Review of Measurement Protocols Applicable to Speed from Damage Programs

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Abstract

The use of computer programs to estimate the changes in velocity (Delta-V) suffered by a vehicle in a collision by estimating the amount of crush energy absorbed have been in use since the late 1970's. Although such programs are often capable of using scene data for simulations and momentum analysis, it is the damage-only option which is of particular interest. A variety of literature exists which describes the algorithms used and their derivation, but little is available which describes exactly what measurements should be taken. Consequently there is a considerable amount of confusion as to which methods of measuring produce the most realistic results. The purpose of this paper is to describe a series of simple measurement protocols which have been developed in the UK to overcome some of the traditional measurement difficulties and also to encourage further debate on this subject.

Background

Building on a 1972 paper by Mason and Whitcomb[1], Campbell[2] would appear to have initiated the discussion of estimating the energy involved in causing vehicle crush and thereby deriving an estimate of the Equivalent Barrier Speed (EBS). This was extended by McHenry[3] over a period of years and eventually developed into the CRASH3 algorithms. Initially designed to run on a mainframe computer, these algorithms were adopted by a variety of manufactures for use on personal computers. In the UK the most common derivatives in use are probably AiDamage, produced by AiTS, EDCRASH, produced by the Engineering Dynamics Corporation and WinCrash produced by ARSoftware.

Alongside the development of the original CRASH program came the descriptive Collision Deformation Classification[4] (CDC) which was developed from a 1969 coding known as the Vehicle Deformation Index. Using the CDC it is possible to concisely define a rough description of the damage caused to a vehicle in a seven digit alphanumeric code. The code is limited in that it can only describe uniform perpendicular crush, as only one digit is allowed to specify the maximum extent of the damage. More complicated damage profiles cannot therefore be defined. An estimation of the CDC is still required in some programs, but the maximum extent is ignored if additional data is supplied in the form of actual measurements describing the damage profile.

One part of the CDC which is not ignored is the user estimation of the principle direction of force (PDOF) which is arguably the most difficult factor to estimate in any case. Those programs which do not use the CDC still require an estimate of this parameter.

Other input data for the damage option takes the form of a series of crush measurements from the vehicles involved together with the width of the damaged area and the offset describing the displacement of the centre of the damaged area with the centre of the vehicle.

Usually the crush measurements are obtained by measuring a damaged vehicle and then comparing these with similar measurements taken from an undamaged vehicle. The crush sustained by the damaged vehicle can then be determined by simple subtraction and entered into the program.

CRASH3 defines three options for the crush measurements. Either two, four or six crush measurements are taken which are labelled C_1 through to C_6 as appropriate. This gives either one, three or five crush zones which are designed to approximate the damage profile. The damaged width is designated L, and any offset by the letter d.

For consistency this paper will use this terminology, although it should be noted that AiDamage uses different terminology and allows for an unlimited number of crush measurements and therefore an unlimited number of crush zones.
Figure 1 summarises the basic measurements required by CRASH3 derivative programs.

