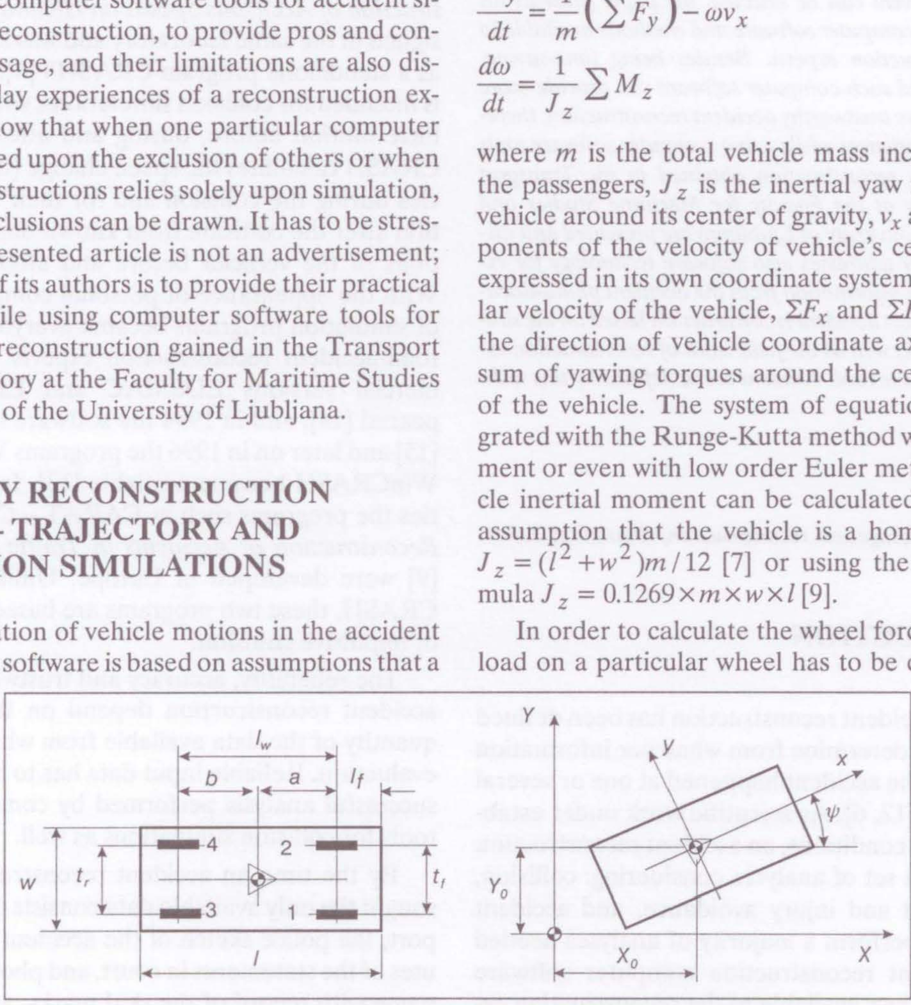

Figure 1 - The variables of vehicle dimensions and position

For the model of a vehicle with suspensions, the vertical forces on a particular wheel are:

$$F_{z1}=\frac{1}{2}\left(\frac{b}{a+b}mg-\frac{h}{a+b}\sum F_x\right)+\frac{hK_f}{t_f K_f+t_r K_r}\sum F_y$$
$$F_{z2}=\frac{1}{2}\left(\frac{b}{a+b}mg-\frac{h}{a+b}\sum F_x\right)-\frac{hK_f}{t_f K_f+t_r K_r}\sum F_y$$
$$F_{z3}=\frac{1}{2}\left(\frac{b}{a+b}mg-\frac{h}{a+b}\sum F_x\right)+\frac{hK_r}{t_f K_f+t_r K_r}\sum F_y$$
$$F_{z4}=\frac{1}{2}\left(\frac{b}{a+b}mg-\frac{h}{a+b}\sum F_x\right)-\frac{hK_r}{t_f K_f+t_r K_r}\sum F_y \tag{2}$$

where g is Earth gravity acceleration, h is vertical position of the vehicle centre of gravity and K_f, K_r are the front and rear suspension stiffness respectively. When the suspension of the vehicle is ignored, the vertical loads on wheels are simply static loads applied on them:

$$F_{z,1}=F_{z,2}=\frac{b}{2(a+b)}mg$$
$$F_{z,3}=F_{z,4}=\frac{b}{2(a+b)}mg \tag{3}$$

The components of the particular force on the k-th wheel are calculated from the following formulas:

$$F_{x,k}=F_{wx,k}\cos\delta_k-F_{yw,k}\sin\delta_k$$
$$F_{x,k}=F_{wx,k}\sin\delta_k+F_{yw,k}\cos\delta_k \tag{4}$$

where δ_k is the wheel steering angle and $F_{wx,k}$ and $F_{wy,k}$ (k = 1,..., 4) are the tyre longitudinal and lateral forces expressed in the coordinate system of a wheel. The total force applied on a wheel cannot exceed the available contact friction between the tyre and the surface of the road:

$$\sqrt{F_{xw,k}^2+F_{yw,k}^2}\le\mu_k F_{z,k} \tag{5}$$

where μ_k is the friction coefficient between road surface and the k-th tyre. Longitudinal force $F_{wx,k}$ on the k-th wheel is defined by driving simulation (i. e. by defining driver acceleration or breaking and road condition). It is given by:

$$F_{xw,k}=\theta_k\mu_k F_{z,k},-1\le\theta_k\le 1 \tag{6}$$

On the other hand the lateral force on the k-th wheel depends on its sideslip angle α_k which is defined as the difference between the direction of velocity vector of the wheel centre and its steering angle and for its calculation various models are used. The simplest is the linear model:

$$F_{yw,k}=-\mu_k F_{z,k}\frac{\alpha_k}{\alpha_{k,max}} \tag{7}$$

While the vehicle trajectory calculation before and after the collision in an accident reconstruction software is exclusively based on rigid body dynamics the collision simulation is basically distinguished between those based upon the impulsive model, and the others based upon the model of vehicle deformations.

