The accuracy of vehicle damage based protocols to quantify impact severity

R. E. Cookson, D. C. Richards and R. W. Cuerden*

*TRL, Crowthorne House, Nine Mile Ride, Wokingham, Berkshire. RG40 3GA. RPN117

Abstract - Impact severity is a fundamental measure for all in-depth crash investigation projects. One methodology used in the UK is based on the US Calspan software package CRASH3. The UK's in-depth crash investigation studies routinely use AiDamage3 [1], a software package which is based on an updated version of the original CRASH3 algorithm, including enhancements to the vehicle stiffness coefficients. Real world accident-damaged vehicles are measured and their crush is correlated with a library of stiffness coefficients. These measurements are then used, along with other parameters, to calculate the crash energy and equivalent changes of velocity of the vehicles (delta-v), which is a measure of the impact severity. UK in-depth accident studies routinely validate the crash severity methodologies applied [2] as the vehicle fleet changes. This is achieved by analysing crash test data and using the appropriate residual crush damage and other inputs to AiDamage3 and checking the program's outputs with the known crash severity parameters. This procedure checks, at least in part, the default stiffness values in the data libraries and the reconstruction methods used.

INTRODUCTION

Impact severity is a fundamental measure for all in-depth crash investigation projects. One methodology used in the UK is based on the US Calspan software package CRASH3. The UK's in-depth crash investigation studies routinely use AiDamage3 [3], a software package which is based on an updated version of the original CRASH3 algorithm, including enhancements to the vehicle stiffness coefficients. Real world accident-damaged vehicles are measured and their crush is correlated with a library of stiffness coefficients. These measurements are then used, along with other parameters, to calculate the crash energy and equivalent changes of velocity of the vehicles (delta-v), which is a measure of the impact severity.

In the UK the principal in-depth accident studies which use AiDamage3 as one of their crash severity assessment tools are the Co-operative Crash Injury Study (CCIS) and the On-The-Spot (OTS) study.

CCIS is an ongoing project which has collected in-depth real world crash data since 1983. Vehicle examinations are undertaken at recovery garages several days after the collision. Car occupant injury information is collected and questionnaires are sent to survivors. Accidents are investigated according to a stratified sampling procedure, which favours cars containing fatal or seriously injured occupants as defined by the British Government definitions of fatal, serious and slight. It also favours newer vehicles. More information about the study is available at www.ukccis.org.

OTS crash investigations have been carried out in the UK since 2000. The UK Government funds two teams whom routinely attend the scene of road crashes within 15 minutes of incidents occurring. This ambitious work is undertaken to allow research to be conducted to investigate the causes of crashes, their subsequent injuries and the associated societal costs. The study selects crashes of all severities and involving all road user and vehicle types. It is recognised that only through a detailed knowledge of these complex causal factors will effective countermeasures be developed and ultimately successfully applied to improve road transport safety. Scene evidence is the primary source of data for crash severity assessment for OTS cases, but damage based assessments provide additional and complimentary information for some crashes. More information about the study is available at www.ukots.org.

The description of vehicle properties built into AiDamage is based on US crash tests from the 1990s and there have been no fundamental changes to the properties in the intervening period. As a result, the procedures and protocols used to estimate impact severity using these CRASH3-based stiffness values are now about 15 years old. However, since the introduction of the European frontal impact directive and EuroNCAP in the last 10 years, it is believed that vehicle structures have become stiffer. If vehicles have become significantly stiffer there is a danger that current crash investigations are underestimating the actual change of velocity that occurred. The work described in this paper outlines the ongoing research programme's methodology, which aims to assess the current accuracy of the UK's residual damage based crash severity assessments and highlight how enhancements to current protocols will be made if necessary.

