A RETROSPECTIVE STUDY IN UNDERSTANDING ‘LOW SPEED CHANGE’ VEHICLE COLLISIONS, OCCUPANT MOVEMENT AND LIKELIHOOD OF INJURY

by

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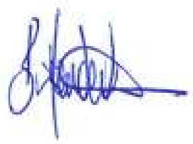
Declaration

I declare that this thesis has been composed by myself and while registered as a candidate for the degree for which submission is made. I have not been a registered candidate for any other higher research degree at this or any other University or institution of learning. No material in this thesis has been used in any other submission for an academic qualification.



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Abstract

The number of reported minor injury cases resulting from road traffic collisions appearing before the courts in the United Kingdom was in excess of 500,000 in 2007. Over 430,000 of the claims presented to the Courts were for 'whiplash' injuries. Whilst whiplash is in fact a mechanism for injury and it is acknowledged that the term almost exclusively relates to soft tissue injury. The United Kingdom is referred to as the whiplash capital of Europe, with 75% of personal injury claims being for whiplash. The cost to the NHS for consultation fees etc for treating whiplash injuries is approximately £8 million annually. It has been felt for some time that the number of reported injury cases cannot all be legitimate. There is a large number which falls under the category of 'Insurance Fraud'. Such is the problem that the Transport Select Committee has been considering how to tackle it now for a number of months. The applicant has personally provided assistance to the Chair of the Committee.

The question: 'How do experts assist in determining the legitimacy of individual cases?' has been addressed by this study. The research in this thesis (which consisted of both full scale crash testing and simulator testing) is based on a simplification of both the classification and understanding of low speed change collisions. Rather than considering a threshold below which individuals are not injured, it was felt that classification would be a much simpler way of defining the nature and magnitude of specific cases when comparing occupant acceleration in collisions with accelerations encountered in daily activity. Indeed, such an approach could also lead to less conflict with the legal system where the two disciplines meet, especially since the expert must not usurp the duty of the Court.

It was initially considered that there must be a threshold (i.e. a speed change) below which injury cannot occur to motor vehicle occupants. Indeed, this has been the position of some

insurers and researchers for a number of years. The work presented in this thesis is both retrospective and current and it spans an 8 year period. At the inception of the study, it was clear that attempting to find a threshold in the manner of 'one size fits all' would be difficult and likely would be impossible, especially since all drivers and passengers in cars are individuals.

International opinion seems to be in favour of the 5 mph 'threshold' of human occupant injury tolerance within the typical time frame of a rear end collision. However, the results from this study (after recording transient symptoms and a lengthy follow up period) have revealed that speed changes at this level produced considerably greater levels of average acceleration than any normal daily activity and provided much higher peak acceleration levels when considering the disparity between head and chest response.

From these initial results it can be concluded that speed changes above 5 mph provide accelerations at a level considerably beyond those experienced in daily activity. The results also show that speed changes below 3 mph provide accelerations at a level generally experienced throughout daily activity and easily tolerated by human beings. That is, normal daily routine ranging from sitting in a chair to light non-contact sport at the upper level etc. The accelerations experienced in speed changes between 3 mph and 5 mph would obviously fall within the two parameters.

Analysis of the numerous tests of varying types undertaken lead to the conclusion that there is no one type of 'everyday activity' test that accurately replicates a rear end collision. The simulator and crash tests are the only way to accurately measure accelerations and understand what actually happens.

Chapter 1

Introduction

1.1 General Background

Studies have taken place throughout the world, particularly in the United States of America (USA), relating to 'low speed' collisions and their effect upon vehicles and vehicle occupants. In real terms, the research dealing purely with low speed rear end collisions is somewhat sparse considering this is a worldwide issue. In the United Kingdom (UK), Whiplash Associated Disorder (WAD) accounts for over 75% of all personal injury claims with a reported cost to society running into many millions of pounds (Association of British Insurers). Factor in the non-existent and exaggerated claims and the cost is in excess of £1 billion annually. It was surprising then to find that direct research in the United Kingdom into 'low speed' collisions was almost non-existent. The insurance industry research centre at Thatcham in Berkshire studies the design and manufacture of seats and vehicle bumper systems, but has not been directly involved in understanding the movement of occupants. It should be noted that as its name suggests, it is funded by the insurance industry and as such has no independence. It is against this backdrop that this study was undertaken.

1.2 How to Undertake an Investigation of Injury

A logical consideration of how car occupants are injured would lead to the conclusion that the higher the speed of the collision, the greater the likelihood of injury. Going a step further, it is also logical that if the acceleration of the occupants is a factor in the frequency and level of injury in car crashes (disregarding direct contact injuries), then what happens to a vehicle after it has been struck lies at the heart of understanding the collision itself. This thesis does not deal with the Conservation of Energy or Conservation of Momentum laws, but takes into consideration that these aspects need to be understood in order to consider the collision phase. Newton's Laws of Motion are at the centre of all such considerations. Applying the laws of physics will provide the speed changes in a vehicle to vehicle scenario (Conservation of Momentum, Conservation of Energy). The speed change for the vehicles is simply known as 'Delta-v' or Δv. It seems logical, therefore, that understanding Delta-v and being able to determine Delta-v lies at the heart of beginning to understand how occupants move.

Damage and crash worthiness has been amply covered in a number of papers including Bailey et al, 1995; Chirwa et al, 1999; Chirwa, 2005; Chirwa 2009.