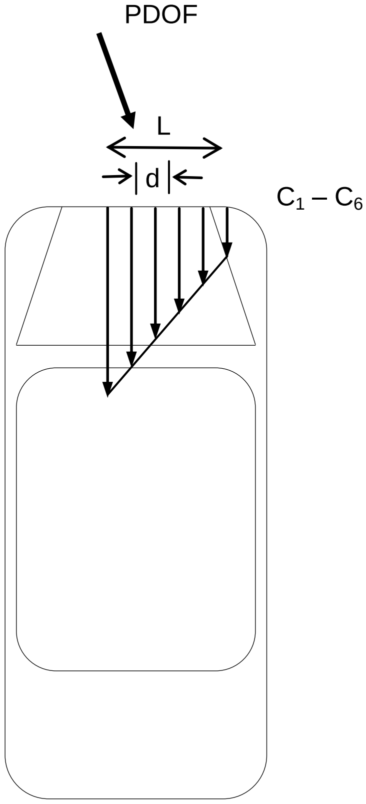


Figure 1
Measurements required by CRASH3 programs

$C_1 – C_6$ Crush measurements

L Width of damage

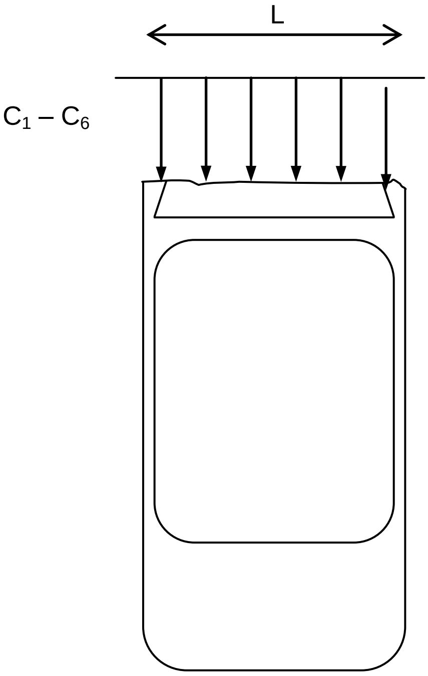
d Offset

PDOF Principle direction of force

Crash testing

A useful point with which to continue the discussion is with the derivation of the crush coefficients. Basic crash testing consists of crashing a vehicle head-on at a known speed into a solid barrier and measuring the residual crush as shown in Figure 2.

Figure 2
Residual crush from a head-on crash test



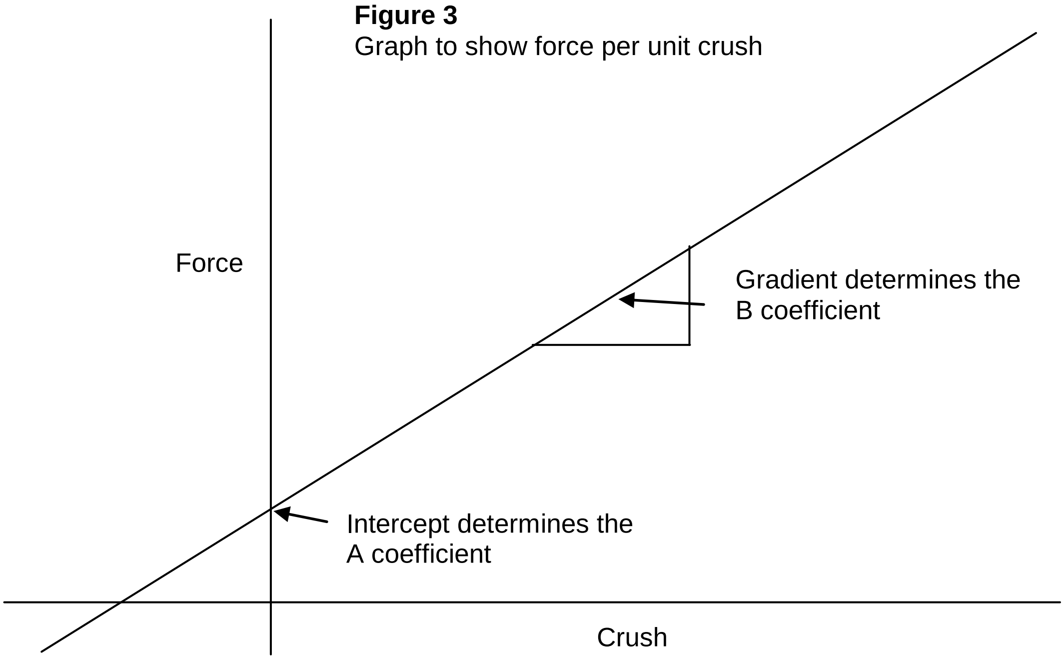
Original body line of vehicle.

Note that d = 0.

A series of equally spaced measurements are taken together with the width of the front of the vehicle in its undamaged state.

From this information the damaged area can be determined and after some mathematical manipulation the coefficients can be calculated. Exactly how they are determined is not relevant to this discussion. The key feature is that two coefficients are derived which determine the slope and intercept on a graph which shows force against unit crush as shown in Figure 3 below.