Crash tests under controlled conditions provide an opportunity to compare AiDamage3 calculations of delta-v with known values. Unlike road accidents, the change of velocity of a crash-tested vehicle during impact is either recorded or can be closely estimated from its pre-impact velocity and the relative mass of the object struck. This provides a reliable, independent assessment of velocity change. By measuring crash-tested vehicles and processing them as if they were regular car crash cases, AiDamage3 estimates of velocity change can be obtained that should be representative of the results of accident studies. In practice, the accuracy of the program depends not only on its internal mathematical model, but on many other factors, including the quality of data provided to it, the use and interpretation of its results, the design of the program's user interface and, most importantly, the default values for vehicle stiffness used in the program. With respect to the quality of data provided, CCIS and OTS have standardised protocols for measuring and recording the damage and identifying the direction of force.

METHODOLOGY

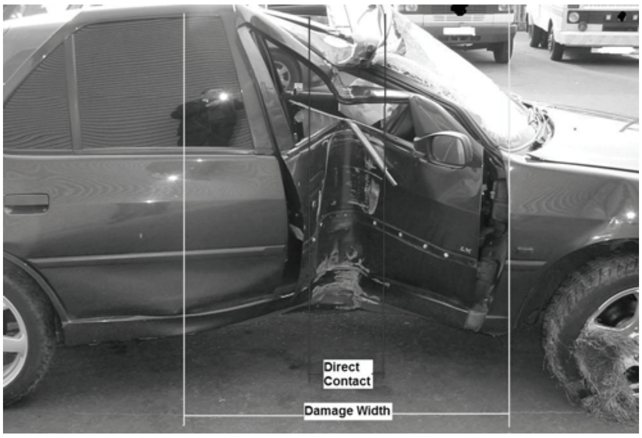
Measurements

Two crash tested vehicles were measured and then processed in the same way as those in general accident studies, in order to produce estimates of the changes in velocity, which could then be compared to the speeds used in the tests. The program used to calculate the severity of the crashes for this paper was AiDamage3, which requires both the crush profile and the mass of the vehicle at the time of impact to be entered.

In order to assess the severity of the accident, a variety of measurements are taken of the impact damage suffered by the vehicles involved. The two elements of measuring this are the damage width and the crush profile. The CCIS protocols for collecting this information are outlined below.

Damage Width

Once the location of the most significant damage is identified the damage width must be measured. This is taken along the area of the vehicle which has suffered both direct and indirect damage. Direct contact damage is the area of the damage which was directly caused by contact with the impacting object. Indirect contact damage is the damage due to transmitted forces which have pulled the body shell inwards. This measurement should be taken along the surface of the damaged vehicle. The measurement should reflect the original width of the damaged area before the impact. The damage width is measured by wrapping a tape measure along the surface of the damaged area, at the height of the stiff structure.



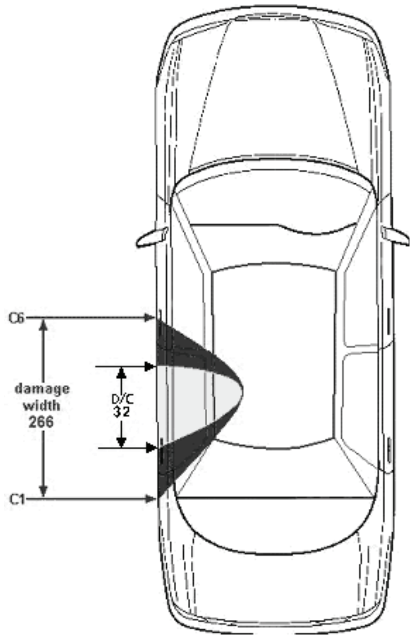


Figure 1. Photograph and diagram to demonstrate direct and indirect damage in a side impact

Figure 1 shows a photograph of a case in which the vehicle collided with a lamp post. The direct contact width was 32cm with the total damage width being 266cm.

