The Accuracy of Crash3 for Calculating Collision Severity in Modern European Cars

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ABSTRACT

CRASH3 is a computer program that enables a vehicle's change of velocity during a crash to be deduced from the observed damage to the vehicle(s) involved. Along with other programs that share similar mathematical techniques, it is widely used internationally, particularly by groups and individuals who have access to damaged vehicles but not the accident scene, and it is applied to a wide range of vehicles and accident circumstances. Crash tests conducted under controlled conditions provide an opportunity to assess the program's accuracy. In this paper CRASH3 is applied to vehicles tested during 1996-98 in the first three phases of the EuroNCAP program. This includes results from 26 models tested in 64 km/h offset frontal impacts and 50 km/h side impacts. On average, velocity changes were underestimated by 1 km/h for the side test and 7 km/h for the frontal test–this includes the effect of a special treatment of deformable barriers not available in the standard program.

INTRODUCTION

Improvements in car occupant protection rely on a close understanding of the events leading to injuries in real-world collisions. In-depth crash research aims to clarify the relationship between vehicle design, the injuries sustained by car occupants, and the injuries that are prevented. This relationship can be presented in the form of a dose-response model[1] [2] with the injuries represented by the response. The dose is frequently a measure of the collision severity, i.e. some measure of the kinetic energy within the system.

Estimates of various collision severity measures provide a fundamental parameter for the assessment of the effectiveness of protection systems and are normally related to crash tests conducted for legal and vehicle design purposes.

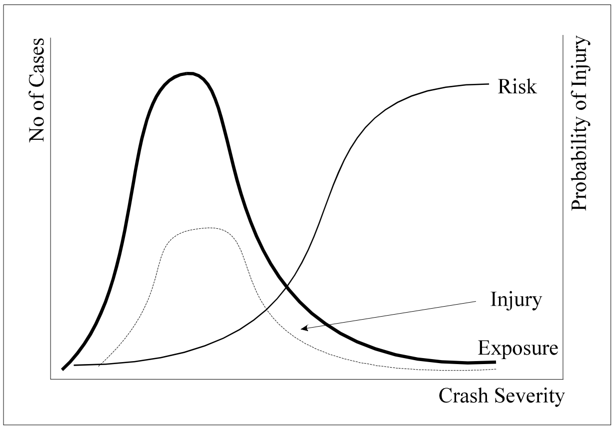

Figure 1. Characteristics of risk, exposure and injury curves.

A sample of real-world crash injury data can be collected either at the scene of the accident or by retrospective vehicle examination, and samples are most efficient statistically when the selection is made using stratified methods; additionally on-scene crash investigations can be highly expensive. Retrospective methods have been chosen by many crash injury data systems including the UK Co-operative Crash Injury Study, the US National Accident Surveillance System, Monash University in Australia and other groups. The main disadvantage of retrospective methods is that the opportunities for estimating collision severity are limited and the only possibilities are based on methods of assessing the energy required to cause the vehicle deformation. The CRASH3[3] programme was developed to provide such estimates using measurements of the vehicle damage, mass and force directions. The software includes a set of generic values of the stiffness of the vehicles that are used to calculate the deformation energy. These stiffness coefficients are based on a set of test collisions conducted in the late 1970s and early 1980s and the accuracy of the programme has been under assessment as vehicle design has progressed.

Smith and Noga[4] compared the predicted and measured results of the change of velocity during impact (delta-V) of 53 vehicles in 27 collisions with a variety of configurations and concluded that the 95% confidence limits lay within ±14% for collisions between 40 km/h and 48 km/h. Within the range 0-48 km/h CRASH3 underestimated the true value typically by 10% for the crashes examined.

The perspective of the crash reconstructionist, who may wish for accuracy in each individual crash, may be different from the safety researcher who deals with groups of crashes on a more statistical basis. Wooley, Warner and Tagg[5] reassessed Smith and Noga's work pointing out that some of the reconstructions could have an error exceeding 20% and therefore the accuracy of 10% could not be substantiated. This perspective was reinforced by Struble[6] who proposed developments in the programme to improve the accuracy in specific crashes.

