Research of Impact Parameters for Traffic Accident Analysis in Case of Small Overlap Crash Test

Validation and comparison of impact parameters between real crash data and computer modelling

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This article presents an executed frontal small overlap crash test of two vehicles moving at a speed of approximately 43 km/h with the emphasis on the resulting crash parameters for application in traffic accident analyses. The experimentally measured data from the crash test were suitably analyzed and important crash parameters were obtained and applied in impact modelling by a simulation program, which is used to analyse traffic accidents.

Key words: Crash Test, Impact, Vehicle, Traffic Accident, Forensic Engineering

I. INTRODUCTION AND GOAL OF THE RESEARCH

This article concerns an issue, which falls within forensic sciences, i.e. special methodologies of forensic engineering through analyses of traffic accidents. The technical assessment of the cause of a traffic accident usually involves a complex analysis of the accident progress, which usually involves a study of the actual collision of the vehicles. Although experts use sophisticated simulation programs to analyse the accident progress, the correctness of the result greatly depends on the parameters input by the expert, which must move within a technically acceptable range. To apply crash parameters within a technically acceptable range during analyses of traffic accidents, it is necessary to draw data from real crash tests on the basis of which it is possible to analyse the input parameters necessary for the actual study of the crash. Issues connected with the technical reconstruction of traffic accidents leading to determination of the cause of the accident have been tackled by many authors, e.g. [2], [3], [7], [8].

Issues connected with the desired collision parameters as regards the force and the related size of the impulse, the energy intensity of the collision, rigidity and the restitution coefficient, are intensively studied by [1], [4], [5], [6], [9] [11], [12] and [13].

In the overwhelming majority of cases, data from crash tests performed in Europe are strictly protected and are not available for the needs of experts, who perform reconstructions especially for forensic purposes. As a result, a frontal small overlap crash test was executed with the active participation of the Institute of Forensic Engineering (IFE, USI in Czech), Brno University of Technology, and its results are used in analyses of crash parameters for validation of the Virtual CRASH simulation program [25]. The work [14] emphasises the fact that in crashes with a small overlap (less than 30 %), the risk of serious injury sharply rises especially because of the misalignment of structures that absorb energy, such as longitudinal girders. This type of collision can cause mutual contact of the wheels and serious movement of the damaged parts into the cabin. The authors documented this fact in an analysis of twenty accidents of this type, where they studied the effect of the impact velocity, the impact angle, the width of the overlap, etc.

The publication [15] also points out issues connected with frontal small overlap collisions in relation to the occupants, specifically by tests from a speed of 64 km/h in various impact configurations with primary action of the force against the wheels, shock absorbers and the B-pillar. It is clear from the content that it causes great damage and penetration of deformations into the cabin. In addition, the impact causes the dummy and the steering wheel to move mutually crosswise, thus reducing the interaction between the frontal airbag and the dummy in most cases. Based on these tests, the Institute for Highway Safety (IIHS) [16] started executing Small Overlap Crash Tests at a speed of 64 km/h with a 25% crosswise overlap of the front part of the vehicle against a solid barrier whose impact corner is rounded with a 150 mm diameter.

NHTSA [17] has developed two moveable deformable barriers for small overlap crashes to allow repeatability of the tests. The work [18] introduces the executed, completely repeatable, tests on these barriers.

The work [19] also sums up the insufficient emphasis car makers place on small overlap crashes, which are very critical due to their consequences for the occupants. Within their work, the authors executed a small overlap crash test of very different cars, following from collected real accidents, and discussed the reconstructions of these collisions.

In certain cases, the given crash configuration causes one vehicle to roll up the other vehicle's tyre and roll over, i.e. a combination of two very serious factors. The work [20]
summarizes issues connected with rollover related to the rotational velocity, the input velocities, deceleration during the rollover, roof deformation, the overall damage, the motion period and the residual space for the driver's head. The data were compared and processed in detail also with a view to repeatable tests executed by the NHTSA on a Subaru car. The analyses also show a comparison of the acceleration peaks and the impact periods.