The software algorithm for the reconstruction of a vehicle collision is based on the impulsive model which comprises the laws of conservation of linear and angular momentum. The fundamental supposition of the impulsive model is that the collision is instantaneous (i. e. the vehicles do not change their positions during the collision phase). The impulse model is mathematically described as follows [1], [9]. First the local coordinate system is centred in the point of assumed vehicle impact, which is named the impact point P. The coordinate system has axes n, t directed perpendicular and tangential to the assumed contact plane (Figure 2).

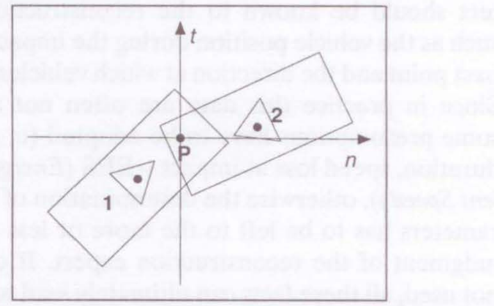

Figure 2 - Oblique collision used in the impulse model

The conservation of linear and angular momentum yields:

$$\left.\begin{aligned} v_{1n}^+-v_{1n}^-&=\frac{I_n}{m_1}\\ v_{1t}^+-v_{1t}^-&=\frac{I_t}{m_1}\\ J_{1z}(\omega_1^+-\omega_1^-)&=I_n y_1-I_t x_1\end{aligned}\right\}\text{first vehicle}$$
$$\left.\begin{aligned} v_{2n}^+-v_{2n}^-&=-\frac{I_n}{m_2}\\ v_{2t}^+-v_{2t}^-&=-\frac{I_t}{m_2}\\ J_{2z}(\omega_1^+-\omega_1^-)&=-I_n y_2+I_t x_2\end{aligned}\right\}\text{second vehicle} \tag{8}$$

where superscript + is used to denote unknown values after collision and – for values before collision, I_n and I_t are components of impulse in the normal and tangent direction to the contact area while x_1, y_1, and x_2, y_2 are coordinates of the centre of gravity of the first and second vehicle respectively in the local coordinate system. To retrieve a solution of the system (5) two additional assumptions are needed for the unknown velocities after collision and two components of the impulse. Therefore, two cases are distinguished. Where there is no relative motion between vehicles at the point of full impact, the velocities at impact point during compression phase of impact are the same for both vehicles. For the case of the sliding impact the assumption is that both vehicles reach the same velocities at impact point in normal direction, while tangential direction of impulse is calculated from the Coulomb law $I_t = \mu I_n$ where μ is the coefficient of friction between vehicles.

The basic assumption that the vehicles do not change their positions during the collision phase represents the major disadvantage of the impulsive model. Considering vehicle collisions such a supposition should be treated only as rough approximation, because of the fact that vehicles can substantially change their positions during the collision phase. Furthermore, before using such a model, a set of parameters should be known to the reconstruction expert such as the vehicle position during the impact, the impact point and the direction at which vehicles collided. Since in practice this data are often not available, some presumptions have to be adopted (e. g. impact duration, speed loss at impact – EES (*Energy Equivalent Speed*)), otherwise the determination of these parameters has to be left to the more or less educated judgment of the reconstruction expert. If caution is not used, all these facts can ultimately lead to a reconstruction which is not objective.

The disadvantages of the impulsive model discussed can be overcome with the use of the model based on vehicle deformations sustained during the collision. Contact forces between the vehicles are also considered in the dynamic equations of such a model. When impact occurs, the model calculates the contact forces on the basis of vehicle mechanical properties and consequently considers them in its equations of motion. In this way the vehicle motion in the collision phase is entirely described without intervention of the reconstruction expert, which results in a more objective reconstruction of the accident.

Usually, in the deformation based models the linear relationship between normal collision force F and the deformation is assumed with K as the coefficient of stiffness of the vehicle and δ as the deformation or the crush depth of the vehicle (Figure 3):

$$F = K\delta \tag{9}$$

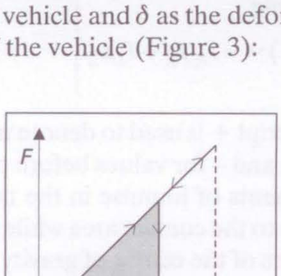

Figure 3 - The force-deflection relationship where δ_f is the final (residual) deflection, δ_m is the maximum deflection

In smac type programs [7] the crush pressures are computed rather before than the crush forces. To do that a set of equally spaced radial vectors from vehicle centre of gravity are established first (Figure 4). Each vector represents a potential crush pressure against the vehicle. To calculate the crush pressures the intersection between the vehicles has to be confirmed first, and then all the potential radials are processed. The first intersection of particular radials is confirmed and then two additional vectors are established. One radial is drawn from the centre of gravity of the base vehicle to the contact point and the other radial from the centre of gravity of the other vehicle to the contact point. The pressure $p_i^{(j)}$ at i-th point on j-th vehicle is:

$$p_i^{(j)} = k_i^{(j)}(\rho_{i,max}^{(j)} - \rho_i^{(j)}) \tag{10}$$

where $\rho_{i,\,max}^{(j)}$ is the vehicle perimeter and $\rho_i^{(j)}$ is the contact point radius. The program then iterates the $\rho_i^{(j)}$ until $p_i^{(1)}$ and $p_i^{(2)}$ are balanced to the prescribed tolerance. When the i-th radial ρ_i is in the restitution phase it is enlarged by:

$$\rho_{\rho,i} = c\,\rho_{max,i} + (1-c)\rho_i \tag{11}$$

where $\rho_{max,\,i}$ is the maximum i-th radial length and $c = 1 - \delta_f / \delta_m$ simulate restitution instead of the coefficient of restitution ε.