Strother, Wooley and James[7] examined 402 NHTSA crash tests and concluded that CRASH3 overestimated the deformation energy of vehicles with low levels of crush and underestimated the energy required to cause higher crush levels. They suggested that the use of the generic stiffness coefficients could result in inaccuracies in the reconstruction of individual accidents. Neptune and Flynn[8] extended this view and suggested that the accuracy of the CRASH3 programme could be improved by the use of stiffness coefficients that related more exactly to the parts of the vehicle involved in the crush taking note of relatively stiff and relatively soft spots. Siddall and Day[9] also criticised the use of generic vehicle data that had not been updated since 1984 and proposed a revised set of vehicle parameters including stiffness coefficients.

The accuracy of CRASH3 has to be compared with that of other methods of collision severity assessment. Cliff and Montgomery[10] examined the accuracy of PC-Crash, a reconstruction programme widely used by reconstructionists in Europe. Using full scene and vehicle information to calculate pre- and post-impact velocities of 46 vehicles in 20 crash tests they estimated the pre-impact speeds and identified that PC-Crash typically underestimated the collision severity by 6%.

Alternative systems for the measurement of delta-V do exist. Kullgren[11] has developed a crash pulse recorder which employs photographic technology to record the acceleration of the vehicle over the crash phase.
Integration of this data has been shown to provide a delta-V estimate with an error below 5%. Norin, Koch and Magnusson[12] have developed an equivalent system using the airbag module but no information has been published on its accuracy.

All of the assessments of the accuracy of CRASH3 have been conducted using vehicles within the US fleet. While some European vehicles may be included it is possible that the construction is different on account of the different legal requirements of the territories. Many European vehicles are not sold in the US and it is unlikely that they will have been considered in any US based assessment. The major driving factor in the performance of the vehicle structures for US vehicles are the requirements of FMVSS 208 and US NCAP. These are not requirements in Europe and vehicles may be designed with different criteria in mind. Since 1990, European consumer magazines[13 14] have been regularly publishing the results of crash tests into a rigid barrier with only partial engagement of vehicle front. More recently the European Union has implemented a new Directive on frontal impact performance with effect from October 1998; this includes a collision into a deformable barrier at 56 km/h. Since 1997 the EuroNCAP consortium has been publishing crash tests into the same deformable barrier but at 64 km/h. At the same time the EU has also implemented a Directive requiring improved side impact protection. The performance of vehicles on European roads has perceptibly changed as a result, with the stiffness of the passenger compartment and the front end design adapted to the new tests. Consequently newer vehicles perform significantly differently from older vehicles. There is the implication that the stiffness coefficients within CRASH3 may no longer reflect the performance of European car design. This paper uses the available crash test data from EuroNCAP to evaluate the accuracy of CRASH3 with modern European vehicles.

METHOD AND TECHNICAL PREAMBLE

The Meaning Of Delta-V

A number of speed-related measures of impact severity have been introduced into the field of accident investigation over the years, including delta-V (ΔV), energy equivalent speed (EES), equivalent test speed (ETS), equivalent barrier speed (EBS), and barrier equivalent velocity (BEV). Unfortunately the literature betrays a lack of common understanding of these terms and it is therefore necessary to take care with their use. In this paper, only delta-V is discussed, and its meaning is drawn from the conventions of standard physics. Delta-V is a *vector*; in other words it is a quantity with magnitude (e.g. 50 km/h) and direction (e.g. northwards). More specifically, it is the *vector difference* between an initial velocity and a final velocity, as indicated in figure 2.