The rollovers, simulations of initialization and progress of these tests, especially with large SUV cars, have long been studied by a team from the University of Virginia [21], which has developed a rollover initiation test system (RITS), mainly for the simulation of initiating conditions for the rollover and simulation of contact conditions of the body with the road during the rollover. The authors of this work personally visited the workplace in 2012.

Important factors of input parameters for the reconstruction of this type of traffic accident include parameters of the deformation, the restitution coefficient, the amount of deformation energy and the post-impact velocities, i.e. \( \Delta V \), which means the differences in velocities during the impact phase, which can indicate the consequences of the accident for the occupants. Changes in velocities during collisions have been tackled by many works; for example, the authors of this work [22] studied 84 rear collisions with twenty vehicles, or research [23], which warned about a great amount of chest injuries in the case of small overlap frontal crashes. The modelling involved a Hybrid III dummy and concentrated on studying the acting force and velocity change in relation to potential rib injury.

Regarding occupant injury, the mentioned tests are tackled e.g. by this work [24].

The mentioned arguments prompted the authors of this work to concentrate on real small overlap crash tests as well. By virtue of this research, experts will be able to work with input data that clarify the solution of the accident progress as close to the real occurrence as possible when solving a comparable traffic accident.

The goal of the research is thus a detailed analysis of a particular real specific small overlap crash test with regard to the input and control values, the application of thus gathered data and their verification by means of modelling in the Virtual CRASH simulation program.

II. DESCRIPTION OF PERFORMED CRASH TEST

A. Vehicles

The vehicles subjected to the crash test included a Fiat Marea Weekend and Mitsubishi Carisma. The basic parameters are listed in table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fiat Marea Weekend</th>
<th>Mitsubishi Carisma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>1.9 JTD - Diesel</td>
<td>1.8 GDI – Gasoline</td>
</tr>
<tr>
<td>Body style</td>
<td>Combi</td>
<td>Sedan</td>
</tr>
<tr>
<td>Model Year</td>
<td>1999</td>
<td>2001</td>
</tr>
<tr>
<td>Total Weight</td>
<td>1430 kg</td>
<td>1510 kg</td>
</tr>
<tr>
<td>Transmission</td>
<td>Manual/5 gears</td>
<td>Manual/5 gears</td>
</tr>
<tr>
<td>Final Drive</td>
<td>Front Wheel Drive</td>
<td>Front Wheel Drive</td>
</tr>
</tbody>
</table>

B. Type of crash test

A Fiat Marea Weekend, moving at a speed of approx. 43 km/h, frontally crashed with its right side, with an approximately 15% overlap, into a standing Mitsubishi Carisma, see Fig. 1 and 2. Because of the small overlap crash, the Fiat Marea Weekend rolled over as a result of the mutual contact of the cars’ right wheels. The Fiat Marea was driven by a driver on dry tarmac and the rollover was not planned during configuration of the crash test.
C. Measuring equipment for data collection

During the crash test, both cars were fitted with data measuring equipment.

The Fiat Marea Weekend carried a PicDAQ machine made by DSD Linz, Austria. The PicDAQ machine is equipped with a three-axis accelerometer and gyroscope. Signals from the sensors were recorded with a maximum possible frequency of 1 kHz.

The Mitsubishi Carisma carried a complex autonomous C-DAQ USI measuring machine, which was developed at the Institute of Forensic Engineering VUT Brno. The measuring equipment was connected to a three-axis accelerometer and gyroscope whose signal was recorded with a 10 kHz frequency.

D. Vehicle Coordinate Systems

To use the measured data from the crash test, it is necessary to define the vehicles' coordinate system. The acceleration sensors and the yaw rate sensors were thus located in the individual vehicles in agreement with the coordinate system specified by the standard SAE J1733 [10], see Fig. 5.