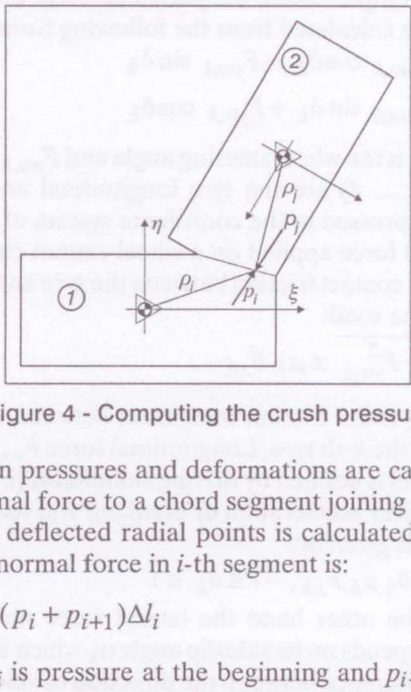

Figure 4 - Computing the crush pressure

When pressures and deformations are calculated, the normal force to a chord segment joining two consecutive deflected radial points is calculated (Figure 5). The normal force in i-th segment is:

$$F_{n,i} = \frac{1}{2}(p_i + p_{i+1})\Delta l_i \tag{12}$$

where p_i is pressure at the beginning and p_{i+1} at the end segment point, and Δl_i is segment length. The tangential friction force in i-th segment is:

$$F_{t,i} = \mu_v F_{n,i} \tag{13}$$

where μ_v is the inter-vehicle friction coefficient. In order to compute the velocity difference, note that the tangential velocity at the middle of i-th crushed segment for the base vehicle is (Figure 5):

$$v_{t,i} = (v_x - \omega\bar{\eta}_i)\cos\phi_i + (v_y + \omega\bar{\xi})\sin\phi_i \tag{14}$$

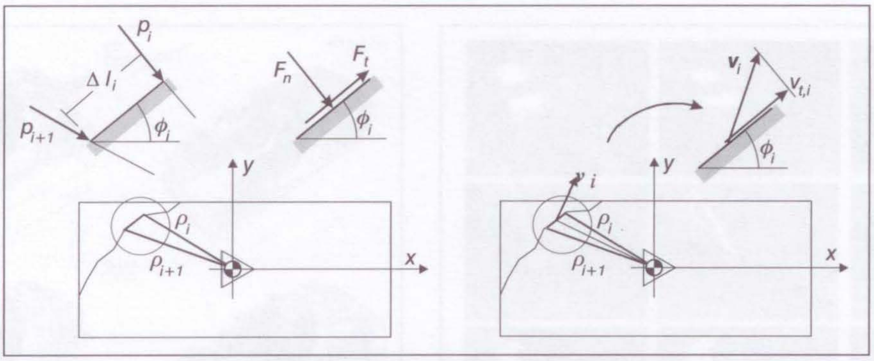

Figure 5 - Forces and velocity at crushed segment

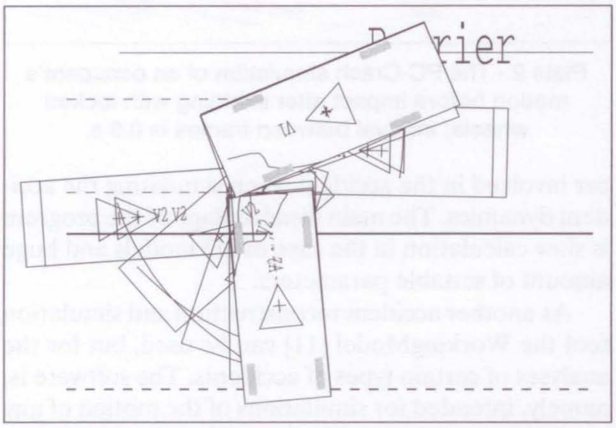

Figure 6 - The results of m-smac computer simulation of a two-vehicle collision; individual positions of the vehicles are plotted in 0.25 s intervals.

where $\bar{\xi}_i = 0.5(\xi_i + \xi_{i+1})$ and $\bar{\eta}_i = 0.5(\eta_i + \eta_{i+1})$ and ϕ_i is the i-th segment direction. A similar formula is used for the other colliding vehicle. Once both velocities at contact point are known the velocity difference can be calculated.

Once normal and tangential forces are known, they must be transformed from the crushed segment coordinates to vehicle coordinates by:

$$F_{\xi,i} = F_{t,i} \cos\phi_i + F_{n,i} \sin\phi \qquad (15)$$
$$F_{\eta,i} = F_{t,i} \sin\phi_i - F_{n,i} \cos\phi$$

The yaw moment caused by collision forces is then:

$$\sum M = \sum(\bar{\xi}_i F_{\eta,k} - \bar{\eta} F_{\xi,k}) \qquad (16)$$

An example of a program based on the deformation model is m-smac [8]. This program allows 2D simulations of two vehicles collisions, collisions of vehicles into a fixed barrier and collisions of vehicles into a narrow barrier (pole, tree). The data is input via tables, while the results are given in tabular or graphical form. The main advantage of this program is its possibility to allow comparison between the calculated and actual deformation of the vehicles at collision. Figure 1 shows the use of the program (analysis of a two-vehicle collision).