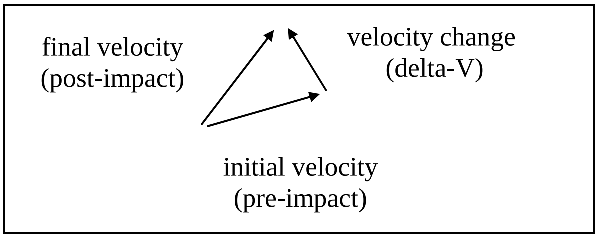

Figure 2. Meaning of Delta-V (ΔV)

The initial and final velocities are the *instantaneous velocities* of the centre of mass of the crash-tested vehicle immediately before and after impact with the deformable barrier. A definition of *instantaneous velocity* may be found in any physics textbook: the intuitive notion of travelling a certain speed in a certain direction at a certain time, e.g. 50 km/h northwards, is apropos. The beginning of impact is when contact is first made. The end of impact may be slightly vague, but when the vehicle separates from the barrier, or when the force on the vehicle from a side impact trolley is similar in magnitude to the frictional forces on the vehicle from the floor, the impact is over. In this sense, the impact is over before a side impact trolley and crash-tested vehicle come to rest.

The direction of delta-V is often not stated, especially when it may be implicitly understood. In the frontal EuroNCAP test, the moving vehicle is essentially brought to rest (possibly with some rebound and sideways deflection) by the immovable barrier, and so delta-V is "negative", i.e. directed opposite to the vehicle's original line of travel. In the side test a moving trolley pushes the stationary vehicle laterally, and so the vehicle's delta-V is directed along the trolley's line of travel. Throughout this paper, the focus on the magnitude of delta-V rather than its direction–this should not be interpreted as a departure from the vector nature of delta-V.

Test Delta-V and CRASH3 Delta-V

Test delta-V. The change of velocity, delta-V (ΔV), is the difference between a vehicle's immediate pre-impact and post-impact velocities. Ideally these would be directly measured during the test. No measurements of post-impact velocity were available for this paper. In the absence of better information, the frontal impact vehicles were assumed to be brought to rest by the barrier impact. This is accurate if any post-impact rebound or "glance-off" speed is negligible compared to the initial speed of 64 km/h. If the vehicles rebound, their true delta-V is higher; if they glance off (forwards) their delta-V is lower. It may readily be seen that our best assessment of a vehicle's true change of velocity in the frontal impact test is closely related to the pre-impact or test velocity: equal in magnitude, opposite in direction. Apart from this coincidence, the pre-impact velocity has no intrinsic importance for the evaluation of CRASH3. The damage-based algorithms of CRASH3 and similar programs are directed towards the estimation of delta-V, not the pre-impact or post-impact velocity.

The side impact vehicles are accelerated sideways by the trolleys. In the absence of direct measurements, an estimate of the velocity they attain may be obtained from the principle of *conservation of momentum*: the combined mass of the trolley and car multiplied by their (shared) velocity after impact equals the mass of the trolley multiplied by its initial velocity:

$$(m_{car} + m_{trolley}).v_{final} = m_{trolley}.v_{trolley}$$

The car is initially stationary, so:

$$\Delta V_{car} = v_{final}$$

This is accurate if the separation speed, if any, of the trolley and car after impact is negligible. If the car rebounds, its delta-V is higher. The value of delta-V obtained this way is referred to here as the *test* delta-V. For the purpose of evaluating the damage-based algorithm of CRASH3, it may be regarded as the true value of delta-V. Even if it is not exactly right, it is considerably more reliable and accurate than one can hope to achieve from vehicle damage. To illustrate, the test delta-V for a vehicle of mass 1100Kg in a EuroNCAP side impact test would be:

$$m_{car.}v_{car} + m_{trolley}.v_{trolley}= (m_{car} + m_{trolley}).v_{final}$$

$$0 + 950.50= (1100 + 950).\ v_{final}$$

$$v_{final} = 23.1 \text{ km/h}$$

The car is initially at rest, so:

$$\Delta V_{car} = v_{final}$$

$$\Delta V_{car} = 23.1 \text{ km/h}$$

CRASH3 delta-V. CRASH3, like other similar programs, is designed to estimate a crashed vehicle's change of velocity during impact. It suffices to gauge the program by its success in accomplishing this goal. In this paper the term *CRASH3 delta-V* refers to nothing else but the estimate of a crashed vehicle's delta-V obtained using the damage-based algorithm of the program.