Figure 3
Graph to show force per unit crush



Several assumptions are inherent in this process. First it assumes that the front of the vehicle is a straight line and that the vehicle is a rectangle. Neither of which is quite true. A real three dimensional vehicle ends up being represented by a two dimensional rectangle. Since real collisions frequently result in a non-uniform vertical crush, the level at which the measurements are taken is of great importance. Crush measurements generally should be taken at frame height around the vehicle. For front and rear impacts this will be at bumper height.

Where there is a distinct difference between the level of maximum intrusion and frame level (which often occurs in side impacts) measuring at sill level tends to generate an underestimate of the total energy absorbed. However if measured at the level of maximum intrusion the energy absorbed tends to be overestimated. A better estimate of the true value therefore probably lies somewhere between these two extremes. It is therefore suggested that for side impacts in particular, the height at which the crush measurements are obtained is the mid-point between sill level and maximum intrusion.

Such a process also ‘averages’ the effect of different structural members across the vehicle. In reality there are strong parts and weaker parts, but an average is very useful since it does away with the need to analyse every single component individually. This of course is one of the main reasons for using these programs in the first place.

Although one crash test does not really yield sufficient data upon which to derive coefficients, a statistical analysis of a large number of tests over a range of test speeds does produce reasonable information. This is essentially the process by which the crush coefficients are produced. Variations on this theme are used to incorporate the crush from angled or offset impacts as well.

The A and B coefficients are used in the CRASH3 programs to determine how much force was required, and also how much energy was absorbed causing a particular amount of deformation. From the crush energy absorbed the Delta-V for each of the vehicles can then be determined. This might seem overly complicated for collisions which result in uniform perpendicular crush. There are however a few more features of the CRASH3 algorithms which allow for variation in the PDOF, non-central impacts and situations where only a proportion of the vehicle width is damaged or where non-perpendicular crush is produced. In these situations, which it is suggested form the majority of practical scenarios, that problems may begin to arise in the measurement process.

The 'L' problem

A fairly extreme example is used to illustrate an important point. Figure 4 shows a vehicle which has sustained oblique crush. Note that the original front of the vehicle is shown in bold.

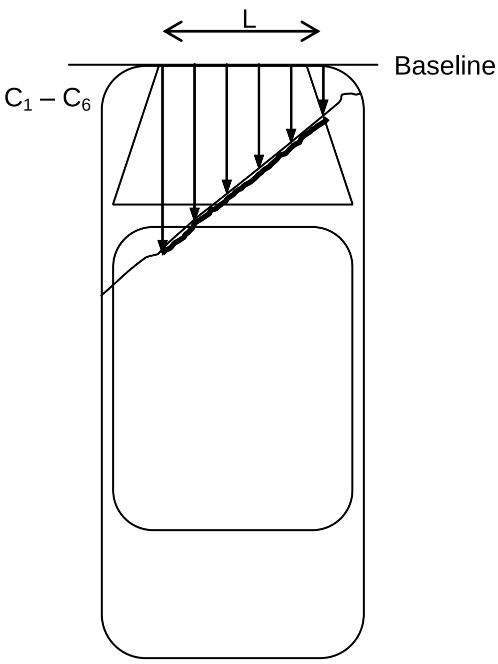


Figure 4
Oblique crush showing traditional measurements and incorrect representation of L

One problem for an investigator is to determine the width of the damaged area L. Traditionally the process as described in the CRASH Manuals seems to have been to split up the baseline into equally spaced segments and take the crush measurements. The baseline width L as shown in Figure 4 then forms the measurement L which could be entered into the program.

Note that this results in a smaller value for the damage width L than the true width of the vehicle. A smaller value for L reduces the area of damage which in turn results in an underestimate of the energy absorbed in crush and therefore an underestimate in the value of Delta-V.