In the m-smac program it is common to start with the known positions of the vehicles at rest after the collision and with the estimated location of a point at which collision occurred. The reconstruction expert's task is then to search for the calculated solutions for the set of positions describing vehicle motion and deformations of the vehicles which best suit the real data. This is done via changes and iterations of the initial vehicle positions and their properties as well. It has to be stressed that there is a large amount of inputs to be made; 27 parameters defining both vehicles involved in an accident (dimensions, mass, yaw moment of inertia, chassis stiffness, tyre stiffness) and 6 parameters defining initial conditions (position, angle of rotation, initial speed, initial angular speed) have to be defined. If also the friction coefficient and the tabulated data describing the forces on tyres and the actions taken with the steering wheel are taken into account, then the search for a suitable solution with m-smac can be very exhaustive. This time-consuming procedure can be abbreviated by some manual calculations before the use of the program, which serve to estimate the initial values (for example WinCRASH).

Another program based on impulsive model in widespread use is PC-Crash. It enables collision simulations up to 32 vehicles. Beside 2D simulations, it also provides 3D simulations of vehicle collision and roll-over, simulations of vehicle collision into fixed barriers, simulations of vehicle-pedestrian and vehicle-motorcycle collisions and also simulations of passenger motion in the vehicle. Some examples of use in reconstruction of real accidents are shown in plates 1, 2, 3 and 4.

Unlike m-smac, PC-Crash has a simple and user-friendly graphical interface, which enables fast definition of vehicles due to its vehicle database, input of different surfaces and settings of initial vehicle positions in a simple way according to the police sketches from the spot or rectified photographic material from the scene of the accident. Instead of time-consuming tabulated inputs for the driver's actions such as braking, acceleration, steering, as in the case of m-smac, the reconstruction expert can benefit from graphical inputs (e. g. vehicle course) and also from automated search of best initial conditions. It can be said that with PC-Crash the reconstruction expert almost drives the

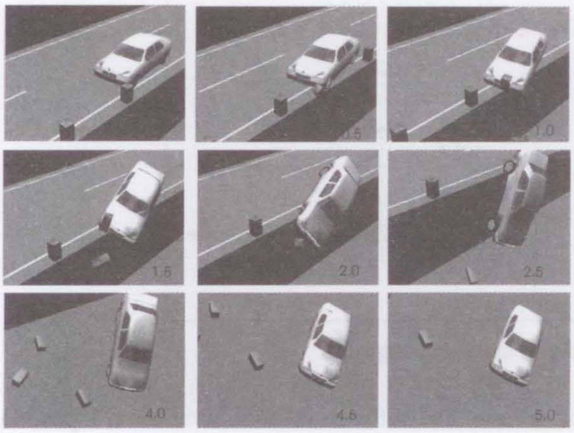

Plate 1 - PC-Crash simulation of a collision of a vehicle into side-road barrier-type stone and the initial motion of a vehicle over side-scarp at the speed of 37 km/h.

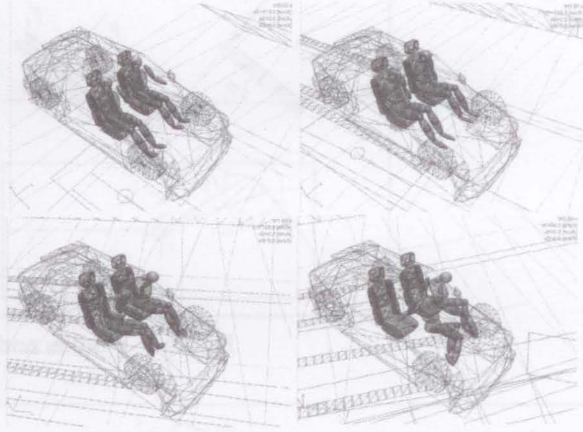

Plate 2 - The PC-Crash simulation of an occupant's motion before impact after skidding with locked wheels; interval between frames is 0.5 s.

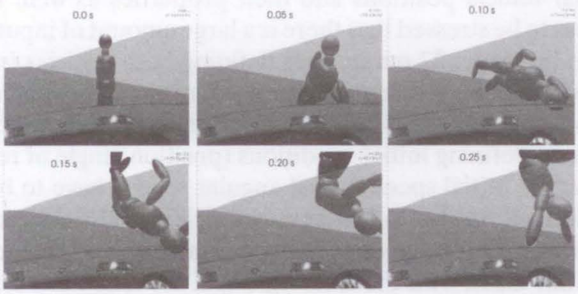

Plate 3 - PC-Crash simulation of a pedestrian's rebound from a car hood shown from the driver's perspective

car involved in the accident when simulating the accident dynamics. The main disadvantage of the program is slow calculation in the case of 3D models and huge amount of settable parameters.

As another accident reconstruction and simulation tool the WorkingModel [11] can be used, but for the analyses of certain types of accidents. The software is, namely, intended for simulations of the motion of any mechanical system in a 2D plane. Therefore, as the accident simulation platform it requires that everybody and everything involved in an accident and an accident event i. e. vehicles, humans and other objects involved in a road accident as well as their motions are 'translated' into mechanical systems by the reconstruction expert him/herself. Plate 5 shows an example of its use in an analysis of an accident.