The Estimation Of Delta-V From Vehicle Damage

It is not the purpose of this paper to conduct a general review of the theory and practice of estimating delta-V from vehicle damage; however the wide range of opinions from critics and proponents of CRASH3 and similar programs warrants a few remarks. The program enables delta-V to be calculated from vehicle damage and other data not pertaining to the scene of the accident. It is essential to distinguish (a) the scientific or physical *principles* of CRASH3, (b) the *scope* of CRASH3–the range of crashes to which it may be applied–and (c) and the *accuracy* of CRASH3.

The basic principles upon which CRASH3 is founded are sound: mathematically, scientifically, technically, and to whatever other high standard one would wish to nominate. The principles may be found in elementary physics books covering Newtonian mechanics. If the 'inputs' are known for all vehicles or objects involved in the collision, it is possible to obtain a calculation of delta-V, properly defined as the vector difference between the vehicle's immediate pre-impact and post-impact velocities. The program must have some means of assessing the total energy dissipated in the collision–for this it uses crush profile–and it must be given the direction of impact force, among other things. The program does not require any specification of the pre-impact or post-impact velocities, either in direction or magnitude.

There are limitations to the scope of CRASH3, and the program has been misused by both its proponents and detractors. Two requirements are (a) that the vehicle damage provides a suitable basis for assessing the energy dissipated and (b) that the contacting surface of the vehicle reaches a common velocity with the surface of the object struck. Under-runs, sideswipes, and highly offset or highly oblique impacts, among others, may violate these conditions. If so, the program should not be run at all. It is no criticism of the program to point out that it delivers inaccurate results for crashes to which it is inapplicable. Except for not containing a model of the deformable barriers, the program is applicable to the EuroNCAP test configurations.

The accuracy of CRASH3 is the accuracy of its estimates of delta-V, i.e. the closeness of the calculated velocity change to the vehicles' true change of velocity (in practice, not usually known). The program's accuracy is highly influenced by its 'built-in' model of the relationship between vehicle damage (crush profile) and energy dissipated. Much of the point of checking the accuracy of the program against crash-tested vehicles is to assess whether modifications need to be made to this relationship. The results described in this paper bear upon the accuracy of CRASH3 and in particular upon the accuracy of the deformation-energy relationship. Such investigations have been reported before, but changes in vehicle fleets over time and in different places demand a continuing effort. It would be laudable if all methods of estimating delta-V were subjected to the same rigours.

Energy Dissipated By Deformable Barrier

When programs such as CRASH3 are used to calculate delta-V for any given vehicle, the energy dissipated or absorbed by *all* vehicles or objects involved in the collision must be taken into account. For the EuroNCAP tests, this means the energy dissipated by the deformable barriers must be included in the calculation of delta-V. The standard version of CRASH3 has no capacity to model the EuroNCAP deformable barriers. This was done separately and the result, energy dissipated, was entered to a modified version of the program. The method used was to take crush profiles of the barrier blocks still available from the crash tests, and integrate (pseudo-static) force-deflection curves to obtain estimates of the energy dissipated by the barriers. This technique is very similar to the method used within the program to deduce the energy dissipated by the vehicles. Where the blocks were no longer available, an average value was used as the best estimate.