This problem was recognised by Smith and Tumbas[5] as early as 1988. Their recommended solution was to measure the L parameter in the field as shown in Figure 4, so that an appropriate spacing could be determined but enter the width of the front of the vehicle into the program. Unfortunately it is fairly common to find that the field L measurement is actually entered as the width of the damage.

Although the Smith and Tumbas solution works well for regular damage profiles such as shown above, it does not work so well for those situations where only part of the vehicle width is damaged, or where the profile is irregular. This is because the crush depths measured in this way do not necessarily correlate when irregular damage profiles are encountered.

A more appropriate solution is that developed by Jennings[6] in 1990 for the police training courses presented at Devizes and subsequently adopted for the AiTS training courses. This method assumes that the damage profile retains a consistent length compared with an undamaged vehicle, although it will be twisted into a different shape. A similar assumption was made by Wood *et al*[7] in 1993 although their calculation of crush energy is somewhat different. In this method the damage width is determined by measuring directly along the face of the damage. The spacing between the crush zones can then be determined and crush measurements taken to the relevant points. The measured value of L is inserted into the program and removes the use of arbitrary adjustments as suggested by Smith and Tumbas.

A secondary beneficial effect is that corresponding points on damaged and undamaged vehicles are compared directly. The reasons why this is considered beneficial can be discovered if the basic representation of the damage profile is investigated.

Representation of damage profiles

The best that the CRASH3 derivatives can achieve is to represent any damage profile as a 'bite' taken out of a bounding rectangle which represents the vehicle outline. The damage profile is further defined by equally spaced crush measurements as already discussed. Crucially however these equally spaced measurements are defined in relation to the ***original*** profile of the vehicle and the individual crush measurements represent the perpendicular displacement of those points from their ***original*** positions.

Once the vehicle has been deformed in a collision, there is no reason to expect the spacing to be regular with respect to a parallel baseline. Indeed this very often the case and by implication means that the points may have moved laterally as well as longitudinally.

Figure 5A shows the front vehicle which has suffered an impact with a narrow pole, the suggested method of measuring such damage and in Figure 5B, the expected damage profile. As is to be expected in such a collision note that the wings of the vehicle have been pulled around. As before, the original front of the vehicle is shown as a bold line.

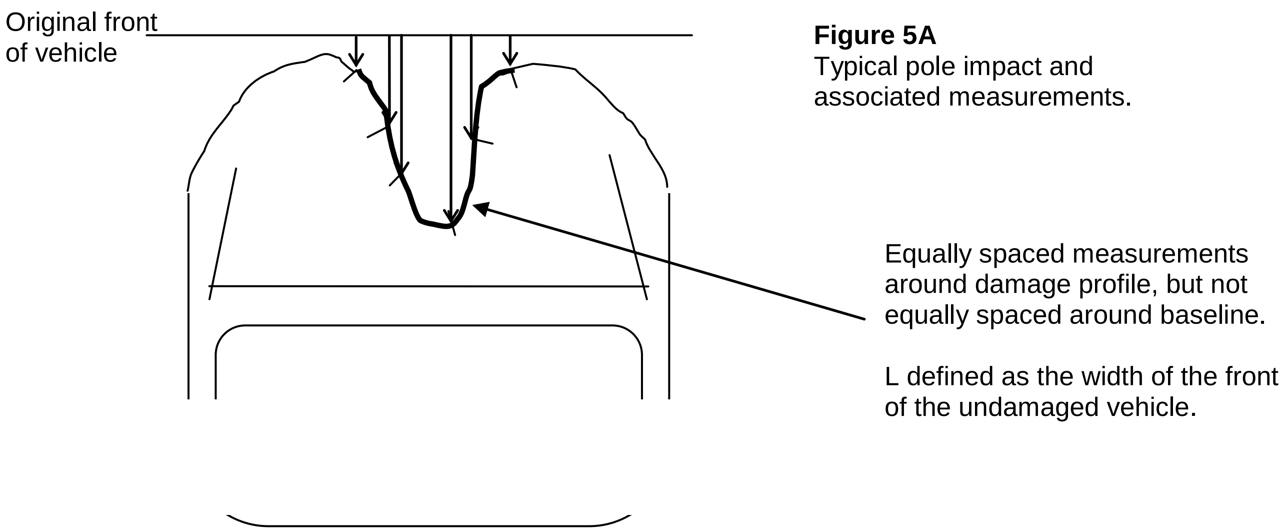


Figure 5A
Typical pole impact and associated measurements.