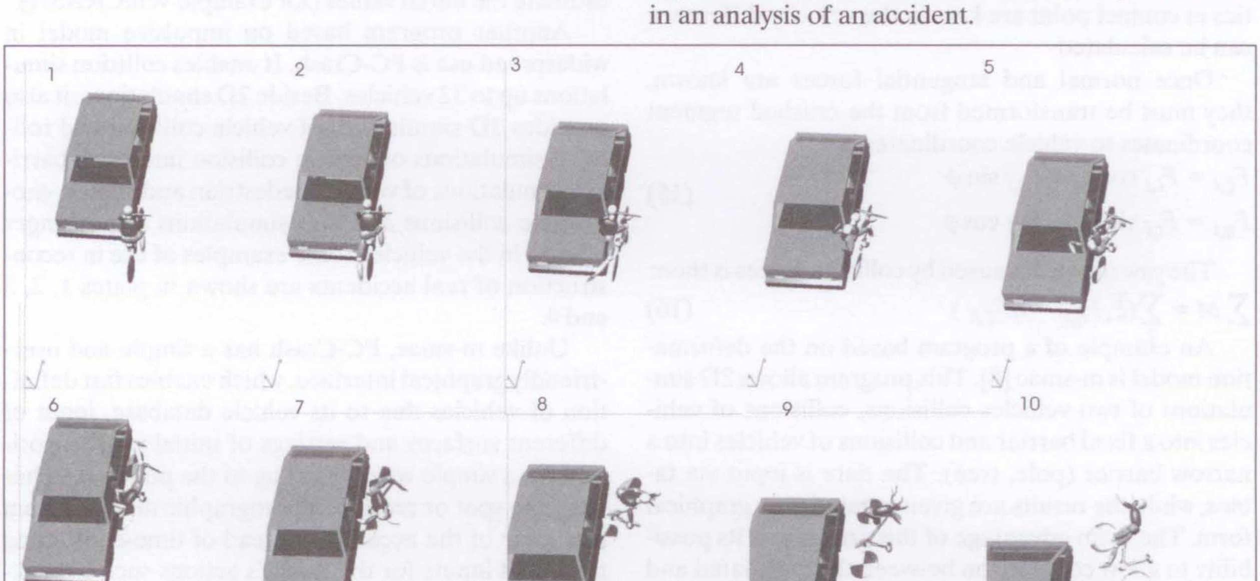

Plate 4 - PC-Crash simulation of a vehicle-cyclist collision at vehicle speed of 40 km/h, and cyclist speed of 10 km/h.

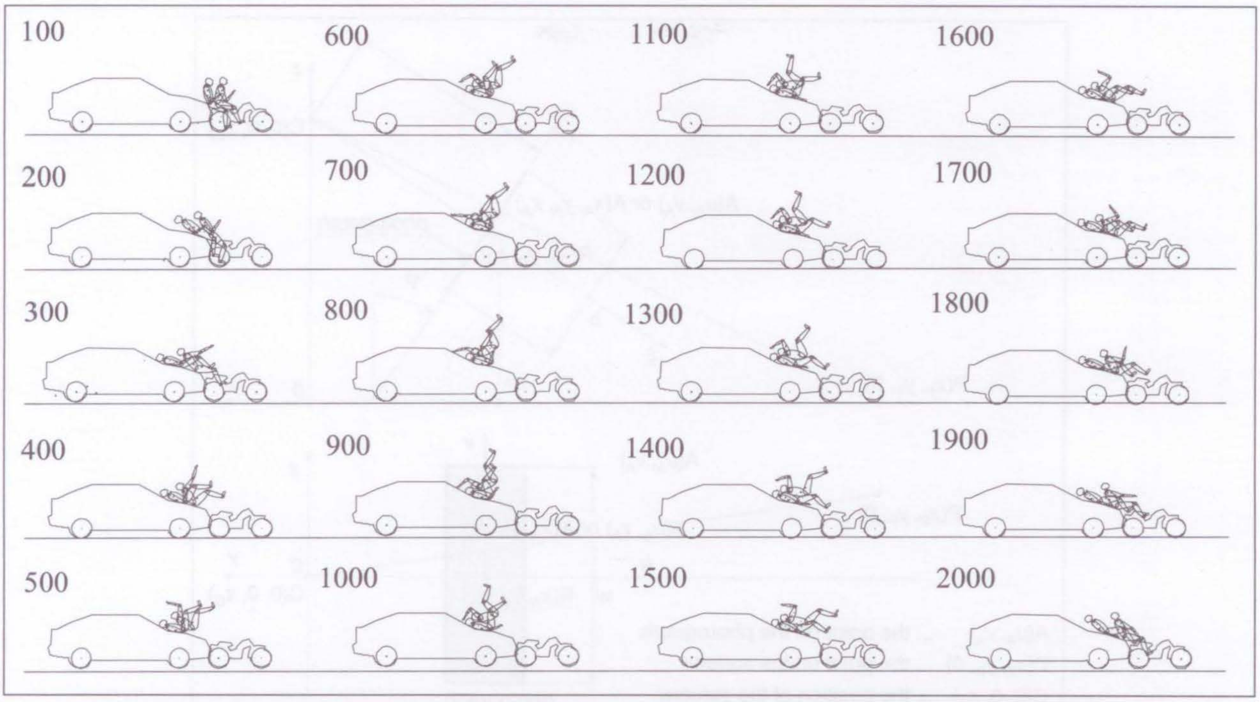

Plate 5 - Working-Model simulation of a vehicle collision into a motorcycle, the simulation of the motorcycle driver and the passenger motion after the initial impact of a vehicle (vehicle speed is 72 km/h, while the motorcycle speed is 36 km/h; intervals between frames are in μs)

3. SECONDARY RECONSTRUCTION TOOL

A prerequisite for the accident reconstruction expert is the creation of accurate accident scene diagram to scale from photographs taken when the accident scene was investigated by the reconstruction expert. If photographs taken on the day of an accident are available, an accident scene diagram with details of the location and the length of skid marks, vehicle positions at rest, and impact location can be created. Software supporting the process of inverse camera projection is applicable when little or nothing is known about the camera that was used to take accident photo-documentation. To transform a surface of an object in true three-dimensional perspective of the photograph into the plan two-dimensional view drawing (Figure 7, and Plate 6) the applicable software should support the process of photographic rectification. When the software for photographic rectification is used in the process of an accident reconstruction then a software algorithm and its characteristics define the field work of the reconstruction expert investigating the accident scene, and a policeman on the accident spot as well.