<table>
<tr><th colspan="7">EuroNCAP Deformable Barrier Elements</th></tr>
<tr><th colspan="2"></th><th>Height (m)</th><th>Width (m)</th><th>Depth (m)</th><th colspan="2">Crush strength (kN/m^2)</th></tr>
<tr><td>Front:</td><td>main block</td><td>0.65</td><td>1.00</td><td>0.45</td><td colspan="2">342</td></tr>
<tr><td>Front:</td><td>bumper element</td><td>0.33</td><td>1.00</td><td>0.09</td><td colspan="2">1711</td></tr>
<tr><td colspan="7"></td></tr>
<tr><th colspan="2"></th><th></th><th></th><th></th><th colspan="2">Stiffness coefficients*</th></tr>
<tr><th colspan="2"></th><th>Height (m)</th><th>Width (m)</th><th>Depth (m)</th><th>a (kN)</th><th>b (kN/m)</th></tr>
<tr><td>Side:</td><td>lower (centre)</td><td>0.25</td><td>0.50</td><td>0.50</td><td>0</td><td>380</td></tr>
<tr><td>Side:</td><td>lower (outer)</td><td>0.25</td><td>0.50</td><td>0.50</td><td>3</td><td>160</td></tr>
<tr><td>Side:</td><td>upper (centre)</td><td>0.25</td><td>0.50</td><td>0.44</td><td>0</td><td>81</td></tr>
<tr><td>Side:</td><td>upper (outer)</td><td>0.25</td><td>0.50</td><td>0.44</td><td>0</td><td>69</td></tr>
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Figure 3. EuroNCAP barrier properties. **Valid to crush of 0.30 m; for the lower (centre) block, 0.16 m.*

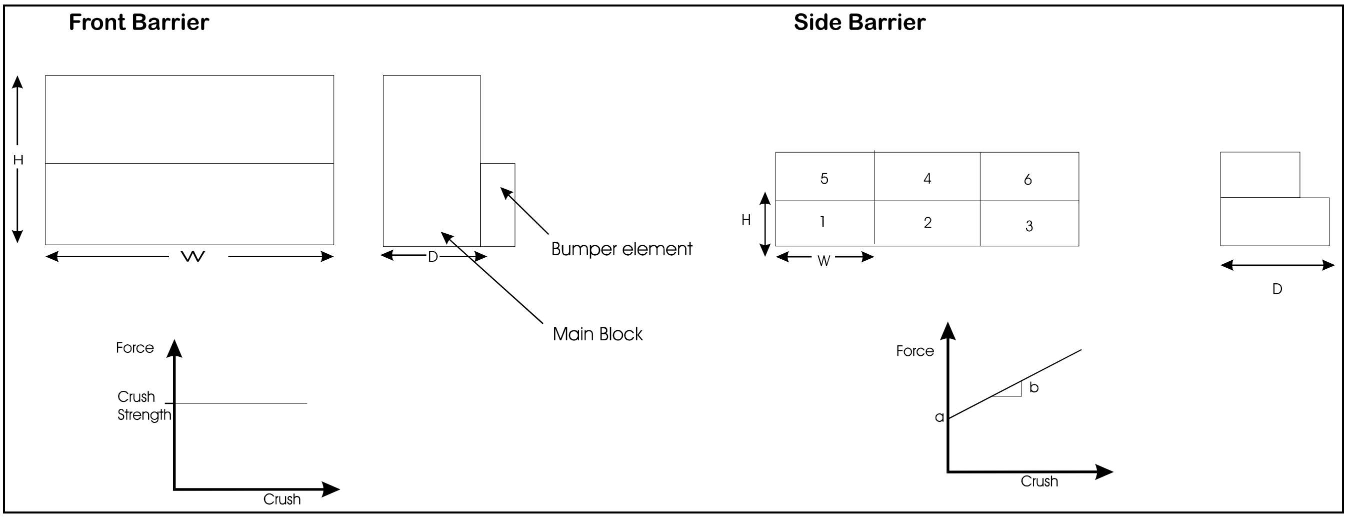


Figure 4. Schematic views of front and side impact blocks with schematic force-deflection curves

The properties of the deformable barrier elements used for estimating the energy dissipated by the barriers are shown in figure 3. These express pseudo-static force-deflection characteristics.

The constant crush strength characteristic of the two frontal barrier components are represented by the flat curve of figure 4. For these components, only the volume of crush is required for an estimation of energy dissipated (E):

$$E_{barrier} = (\text{crush strength}) \cdot (\text{volume of crush})$$

The volume of crush was determined by taking crush measurements at a number of points over the surface of the deformed barrier elements.