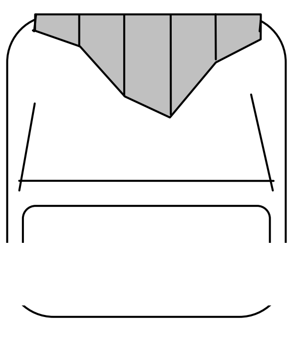


Figure 5B
Expected damage profile shown shaded.

It might be argued that this does not represent a very accurate picture of the damage which was caused to the vehicle. However it coincides exactly with the definition stated above for a damage profile and allows the program to produce a more representative estimate of the crush energy and therefore a more realistic Delta-V.

It should be noted that a side effect of using rectangles to model vehicles leads to few anomalies with graphical representation in general. For example, since the front of a vehicle is often slightly narrower than the centre this results in ‘shoulders’ of apparently undamaged areas surrounding a central damage profile even where the entire vehicle front is damaged. The results produced are unaffected, but the graphics can look a little odd at first sight. An illustration of this effect is shown in Figure 6.

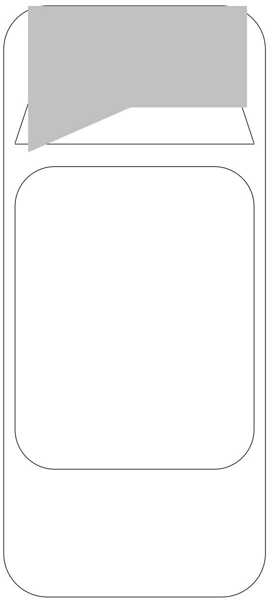


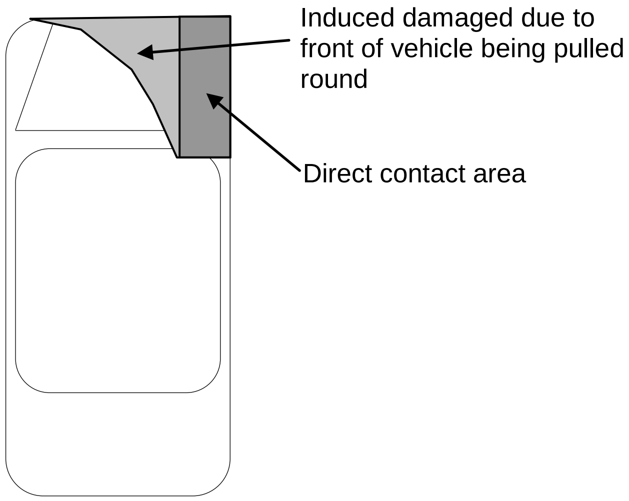
Figure 6
The effect of using rectangular vehicle models.

Shoulders of apparently undamaged vehicle surround a central damaged area.

Direct and induced damage

There is a potential problem concerning how much damage should be included in the damage profile. To explain this aspect it is helpful to define the two terms used, direct and induced damage. Figure 7 illustrates these features in respect of an offset head-on collision such as might be expected from a collision with a solid barrier.

Figure 7
Differentiation of direct and induced damage.



The original CRASH manual stated that only direct contact damage should be included. However it is apparent that energy must be absorbed in causing the induced crush and later versions of the CRASH manual concluded that induced damage should also be incorporated into any damage profile.

It is recommended here that both direct and induced damage are measured, provided that the induced damage is contiguous with the direct damage. Other areas of damage, remote from the main contact area, tend to be of a minor nature and can therefore be ignored.

The 'd' problem
All of the examples used so far have assumed damage across the entire front of the vehicle, and that the damage remains within the original bounding rectangle. Collisions do not always extend over the whole of the vehicle width, particularly those involving side impacts. Some collisions result in damage which not only crushes the vehicle but also distorts the original to such an extent that it moves outside the bounding rectangle.