Rectification is a procedure or geometrical tool which determines the relationship between the three-dimensional space and the two-dimensional image in the photograph with objects in true perspective. To convert a point in the two-dimensional photograph $A(u_A, v_A)$ into the corresponding three-dimensional point $P(x_P, y_P, z_P)$, position $C(x_C, y_C, z_C)$, orientation (rotation around x-axis ψ, around y-axis ϕ, and around z-axis ζ) and the focal length f of the camera should be given as well as the photograph height h and width w, and coordinates of the point in the photograph $A(u_A, v_A)$ expressed in two-dimensional u–v coordinate system of the photograph. When point P lies on a flat surface on the x–y plane of the three-dimensional space (Figure 7) then its coordinates are $P(x_P, y_P, 0)$. The camera should be positioned on the z-axis above the origin of the three-dimensional coordinate system and its coordinates are then $P(0,0,z_P)$ as shown in Figure 7.

If the visual reference point R lies in the middle of the photograph, and if the camera is not rotated around z-axis, therefore $\zeta = 0$, and the axis ξ through reference point R from camera C lies on the y–z plane, then according to Figure 7, its coordinates in the three-dimensional x–y–z space are:

$$\begin{aligned} x_R &= 0 \\ y_R &= -f\cos\psi \\ z_R &= z_C - f\sin\psi \end{aligned} \tag{17}$$

Vectors $\boldsymbol{u}$ and $\boldsymbol{v}$ defining the two-dimensional plane u–v of the photograph must be orthogonal to each other $\boldsymbol{u}\perp\boldsymbol{v}$, they also must be orthogonal $\boldsymbol{u}\perp\xi$, and $\boldsymbol{v}\perp\xi$ to the axis ξ through reference point R from camera C (Figure 7). When the described conditions for the vectors $\boldsymbol{u}$ and $\boldsymbol{v}$ are met and when camera is not rotated around y-axis, therefore $\phi = 0$, and around z-axis, therefore $\zeta = 0$, then vector $\boldsymbol{u}$ is orthogonal to

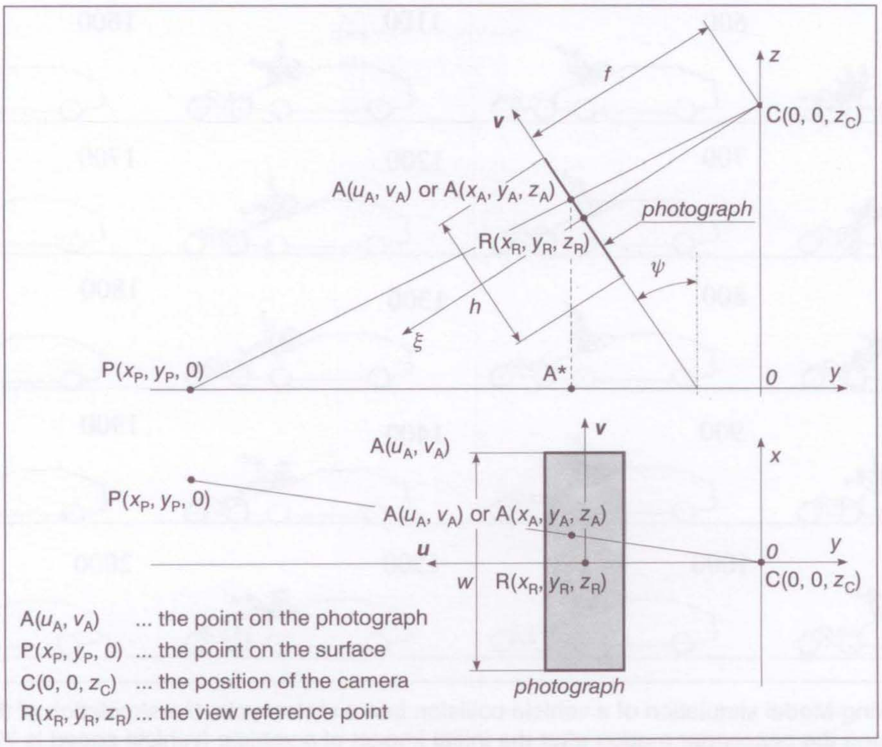

Figure 7 - Transformation of a photograph point A into a surface point P

the y-axis $\boldsymbol{u} \perp y$ and also to the z-axis $\boldsymbol{u} \perp z$, therefore, as shown in Fig. 7 its projections in the three-dimensional x–y–z space are $u_x = 1$ and $u_y = u_z = 0$; since vector $\boldsymbol{v}$ is orthogonal to the x-axis $\boldsymbol{v} \perp x$ its projections in the three-dimensional x–y–z space are $v_x = 0$, $v_y = -\sin\psi$, and $v_z = \cos\psi$ (Figure 7).