III. ANALYSIS OF DATA MEASURED IN THE CRASH TEST

A. Data analysis

Data measured in the crash test were further processed to acquire the impact and post-impact parameters of the vehicles. The signal from the accelerometer was filtered by a CFC (Channel Frequency Class) filter, which is designed for application in crash tests pursuant to the Crash Analysis Criteria Description [9]. For filtering of the recording from the accelerometers located in the vehicle, we used a CFC 60 filter pursuant to the standard SAE J211 (Vehicle Instrumentation for Impact Test). We calculated the speed progress over time by integration of the acceleration over time (formula 1). Then we calculated the path progress over time by a second integration of acceleration over time (formula 2). The output signal from the gyroscope, which showed the immediate value of angular velocity, was integrated over time (formula 3) to obtain the progress of the angular velocity over time. Based on Newton's second law (formula 4), we calculated the force in the progress of the impact and used it to calculate the force impulse (formula 5). The overall energy balance during the impact can be calculated by integration of the force over the depth of the deformation (formula 6). The ratio between the amount of elastic and plastic parts of the energy served to calculate the restitution coefficient of the vehicles' impact (formula 7).

\[
\tilde{v}(t) = \int_{\eta_1}^{\eta_2} a(t) \, dt \tag{1}
\]

\[
\tilde{s}(t) = \int_{\eta_1}^{\eta_2} \tilde{a}(t) \, dt \, dt \tag{2}
\]

\[
\varphi(t) = \int_{\eta_1}^{\eta_2} \tilde{\omega}(t) \, dt \tag{3}
\]
\[ \vec{F} = m \cdot \vec{a} \]  
(4)

\[ \vec{I}(t) = \int_{t_1}^{t_2} \vec{F}(t) \, dt \]  
(5)

\[ E(t) = \int_{t_1}^{t_2} \vec{F}(t) \, ds \]  
(6)

\[ e = \sqrt{\frac{E_{DE}}{E_D}} \]  
(7)

Where:  
- \( a_{(t)} \) [m/s^2] Acceleration,  
- \( e \) [-] Coefficient of Restitution,  
- \( E_{(t)} \) [J] Energy,  
- \( E_D \) [J] Deformation energy corresponding to plastic — permanent deformation of the vehicles,  
- \( E_{DE} \) [J] Elastic part of the energy corresponding to elastic deformation of the vehicles,  
- \( F_{(t)} \) [N] Impact force,  
- \( I_{(t)} \) [N.s] Impulse,  
- \( m \) [kg] Weight of the vehicle,  
- \( s_{(t)} \) [m] Distance,  
- \( t \) [s] Time,  
- \( v_{(t)} \) [m/s] Speed,  
- \( \varphi_{(t)} \) [°] Angular distance,  
- \( \omega_{(t)} \) [°/s] Angular velocity.

### B. Presentation of data analysis from Fiat Marea Weekend

Fig. 6 shows a graphic illustration of all the significant parameters of the impact and the post-impact motion of the Fiat Marea Weekend. Fig. 7 shows the progress of acceleration, velocity and path during the impact, which lasted 0.276 s. Fig. 8 shows an illustration of velocity change during the impact from 43 km/h to 16.5 km/h, then the progress of the path and velocity up to the final position of the vehicle, which is located 2.9 s and 9.6 m behind the crash point.

Fig. 9 shows the angular velocity and angular path round the longitudinal axis of the vehicle - Roll and round the vertical axis - Yaw in agreement with the coordinate system shown in Fig. 5. Rotation round the longitudinal axis caused the vehicle to roll over by 180° onto the roof. Rotation round the vertical axis of the vehicle results in initial locking of the vehicles, with a slight clockwise rotation towards the collision and then, approximately in the half-period of the actual collision, to anti-clockwise rotation outwards from the collision.
C. Presentation of data analysis from Mitsubishi Carisma