The force-deflection curves of the side impact barrier blocks have a linear slope, and more complicated equations are needed to ascertain the energy dissipated. (These are the same as CRASH3 applies to the vehicles.) Energy is represented by the area under the force-deflection curve. The energy dissipated between two points with crush C_1 and C_2 is given by:

$$E = (a\,(C_1+C_2)/2 + b\,(C_1^2 + C_1C_2 + C_2^2)/6)\,d$$

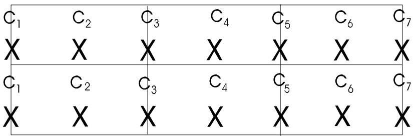
where d is the distance between the measures and the stiffness coefficients a and b are scaled to a 'per unit length' value. Further details of the method are available in the literature. Three-point crush profiles of each of the six side barrier components were measured and used to obtain an estimate of the energy dissipated by the side impact barriers.

Volume of crush of Main Block = 40%, Energy dissipated by Main Block (E_M) = 40kJ

Volume of crush of Bumper Elements = 5%, Energy dissipated by Bumper Elements (E_B) = 2.5kJ

Total Energy dissipated by Frontal impact barrier = $E_M + E_B$ = 42.5 kJ

Figure 5. Frontal impact EuroNCAP vehicle and corresponding barrier with sample barrier energy calculation



	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Upper Blocks	0.28	0.18	0.13	0.17	0.16	0.14	0.22
Lower Blocks	0.24	0.15	0.11	0.13	0.15	0.23	0.25

Crush to Energy relationship: $E = (a\,(C_1+C_2)/2 + b\,(C_1^2 + C_1C_2 + C_2^2)/6)\,d$

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Total Barrier
Energy (kJ)	1.6+0.7 = 2.3	1.1+1.4 = 2.5	0.8+1.5 = 2.3	0.4+0.5 = 0.9	0.9+0.4 = 1.3	0.4+0.6 = 1.0	10.3

Figure 6. Side impact EuroNCAP vehicle and corresponding barrier with sample barrier energy calculation.

RESULTS

The EuroNCAP frontal test specifies a 40% offset impact into an immovable deformable barrier, with a vehicle impact speed of 64 km/h. In the side impact test, a 950 kg trolley fitted with a deformable front block moves parallel to the lateral axis of the car and strikes the passenger compartment with a speed of 50 km/h.

Table 1. Energy absorbed by vehicles and barriers

	Vehicle (kJ)		Barrier (kJ)	
NCAP	Average	Range	Average	Range
Front	116	55-176	45	37-56
Side	33	18-51	13	6-18

Table 1 shows the calculations of the energy dissipated by the vehicles and deformable barriers. In both tests the barriers absorb about 30% of the total impact energy.

Figure 7 shows CRASH3's estimate of velocity change against the 'true' test value. Points above the diagonal line are overestimates of delta-V while points below the line are underestimates. The higher cluster of points are results from frontal impact testing and the lower cluster of points are from side tests. The average of the frontal test estimates is 7 km/h low with a scatter of ±10 km/h. The centre of the side test estimates is 1 km/h low with a scatter of ±5 km/h.

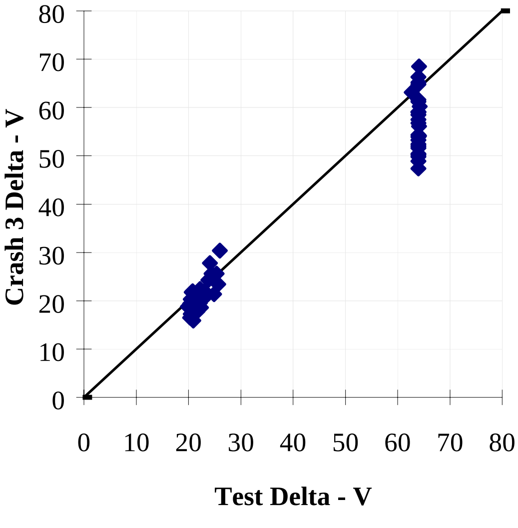


Figure 7. True velocity change vs Crash3 estimate

DISCUSSION

The side impact results are as accurate as one could realistically hope to achieve, and call for no remedial action. The main question here is whether additional side impact calculations at other speeds and with other objects will also work out well.