Based on (17) and presumptions described the point $A(u_A, v_A)$ from the two-dimensional u–v photograph can be defined in the three-dimensional x–y–z space as $A(x_A, y_A, z_A)$ with coordinates:

$$x_A = w u_B$$
$$y_A = -f\cos\psi - h v_B \sin\psi \qquad (18)$$
$$z_A = z_C - f\sin\psi + h v_B \cos\psi$$

When the point in the photograph is defined in the three-dimensional space $A(x_A, y_A, z_A)$ then the coordinates of the corresponding three dimensional surface point $P(x_P, y_P, 0)$ can be calculated based on the similarity between triangles $\triangle C0P$ and $\triangle AA^{*}P$ shown in Figure 7 and considering (17) and (18) it follows:

$$x_P = w^2 u_B^2 \frac{1}{f\sin\psi - h v_B \cos\psi}$$
$$y_P = -w u_B \frac{f\cos\psi + h v_B \cos\psi}{f\sin\psi + h v_B \cos\psi} \qquad (19)$$
$$z_P = 0$$

When relationship between the point of an object in the three-dimensional space and the point of the same object in the two-dimensional image in the photograph (19) is determined an orthographic projection of the surface can be generated; where an orthographic projection is a remapping of the image on a flat surface. Adequate software tools for photographic processing, such as PC-Rect, which is an additional module to the program tool PC-Crash for the reconstruction of vehicle motion dynamics, offer practically automated inverse camera projection and rectification and are therefore indispensable in the analyses and reconstruction of traffic accidents [9]. The work with the rectification software as PC-Rect is not demanding but might become time-consuming. If the photographs of the surface (meant for rectification) are taken with an analogue camera, their digitalization is needed. When scanning, the coordinate systems of the scanned picture and the original photo have to be in accordance.

The rectification procedure starts already at the scene of the accident, the surface intended for rectification has to be prepared scenically even before the photographs are taken. This preparation is dependent on the working principle or geometrical model of transformations from two-dimensional plane into three-dimensional space of the software tool which is used for rectification.

In order to rectify an image of a surface in the photograph and in order to determine the camera characteristics at least four points have to be defined on that surface (of the accident scene for example) first. The reference points can be defined either with drawing on the surface or with displacing objects of the known height. Those reference points should form a polygon with sides of at least 15 m. Field work showed that oblong polygons disfigure rectification and produce non--negligible rhomboid shape deviations of the rectified photograph from real geometry with lateral errors increasing in the direction of the camera objective. Longer sides of a polygon result in difficulties while taking photos on the spot. The surface of interest in the photograph for rectification must also be identified in the process by choosing control points which will enclose this surface of interest into an arbitrary polygon. Within its boundaries an arbitrary polygon should contain only limited number of reference points; in case of PC-Rect one photograph should show only six points at the most. The software, namely, enables the input and processing of a maximum number of ten reference distances for the single rectification. Furthermore, this arbitrary polygon should follow the edges of the surface of interest as accurately as possible. The deviations namely produce disfigurements of the rectified picture.

In order to make a plan view drawing of the surface of a curved road, such a surface should be broken down into as many pieces as reasonable to best represent the curvature of the road because a rectification plane cannot be curved. Each piece can then be rectified separately and composed after rectification as shown in Plate 6. The multiple planes should be identified for separate rectification for any extensive area or an area which is not planar and is intended for rectification. Multiple planes rectified separately can be stitched together to form an extensive area or a surface of a curved road by means of adjacent reference distances of a pair of polygons from the adjoining planes. A deviation condition of their rectified lengths for a pair of adjacent reference distances exists. If those lengths differ too much, the composition of the two photos is not possible due to their disfigurement.

An arbitrary number of reference points has to be defined on a surface which will be later made up of multiple planes rectified separately. After the measurement of all the combinations of reference distances among the reference points, the surface has to be photographed in such a way that a single photo shows limited number of reference points; in case of PC-Rect one photograph should show only six points at the most. Whenever possible the reference distance, which will be later in the process used for stitching of multiple planes rectified separately should appear on the photograph taken closest to the camera to minimize deviations on the rectified flat surface. The latter means that the area of concern should be photographed from opposite directions.

Beside the determination of the reference points and measurement of the reference distances on the surface intended for rectification, at least the focal length of the camera, and height of the camera have to be determined for every photo according to (19). In order to minimize deviations of the rectified picture from actual geometry, it is also recommended for every photo that the inclination angle ψ of the camera is determined (Figure 7, and (19)). An automated inverse camera projection routine optimizes the position of the camera objective with regard to the minimum of four reference points defined within the arbitrary polygon of chosen surface of interest in the photograph for rectification and calculates the missing parameters of the camera position when the two-dimensional plane of a photograph is misaligned with the three-dimensional coordinate system and missing ori-