Crush Profile

In order to measure the crush profile of the front of a vehicle, a datum line at the back of the vehicle must be set. This is set from the undamaged end of the vehicle to either the undamaged length of the vehicle or a known length. For a side impact, the datum line is set either as a line between two undamaged sections of the vehicle or from the undamaged side of the car to either the undamaged width of the car or a known length.

The crush profile is measured by measuring back from the front datum line to the car at a minimum of three equally spaced points, though it is more usual to take six measurements. These measurements are referred to as C1, C2, C3, C4, C5 and C6, where C1 is always on the nearside for a frontal or rear impact and at the rear in a side impact and C6 (or the last measure) is always on the offside for a front or rear impact and at the front for a side impact. This method is illustrated in Figure 2.

The crush measurements should be taken at points an equal distance apart along the crush profile (not necessarily equidistant along the datum line) at the height of the stiff structure.

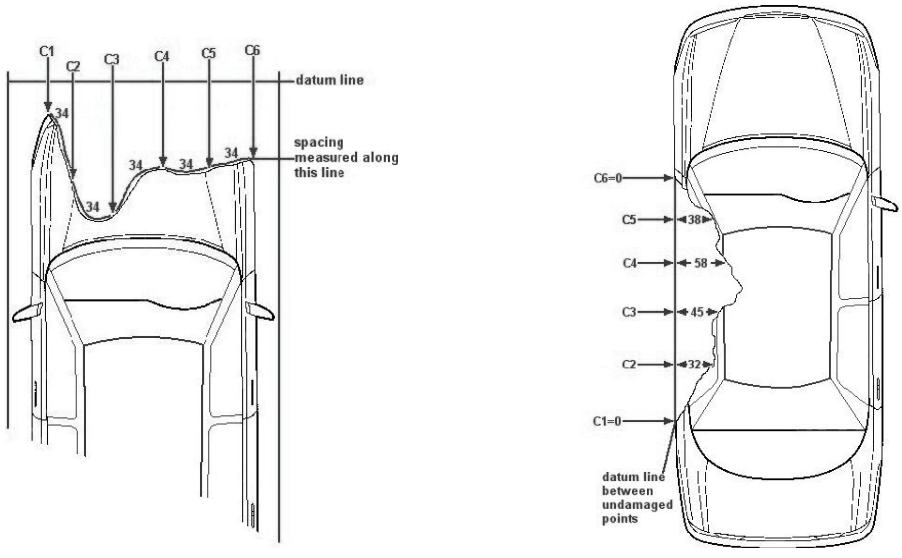


Figure 2. Equally distanced measurements to be taken along the crush profile

The damage width should be assessed so as to avoid consecutive measures of zero in the crush profile as demonstrated in Figure 3. The figure on the left shows measurements with consecutive zeros, whereas the figure on the right, the correct method, includes only measurements across the damaged area with just one measurement of zero at the start of the damage.

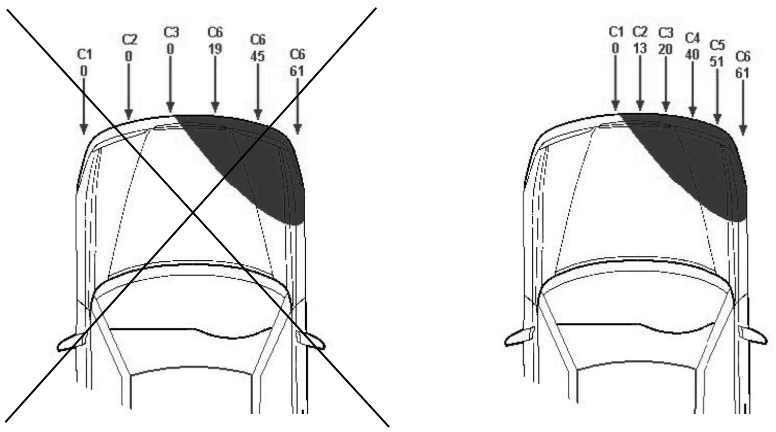


Figure 3. Distribution of measurements across the vehicle

The midpoint offset is also required. It is defined as the distance from the midpoint of the damage profile to the centre of the vehicle. A point is taken half way between the C3 and C4 crush measurements. A measurement of the distance along the crush profile to the original centre line of the vehicle is then taken as the midpoint offset.