The reason that the offset measurement is important is that this, together with the PDOF, determines the moment arm of the force. In turn this affects the calculated Delta-V for the vehicle because a force acting at a distance from the centre of mass tends to produce rotation as well as translation. In basic terms, assuming the same force is acting, a larger moment arm produces a lower Delta-V at the centre of mass but a higher rate of rotation.

The EDCRASH Training Manual[8] follows the CRASH3 notation and states that the offset measurement 'd' is the difference between the centre of the damaged area and the centre of mass of the vehicle. This seems a reasonable definition although it does presuppose that the location of the centre of mass is readily identifiable.

Ai Damage redefines this to become the distance between the centre of the damaged area and the centre line of the vehicle which should be somewhat easier to determine in the field. The program then uses the vehicle data to determine the true offset about the centre of mass. Using a side impact example, the standard CRASH3 and AiDamage definitions of 'd' are described in Figure 8.

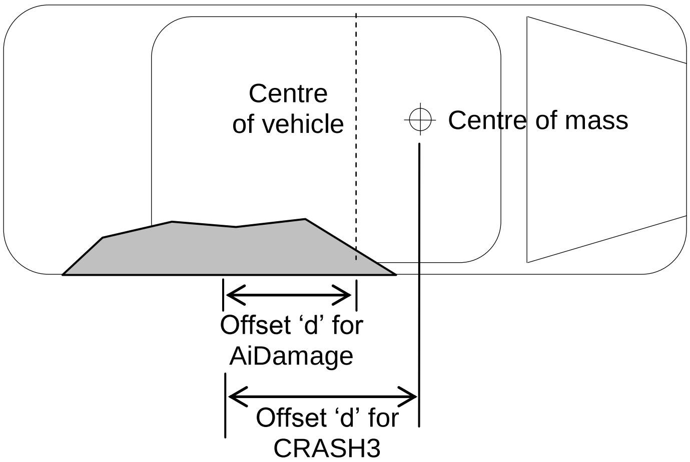


Figure 8
Definition of 'd' measurement

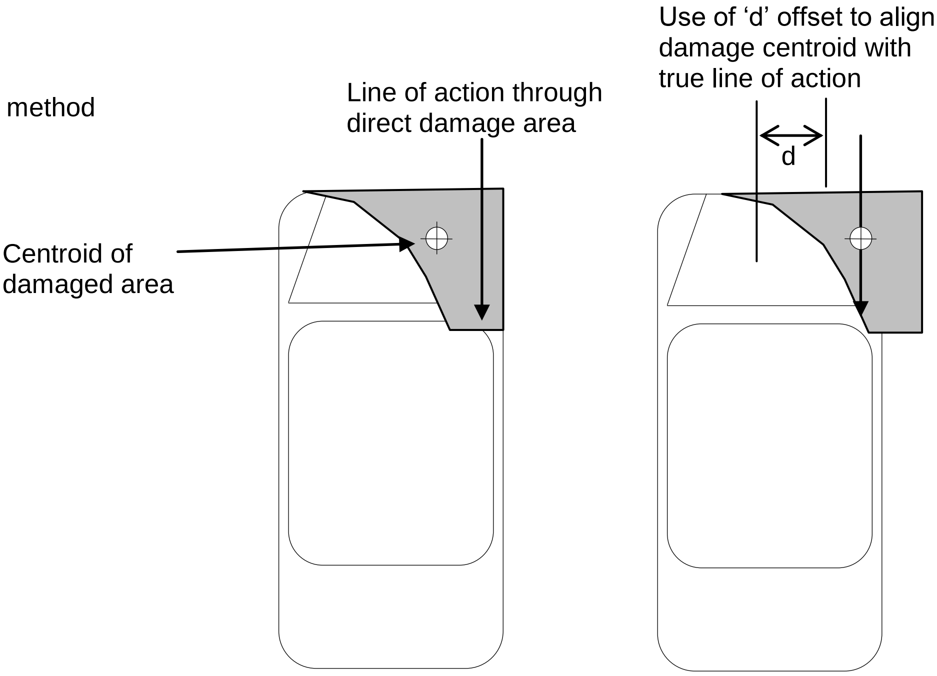
Using this simple definition any damage which extends across the entire vehicle, whether front, side or rear will have an offset measurement of zero. For partial damage the offset measurement can be determined as above. Note that the offset measurement, as with the other measurements, is defined in respect of the position of the centre of damage profile in relation to the centre of the undamaged vehicle. This necessitates a little care on the part of the investigator, but is relatively straightforward to achieve in practice.