Fig. 10 shows a graphic illustration of all the significant parameters of the impact and the post-impact motion of the Mitsubishi Carisma. Fig. 11 shows the progress of acceleration, velocity and path during the impact, which lasted 0.276 s. Fig. 12 shows an illustration of the velocity change during the impact from 0 km/h to 24 km/h, then the course of the path and velocity up to the final position of the vehicle, which is located 3.2 s and 9.4 m behind the crash point. Fig. 13 shows the angular velocity and angular path round the vertical axis of the vehicle - Yaw in agreement with the coordinate system shown in Fig. 5. Unlike the previous vehicle, rotation round the longitudinal axis is not significant, because the car did not roll over onto its roof. The vehicle's rotation round the vertical axis results in initial locking of the vehicles, with almost minimum clockwise rotation towards the collision and then, approximately in the half-period of the actual collision, to anti-clockwise rotation outwards from the collision. In the progress of the post-impact motion, the vehicle slightly yaws in a clockwise rotation to the final position.
D. Presentation of the vehicle impact parameters

Fig. 14 shows a graphic illustration of the progress of acceleration, velocity and difference in the covered paths of the individual vehicles during the impact. The difference in the vehicles' paths determines the vehicles' overlap during the impact, or more precisely, the overall depth of the deformation. To make it more illustrative, the sign convention in the Mitsubishi Carisma was reversed against the coordinate system shown in Fig. 5. Fig. 14 documents the boundary between the compression and restitution phases of the impact, which is characterised by the maximum depth of deformation, and equalizing of both vehicles' speeds during the impact (crossing of the cars' velocity courses). In the restitution phase, the vehicles bounce, thus reducing the deformation depth and changing the velocities. Fig. 15 shows an illustration of the impact force progress during the vehicles' impact, with the compression and restitution phase marked. Fig. 16 shows an illustration of the energy balance during the impact with the energy cumulated in the elastic part of the deformation marked, which moves back by the action of restitution, and with the deformation energy marked, which represents the action of the impact force within the path - the depth of plastic (permanent) deformation.

![Figure 14. Acceleration, Speed and total Deformation of both vehicles](image1)

![Figure 15. Force during the impact](image2)

![Figure 16. Energy during the impact](image3)

<table>
<thead>
<tr>
<th>TABLE II. PARAMETERS OF THE IMPACT AND POST-IMPACT MOTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>Start impact (time, speed, distance)</td>
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<tr>
<td></td>
</tr>
<tr>
<td>End of the compression phase (maximal deformation)</td>
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<tr>
<td></td>
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<tr>
<td>Finish impact – end of the restitution phase</td>
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<td></td>
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<tr>
<td>Delta V (between pre and post-impact)</td>
</tr>
<tr>
<td>Final position of the vehicles</td>
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<tr>
<td></td>
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<tr>
<td>Impulse</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
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<tr>
<td>Total deformation energy</td>
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</tbody>
</table>
Table II summarizes all the significant parameters of the impact and post-impact motion of the vehicles to their final positions.

The mentioned impact parameters were evaluated from a real impact test, thus they can be suitably applied as input and control parameters in analyses of comparable traffic accidents within forensic engineering. Considering the fact that it is a relatively complicated type of collision with a strong skid, the following part of the article is dedicated to validation of the collision in the environment of the Virtual CRASH simulation program, version 3, to ensure that the resulting analysis of the impact and post-impact motion of the vehicles in the simulation program corresponds with the experimentally detected impact parameters during the crash test. The overall experimental analysis of the impact test and the subsequent reverse analysis of the accident progress in the simulation program will assist forensic experts in analysing traffic accidents.

IV. MODELLING OF THE IMPACT WITH ASSISTANCE OF A SIMULATION PROGRAM

The experimentally measured data from a real crash test were further used in the modelling of the impact assisted by a simulation program. The impact modelling proceeded in the Virtual CRASH simulation program, which, like other programs applied in reconstructions of traffic accidents, allows modelling of the impact and post-impact motion with gradual optimization of the input data.

The impact modelling proceeds by using the forward method, i.e. from the impact to the final positions. The program uses the so-called impulse-momentum model, which supplies all contact forces acting in the deformed section of the damaged part of the vehicle with a single force resultant, which passes through the so-called impact point.