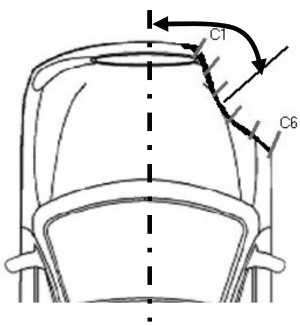


Figure 4. Midpoint offset measurement

If the crush profile incorporates the entire front of the vehicle, then the midpoint offset is zero. The midpoint offset must also be determined as positive or negative as shown in Figure 5.

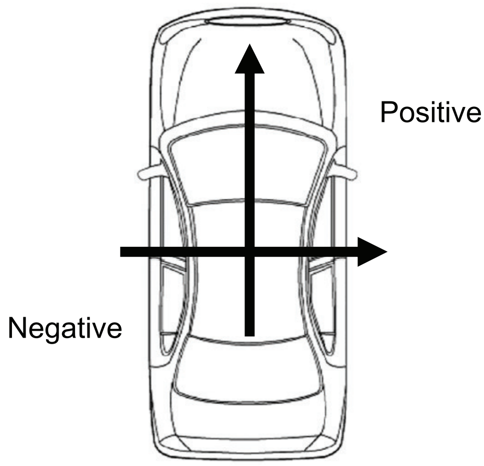


Figure 5. The sign of midpoint offset

If the midpoint offset is towards the rear or nearside of the vehicle then the value is negative. If the midpoint offset is towards the front or offside of the vehicle then the value is positive.

Once all these values have been determined, they can be entered into the AiDamage3 software, along with the mass of the car, in order to obtain values for the energy of the impact, closing speed, and other speed-related measures of impact severity.

Calculation of delta-v

Since the 1950s, a number of papers have been produced on the various aspects of the relationship between the damage caused in an accident and the vehicle's speed. A number of speed-related measures of impact severity have been introduced into the field of accident investigation, including energy equivalent speed (EES), equivalent test speed (ETS), equivalent barrier speed (EBS) and barrier equivalent velocity (BEV). This paper focuses on one of the measures which is used most frequently for analysis: delta-v. Ventre and Provensal (1973) [1] initiated the concept of delta-v as a measure of damage severity, and this is the method used by AiDamage3 to describe accident severity.

Delta-v is the difference in the velocity vector of the centre of gravity of a vehicle between first contact with the impacting object and separation. It has a number of advantages for the type of collision usually discussed in accident investigation. It is determined by the relative velocities of the vehicles at impact and by the relative masses of the two vehicles. It is important to note that, although delta-v is independent of the relative stiffnesses of the vehicles, the damage caused to each vehicle will be related to their stiffnesses.

Crash Tests

This paper is based on two crash tests that have been reconstructed using AiDamage3.

Test 1
The first of these crash tests, between a Renault Clio and an Opel Vectra, was carried out for the CHILD project [4]. The front of the Clio collided with the side of the Vectra. The Vectra was stationary and the Clio was travelling at 80kph, making the closing speed for this collision 80kph. The delta-v of the vehicles was 34kph for the Vectra and 46kph for the Clio.