Smith and Tumbas[5] proposed an method for determining the offset measurement which cannot be so easily determined in the field. It includes only using the direct damage to determine the offset, since that is the portion through which the impulse acts.

It also requires the operator to perform trial program runs to determine the position of the damage centroid (centre of mass of damaged area) so that adjustments can be made to move the damage centroid onto the line of action defined as the centre of the direct damage.

This is illustrated in Figure 9.

Figure 9
Smith and Tumbas method of adjusting the ‘d’ measurement

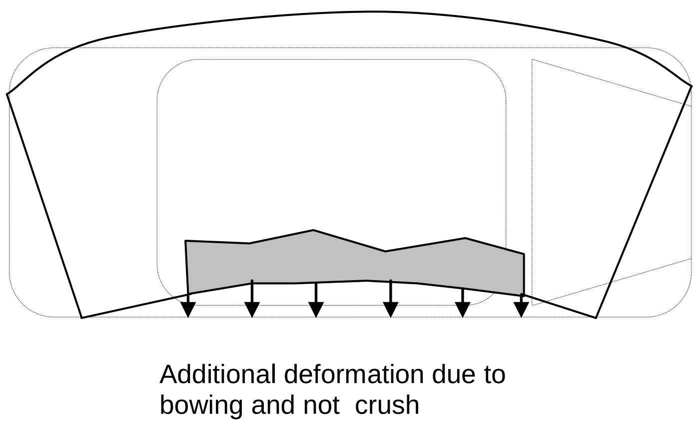


It should be noted that AiDamage allows the user to define the point of action of the impulse manually if required so that the use of ‘d’ to adjust the point of action should not be necessary.

Smith and Tumbas also suggest including an offset measurement when the vehicle is so severely distorted that the damage lies outside the original bounding rectangle of the vehicle. In the absence of empirical data to support this suggestion however, it is suggested that this particular adjustment is not applied.

Side impact problems
Side impacts can usefully be categorised into two groups, those which do not cause significant bowing and those which do. Bowing is defined as a vehicle which distorts during the impact so that the ends of the vehicle curl round towards each other. A similar effect is noticed in end-wise collisions where the wings fold inwards due to a pole impact. This effect is shown in Figure 10.

Figure 10
Bowing of a vehicle due to side impact. Original vehicle line shown in outline



Vehicles which are not bowed can be measured in much the same way as described previously. Damage length, 'L' is measured along the line of damage and the crush measurement taken to equally spaced points along the damaged profile.

A vehicle which is significantly bowed however would result in the investigator recording higher crush measurements, since the bowing contributes to the net depth as illustrated in Figure 10. It is possible to quantify the amount of bowing present by measuring the lateral displacement of the non-struck ends of the vehicles as described by Smith and Tumbas[5], but this does not lead to a simple method for recording the true crush of the vehicle.

It could be argued that since the bowing of the vehicle is caused by a force acting through a distance, then any apparent additional crush ought properly to be included in the measuring process. However this *may* lead to an overestimate of the Delta-V for the vehicles involved. In the absence of empirical data to support this argument, it is suggested that any apparent crush due to bowing is removed.

Quite what constitutes significant bowing is of course open to debate. Smith and Tumbas[5] suggest that 4" (10 cm) is significant and more importantly note that in the field investigators in a trial only correctly identified bowing in 20% of cases.