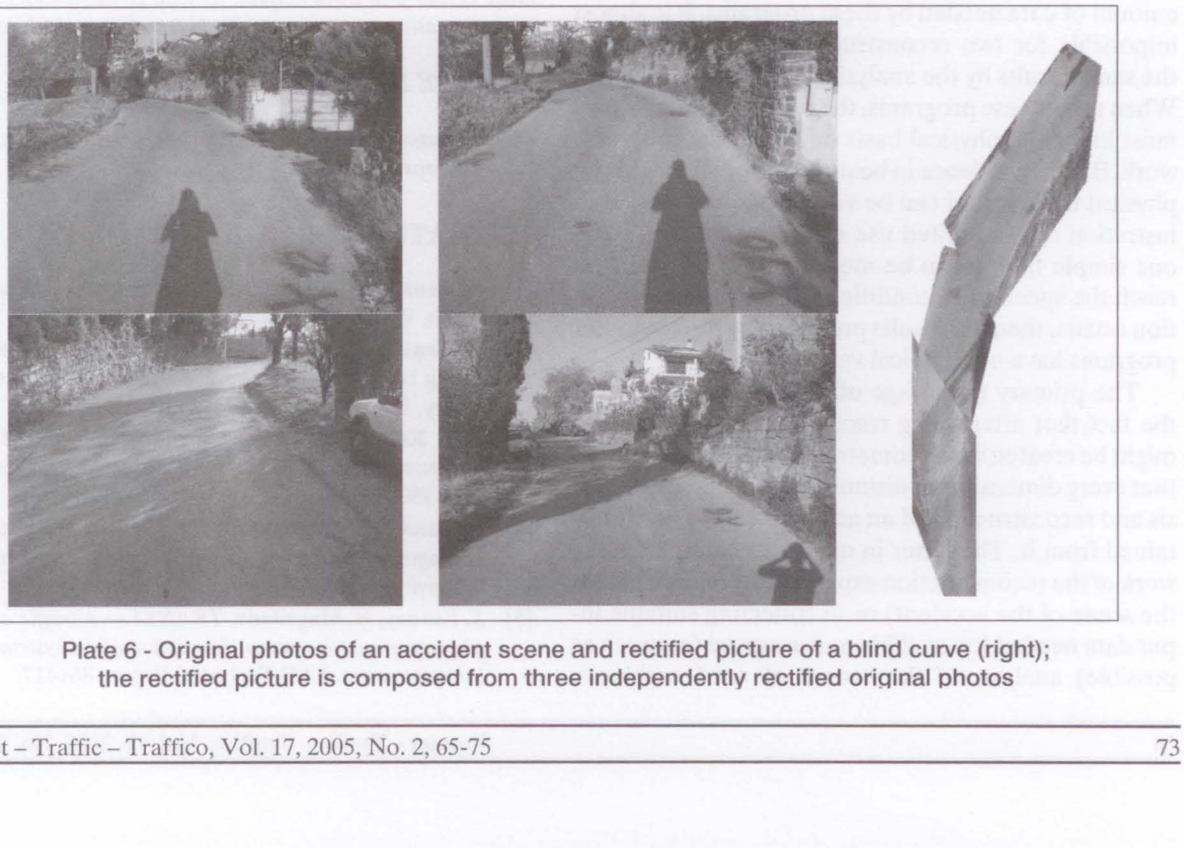

Plate 6 - Original photos of an accident scene and rectified picture of a blind curve (right); the rectified picture is composed from three independently rectified original photos

entation parameters of camera rotation around y-axis ϕ, and around z-axis ζ in such a way that the weighted error of the reference distances is minimal. If the work is sufficiently accurate, the weighted error of the PC-Rect will be in the range between 0.3% and 3% [10]. Reported error when photographs are rectified using PhotoModeler are in the range between 0.4% and 0.9% [2].

4. CONCLUSION

The comprehensive illustrations and descriptions present the applicability and practicability of available software for road accident reconstruction and reliability of its simulations. In the Transport Safety Laboratory at the Faculty of Maritime Studies and Transport of the University of Ljubljana we do not prefer particular software package over another; they are used individually or in combination according to the type of the accident reconstructed. It is advantageous and sensible to substantiate any conclusions drawn from as many different directions as possible. This cross-checking renders additional weight to the final option.

Modern software tools become indispensable for the reconstruction of some types of traffic accidents. Instead of speculations and rough estimates, they offer more accurate calculations of the motion of the participants in an accident. With the aid of these tools, injuries to humans and damage to vehicles can be calculated more reliably and the results can be presented in a graphical form as pictures or animations. However, attention should be paid in their usage and in interpreting the obtained results. Because of the large amount of data needed by these programs, it is almost impossible for two reconstruction experts to obtain the same results by the analysis of the same accidents. When using these programs, the reconstruction expert must know the physical basis on which the programs work. Blind confidence in beautiful animation without physical background can be very dangerous. As an illustration of the limited use of these programs, only one simple fact has to be mentioned. If the vehicles reach the speeds and conditions in which decomposition occurs, then the results produced by the computer programs have no practical value.

The primary advantage of the rectified picture is the fact that after being traced a plan view drawing might be created with geometry of details preserved so that every dimension or distance relevant to the analysis and reconstruction of an accident can be easily obtained from it. The latter in many ways simplifies the work of the reconstruction expert either in the field (at the scene of the accident) or in collecting suitable input data needed for credible and accurate (as much as possible) analysis of the causes of road accidents. There is no need to survey the scene with traditional survey instruments; therefore, there is no need to get into traffic, which can be dangerous and time-consuming. One should always be aware that the process of rectification and its results are as good as the quality of the photographs and camera used.

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POVZETEK

IZKUŠNJE PRI RAČUNALNIŠNO PODPRTEM REKONSTRUIRANJU CESTNO-PROMETNIH NESREČ

Ker analize in rekonstrukcije cestno-prometnih nesreč vsepogosteje podpira specializirana programska oprema, ki omogoča simulacijo dinamike vožnje vozil in trkov, omogočajo pa tudi simulacijo niza poiskusov med katerimi je moč izbrati tisti model dogajanja, ki najverodostojneje opisuje resnično dogajanje v času nesreče, podaja pričujoči prispevek pregled nekaterih računalniških programov in metod, ki so na razpolago izvedencem pri raziskavi cestno-prometnih nesreč. Poleg tega, da je z njihovo uporabo moč prihraniti čas, omogoča tovrstna programska oprema realnejše in verodostojneše rekonstrukcije cesto-prometnih nesreč, zato so v članku predstavljene praktične izkušnje njihove uporabe v Laboratoriju za varnost v prometu na Fakulteti za pomorstvo in promet Univerze v Ljubljani. Članek obravnava tudi tehnologijo programskih orodij, ki omogočajo zajem merodajnih informacij iz fotodokumentacije cestno-prometne nesreče, ter delo izvedenca ali policista na kraju cesto-prometne nesreče, ki temelji na tej tehnologiji.

KLJUČNE BESEDE

cestno-prometna nesreča, preiskovanje, rekonstrukcija, simulacija, varnost.

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