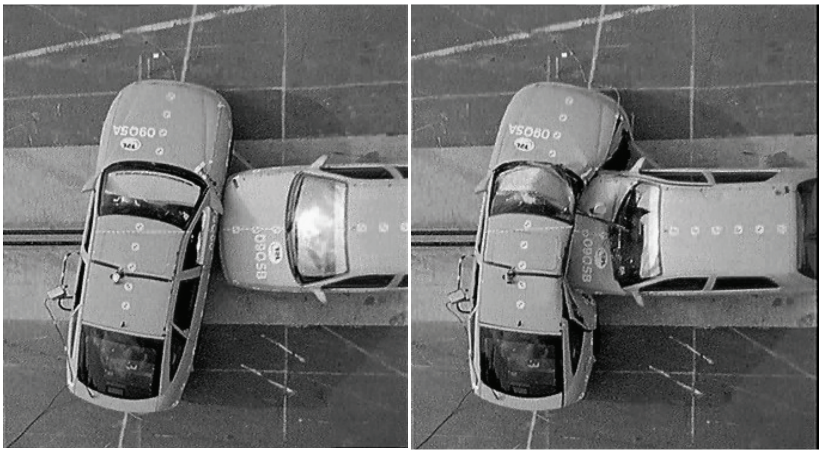


Figure 6. Clio impacting the side of the Vectra

Test 2

The second crash test was between a Vauxhall Combo van and the rear axle of an HGV. Here, the impact speed of the van was 48kph.

Figure 7. The damage to the Vauxhall Combo Van

AiDamage3 Calculations

In order to calculate the energy required to deform each of the vehicles in a car-to-car crash, it is assumed that the crush force per unit width has the form shown in equation 1 [5]. A constant is added in order to account for the maximum possible force that can be applied which results in no residual crush (A):

$$F/w = BC + A \qquad [1]$$

where F is the force required to compress a spring by a certain distance (C), B is the stiffness of the spring and w is the damage width.

The energy is then determined by integrating equation 1 over the damage width, which results in the final energy equation used in CRASH3, and therefore in AiDamage3, as follows:

$$E = w\left(\frac{BC^2}{2} + AC + \frac{A^2}{2B}\right) \quad [2]$$

where A and B are stiffness coefficients specified in the program, w is the damage width and C is the crush depth.

From the energy absorbed and the masses of the vehicles, the value of delta-v for the vehicle is calculated using the following equation: [3]

$$\Delta v = \sqrt{\frac{2m_2(E_1 + E_2)}{m_1(m_1 + m_2)}} \quad [3]$$

where m_1 is the mass of the first vehicle, m_2 is the mass of the second vehicle, E_1 is the energy absorbed by the first vehicle and E_2 is the energy absorbed by the second vehicle.

From research in the 1990s, AiDamage3 was updated, to use the following default stiffness values (A and B) for its calculations (these are from the vehicle library newdata.lib) [6]:

Table 1. Default values used by AiDamage3

Value	**Class 1**	**2**	**3**	**4**	**5**	**Barrier**
Mass (kg)	945	1119	1332	1669	1756	10^7
Wheelbase (cm)	205-241	241-258	258-280	280-298	298+	100
Length (cm)	403	443	484	522	551	100
Width (cm)	165	172	177	188	189	100
Track (cm)	140	144	149	152	152	100
Overhang (cm)	83	88	105	102	105	0
CoG to front (cm)	180	180	206	222	230	50
Front						
A (N/cm)	316	324	362	377	506	-
B (N/cm^2)	49.7	45.1	48.3	46.0	78.2	-
Side						
A (N/cm)	155	175	170	240	240	-
B (N/cm^2)	41.2	45.7	53.6	65.5	65.5	-

However, the CCIS study has been running since the 1980s and, to preserve compatibility with earlier results, it was decided that CCIS would avoid making a step change in the calculation methodology, and would continue to use the original default values. This decision was supported by a validation exercise undertaken by Lenard et al.[2]. This study found good correlation between real crash test delta-v values and the associated calculated results derived from the CRASH3 default values highlighted in Table 2.