Instead of trying to quantify the bowing and making an allowance, an alternative protocol is proposed here which negates the effect of any bowing and generates a better representation of the true crush sustained by the vehicle. In essence this method requires the construction of a reference box around both the damaged vehicle and its undamaged counterpart.

Measurements are taken at the same equal spacing along either side of the vehicle together with the distance measured along the datum lines. It is important to start the measurements at a readily identifiable point on the vehicle so that measurements from an undamaged vehicle generate a one-to-one correspondence with the damaged widths.

The method suggested allows the calculation of the width of the vehicle at various points along the damage profile as shown by the dashed lines in Figure 11. For clarity only the calculation of the first damaged width (W) is shown. The same method when applied to all the points allows the true width of the vehicle to be determined at each point.

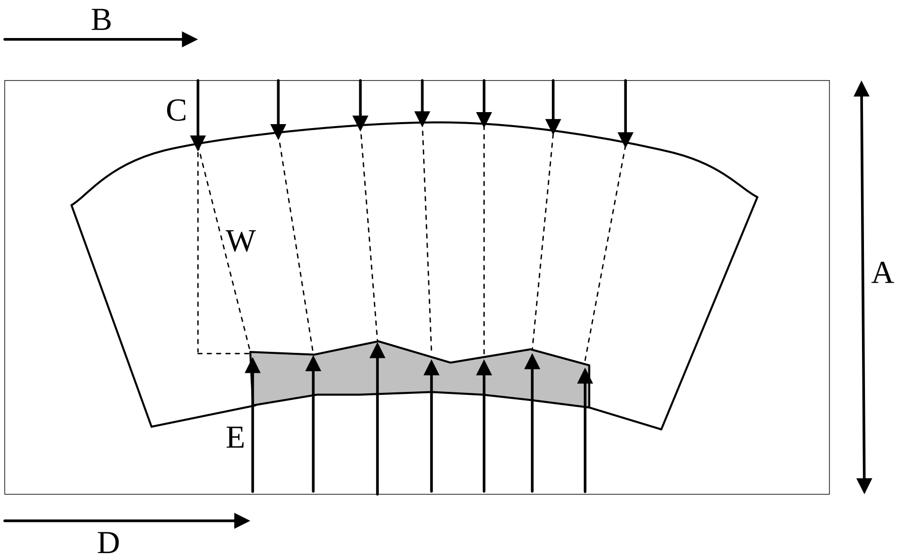


Figure 11
Protocol for measuring bowed vehicles.

Note that the spacing between measurements is still measured along the line of the damage.

By Pythagoras, the width (W) can then be calculated from the equation,

$$W = \sqrt{(B-D)^2 + (A-C-E)^2}$$

Measurements are also taken at corresponding points on an undamaged vehicle to generate the undamaged width at those points. The difference between the two widths must therefore be the crush depth sustained at that point.

Variations in stiffness

Side impact testing is generally performed using a vehicle sized barrier into the middle of the target vehicle. This naturally tends to miss the very stiff parts of the side of a vehicle such as the wheels and suspension.

Since a considerable proportion of collisions do involve an impact over these areas, then it seems reasonable to be able to quantify the effect. One way of performing this adjustment would be to vary the stiffness coefficients for those parts of the crush profile which include the wheels. Unfortunately there seems an absence of empirical data upon which to base any increase in the coefficients. Additional research is therefore desirable in this area. Without this information, side impacts which include a proportion of crush through the wheels and suspension will tend to result in an underestimate of the energy involved in deformation and consequent underestimate of the Delta-V.

It is also noted that vehicle design has changed over the years. This has resulted in more modern vehicles being stiffer than their older counterparts. Considerable research has been devoted into determining the most appropriate stiffness coefficients to use for more modern vehicles. Where possible it is suggested that the most appropriate coefficients are used depending on the age of the vehicle. (See Siddal & Day[9] and Hague[10])

Summary

This paper has attempted to explain some of the many problems which may result from the measurement of damage profiles. Measurement protocols developed over the last 19 years in the UK but not covered in the original US training manuals should provide a realistic and systematic method for recording most types of damage.

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