The underestimation of delta-V for the frontal vehicles indicates that there is more energy around than CRASH3 'realises'. To be more precise, the program underestimates the total amount of energy dissipated by the crashed vehicle and deformable barrier. Part of the discrepancy may lie in the estimation of barrier energy, which was calculated independently of CRASH3 and entered into a modified version of the program. It would be helpful to have the dynamic force-deflection or crush-energy characteristics of the deformable barrier elements determined directly by impact tests. Even without this, there are techniques used in branches of engineering that may assist in extrapolating from pseudo-static tests to dynamic performance. Some of the barrier elements crushed in a manner most unlike their pseudo-static response, with tearing, gouging, and swaying–for these cases any analytic method is subject to a considerable degree of uncertainty.

The shortfall in estimated energy could of course also arise from the relationship between vehicle damage and energy implicit in the program. This relationship is currently expressed by stiffness coefficients, as described above, although if better correlations could be found, CRASH3 could be modified to adopt them. Underestimating delta-V implies that one or both of the stiffness coefficients used by CRASH3 is too low. The coefficient *a* referred to in figure 4 expresses the degree of elastic rebound of the vehicle's front end (the difference between maximum dynamic crush and post-impact residual crush) and the coefficient *b* expresses the vehicle's increasing resistance to deformation; so the vehicles with delta-V calculated too low are either more elastic or stiffer than CRASH3 assumes.

The stiffness values of the vehicles tested could be adjusted–either individually or as a group–to align the CRASH3 estimate of delta-V with the test value. Calibrating CRASH3 in this way would improve the assessment of energy dissipation for crashed vehicles that resemble EuroNCAP frontal impact vehicles, with correspondingly favourable implications for the program's estimation of velocity change. Work is continuing, however, to check the accuracy of CRASH3 against a considerably wider variety of crash tests; and a better basis for modifying the front (and other) stiffness coefficients of modern European cars should exist in the relatively near future.

Even without introducing custom stiffness coefficients, the results obtained in this paper may still be used to interpret data from CRASH3 and similar programs. It is likely that the energy calculated for vehicles from real crashes that resemble the EuroNCAP vehicles in damage is systematically underestimated by the equivalent of about 7 km/h for frontal impacts, but fairly accurate for side impacts. This applies to modern European vehicles. The likely scatter of CRASH3's estimation of delta-V under these circumstances is about ±10 km/h for the frontal impact and ±5 km/h for the side impact. As more crash test results are incorporated into the continuing work being carried out for the UK Co-operative Crash Injury Study, it will be possible to comment on a wider range of impact types.

The crush profiles of the damaged vehicles tested under EuroNCAP were collected by a number of investigators, working under time pressure and circumstances comparable to those in the field. The scatter of CRASH3 results is therefore representative of data collected under normal working conditions rather than the best that could conceivably be achieved from inspecting vehicles under 'laboratory conditions'.

CONCLUSION

Under conditions of a 40% offset, 64 km/h frontal impact into a immovable deformable barrier, the accident reconstruction program CRASH3 underestimates the change of velocity for modern European vehicles by about 7 km/h with a scatter of ±10 km/h. For a side impact from a 950 kg movable deformable barrier at 50 km/h, the CRASH3 estimate is about 1 km/h low with a scatter of ±5 km/h. This includes the effect of providing the program with an estimate of the energy dissipated by EuroNCAP deformable barriers, which is not within its normal capability. Further work progressing for the UK Co-operative Crash Injury Study will broaden the scope of these conclusions to a wider diversity of crash test types.

ACKNOWLEDGEMENTS

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