It thus represents a significant simplification compared with the real situation. Regarding the time action of the force, this is an impulse whose size corresponds to the control value in solving the impact. The size of the impulse is determined by the restitution coefficient and its direction is determined by the impact plane in which a potential skid is realized. In terms of direction, the impulse moves in the area of the so-called friction cone, [27].

The other significant control values include the impact point velocity (the size of the velocity describes whether the impact is with a skid or without a skid), the vehicles' velocity changes during the collision, i.e. $\Delta V$, and the amount of deformation energy. The equivalent energy speeds (EES) of both vehicles are calculated from the deformation energy value, based on the position of the impact point from the contours of both vehicles at the moment of maximum deformation depth in the direction of the impulse.

At least the following parameters should be observed in the modelling:

- The dimensions and weights of the vehicles, the position of the vehicles' centres of gravity against the selected impact point position
- Impact positions of the vehicles and turning

- Impact and post-impact velocities and paths, which the vehicles have reached from the impact to the final position
- Size of the overall deformation energy
- Overall corresponding character of the vehicles' movement

At the start of the modelling, it is necessary to create a system of essential values for the particular studied case. In case of an executed crash test, it is necessary to monitor the position of the impact point, the direction and size of the impulse and the size of the deformation energy in addition to the impact configuration and the known impact velocities. If these basic parameters are in harmony, the basic goal for the reconstruction is satisfied. Modelling assisted by a simulation program allows research to move closer to the executed test. The example of the introduced frontal collision of a moving and standing vehicle with a very small overlap and subsequent rollover is relatively specific and complicated. With a view to the vehicle's rollover caused partly by contact of the tyres, i.e. rolling up, the actual post-impact progress is fundamentally affected by the exactly determined position of the centre of gravity in the longitudinal as well as vertical direction, the turning of the wheels, friction between the body and the surface during the rollover, deceleration during the motion and the used model of tyres. A combination of the mentioned values within a technically acceptable range enables one to find the control parameters to a satisfactory extent.

In this way, it is possible to model the effect of an individual parameter's modification on the overall progress of the impact.

The actual modelling is initiated at the end of the compression phase of the impact, in the maximum overlap depth and width and with the positions and velocities which were detected during a real crash test. The depth of deformation came from measured data and vehicle scans, which were made with the help of 3D scanner after collision.

Figure 17. Start of the modelling at the end of phase of compression, cca 0.19 s post the first contact of vehicles
The impact point is located in the vehicles' overlap area, approximately at the centre of the tyres which came into contact with each other during the given collision.

When modelling the impact based on the measured data, we found a number of suitable combinations of important input values in a practically identical movement of the vehicles to the final positions in this extent:

- Impact impulse between 8000 and 8800 N.s
- Deformation energy between 44000 and 48000 J, in a balanced extent of damage to both vehicles corresponding to EES values of ca 19 to 21 km/h, which corresponds to the documented extent of damage
- The joint post-impact velocities at the end of the compression phase of the impact between ca 20 and 22 km/h
- The coefficient of restitution between 0.15 and 0.2

**CONCLUSION**

The introduced crash test showed the potentialities for the detection of significant values when evaluating the progress and cause of a traffic accident, and verification of their correctness by means of a standardly available simulation program. The simulation software uses many simplifications when verifying the input values, despite its advanced level. It is necessary to consider the input values within a technically acceptable range because they are not exactly known from data based on real traffic accidents. Reconstructive modelling represents an inversion task where it is necessary to detect the impact configurations and initial parameters of the motion from the effects of the traffic accident.

The presented article has also documented the suitability of the applied instruments and their sufficiency in the collection of essential dynamic parameters in the course of a sudden change in speed for this type of researched task, and the suitability of the selected SW for the analysis of a relatively specific traffic accident with a large number of influences affecting the resulting progress.

The accuracy of the vehicles' movement modelling assisted by simulation programs in accident analysts' standard conditions is perfectly sufficient and can achieve good conformity with a view to standard qualitative potentials in acquiring input values from the effects of a real accident.

**ACKNOWLEDGEMENT**

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REFERENCES