Table 2. Previous default values used by AiDamage3

Value	Class 1	2	3	4	5	Barrier
Default Mass (kg)	1000	1380	1600	1926	220	10^7
Wheelbase (cm)	205-241	241-258	258-280	280-298	298+	100
Length (cm)	406	444	498	541	568	100
Width (cm)	154	170	184	196	203	100
Track (cm)	130	139	150	157	162	100
Overhang (cm)	78	94	98	112	112	0
CoG to front (cm)	193	212	228	251	259	50
Front						
A (N/cm)	528.2	454.4	556	623.5	569.7	-
B (N/cm^2)	32.4	29.8	38.6	23.3	25.5	-
Side						
A (N/cm)	135.2	246	303.6	250.5	309.2	-
B (N/cm^2)	25.5	46	39.4	34.8	32.5	-

In order to replicate the method by which the program is used in general accident studies, the class of each vehicle was selected based upon its wheelbase. The actual masses of the vehicles were input into the program, but apart from this the program used the default values appropriate to that class. The masses of the vehicles were taken as the kerb mass plus the masses of any dummies and equipment that would have been in place for that test.

RESULTS AND DISCUSSION

Clio/Vectra impact

The damage to the vehicles was measured as it would be for a CCIS case and reconstructed using the AiDamage3 software. The Vectra was reconstructed as a vehicle in stiffness category 3 and the Clio was stiffness 9 as it was a front wheel drive car in a frontal impact. The A and B values for the Vectra and Clio were 303.6, 39.4 and 653, 26.2 respectively, these being the default values used by current UK in-depth accident investigation studies.

The AiDamge3 result was a closing speed of 83kph, which is slightly higher than the actual value, but this difference is minimal. The delta-v for the Vectra was calculated to be 35kph and 48kph for the Clio, which are very close to the actual test speeds. In this crash, as it was a crash test and set up to the specifications, the angle of the impact was known exactly. The direction of force for the Clio was entered as 10 degrees and that of the Vectra was 80 degrees. In a real CCIS case, it is possible that the angle of the impact would not be judged this precisely as it is difficult to do so from the damage alone without the resting positions of the vehicles. If this had been a real CCIS case, the angle is likely to have been estimated at 0 degrees. This would have resulted in a closing speed of 82 kph.

Combo/HGV impact

Using change in momentum calculations, where the weight through the rear axle of the HGV was estimated at 2.5 tonnes and the pre-impact velocity of the van was known to be 48kph, the delta-v of the van was calculated to be 35kph. As is usual CCIS practice with large vehicles of unknown actual mass, the HGV was entered into AiDamage3 as a “barrier” that was stationary both before and during the crash, with the van entered as a vehicle of size 3, stiffness category 9 (A = 653, B = 26.2). The reconstruction results for this test found the delta-v to be 31kph, which is an underestimate of 4kph compared to the actual delta-v of the test.

Summary

The work described forms part of an ongoing research programme seeking to validate one of the impact severity assessment methodologies used by UK crash investigation studies. Two crash test case examples are presented as part of this work to highlight the current ongoing activity. Where the calculated delta-v and real crash severity values differ significantly, the stiffness values in AiDamage3 are adjusted until the calculated delta-v values are closer to the associated test delta-v values. New values for the stiffness of vehicles are derived where appropriate which relate to the vehicle dimensions. This paper sets out the methodology currently being applied and future publications will outline the precise findings of this work and any changes which have been applied to the stiffness coefficients used.

CONCLUSIONS

From this early analysis presented, it can be seen that the delta-v values calculated are good estimates of the real crash severities observed in tests. However, this work is still ongoing and many more crash test impact configurations involving different impact severities will be analysed to fully validate current procedures and where necessary the appropriate stiffness coefficients used in the AiDamage software will be updated to replicate any changes in the stiffness characteristics of the vehicle fleet.
The authors are working in partnership with AiTS, Birmingham Automotive Safety Centre (University of Birmingham) and the Vehicle Safety Research Centre (Loughborough University) to enhance, where appropriate, the default and specific stiffness coefficients used to make them more representative of newer cars

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