1.3 What is Delta-v?

Collision severity has often been expressed by use of the term 'Delta-v'. This is true for serious collisions as it is for minor collisions. Understanding Delta-v in the context of the collision environment therefore is a fundamental requirement to better understanding the collision and its consequences. Husted et al (1999) suggested that whilst the term Delta-v had become widely used as a descriptor of accident severity for automotive crash investigations and safety research, its term was poorly defined and vaguely used in too many situations. Their definition of Delta-v was "the velocity vector difference between a pre and post impact". They felt that the term was too loosely being used and that it caused confusion in some circumstances. In the candidate's personal experience this is still true today.

Husted et al (1999) spoke of treatment of Delta-v not having properly reflected crash pulse factors which are fundamental in determining the biomechanical exposure to injury. Acceleration (g) versus time is used to establish injury thresholds and probability distributions of injury. Currently a number of vehicles are now fitted with diagnostic/memory modules and crash recorders (black boxes for want of a better term) and it was noted in 1999 that it would take some time before significant numbers of vehicles are so equipped.

This is still the case today and the reality is that the low speed collisions are the most difficult to detect as the equipment needs to be particularly sensitive. Secondary indicators and calculations must also be used in order to arrive at estimates of accident severities. Delta-v is still the best indicator, so long as the context in which it is used is correct.

In their research paper, Husted et al (1999) rightly pointed out that in itself Delta-v does not allow for either average acceleration, peak acceleration or other characteristics of the crash pulse. Much of this will be discussed later within this research, but the easiest understanding of Delta-v could be the consideration of vehicle manufacturers' performance figures. The 0 – 60 mph times are often quoted. For example, an average car travelling from 0 – 60 mph in 9 seconds experiences exactly the same Delta-v as the car which takes 6 seconds. The differences between the two are the rates of acceleration. Similarly, a vehicle braking to a stop can typically experience a deceleration rate of 0.7 g (typical skid to stop figures). If the speed of the vehicle was 10 mph then the time taken to stop would be 0.65 seconds ($v = u+at$ transposed). In a rear end collision, the typical duration is around 0.2 seconds. A Delta-v under such circumstances provides an average deceleration rate of 22.35 m/s^2 or 2.28 g. Note: <u>peak</u> acceleration in this research was noted as occurring in around 0.1 seconds, Henderson et al (2009).

Cheng et al (2005) in undertaking collisions into barriers found that the duration of the impact was in the region of 0.1 to 0.12 seconds. Vehicle to vehicle tests were merely reported as being longer. It is clear, therefore, that for Delta-v to have any real meaning, the time over which the speed change takes place is vital. The researchers had long held the view that merely quoting the Delta-v figure leads to confusion and in a number of cases ambivalence, where the matter is disregarded completely.

1.4 What is Restitution?

The time over which a collision occurs is a major factor in understanding low speed change collisions and this is affected by restitution. There are a number of influencing factors which are associates with restitution. In a SAE paper by Robinette et al (1994), they reported the questionable application of the coefficient of restitution in deriving impact Delta-v. They also demonstrated that during the initial deformation or approach phase of the collision, the vehicles undergo interaction such that at the maximum deformation, the vehicles achieve a point of equal or common velocity. Impact damage analysis theories accepted today are based upon the hypothesis that the two vehicles achieve a common velocity at the point of crush. The paper reported that the total change in velocity is the accumulative result of the change during the initial impact phase up to maximum crush, plus the change that occurs during the separation phase. The difference in the values is related by the coefficient of restitution which is defined as the ratio of the differences in the impact and rebound velocities (see below).

$$e = \frac{V2 - V1}{U1 - U2}$$

Where e is the coefficient of restitution, V_2 is the post impact speed of the target vehicle, V_1 is the post impact speed of the bullet vehicle and the 'U' values are pre-impact speeds. (Sometimes, c.o.r. is used for the coefficient of restitution rather than the letter e to avoid confusion with the exponential function which is also identified by the letter e) For a completely inelastic or plastic collision, the restitution figure would be zero, e = 0. For an elastic collision where no damage occurred, the figure would be 1, e=1. Moderate and high speed collisions where there is permanent deformation of the vehicle structure and negligible elastic rebound are considered as plastic impacts.

Controlled barrier tests in the 30 – 35 mph region included rebound speeds of 2 – 4 mph and a coefficient of restitution figure in the 0.1 or smaller range. Controlled tests in the 60 mph region usually result in smaller coefficients of restitution. Kerkhoff et al (1993) presented a similar trend from barrier tests with similar Ford Escort vehicles [Note: USA Ford Escorts] with e=0.24 for a 10 mph barrier and e=0.093 at 15 mph continuously dropping to e=0.032 for a 50 mph barrier impact speed. Restitution notably influences Delta-v in very low speed impacts. Emori et al (1990) found that the coefficient of restitution dropped from the hypothetical e=1 near 0 mph impact to e=0.5 to 0.6 at 0.9 mph but remained fairly constant up through 2 mph impacts. Similar research studies (Braun et al, 2001; Malmesbury and Eubanks, 1994) have found that Delta-vs from barrier collisions in the 2 – 5 mph range produced restitution figures in the range of 0.2 – 0.4 as impact speeds go up and damage is observed and thus the coefficient will continue to decrease.

In an SAE (Society of Automotive Engineers) paper entitled "Rear End Impact Testing with Human Test Subjects" by Braun et al (2001), they reported on a number low speed rear end aligned bumper to bumper crash tests. Their results show that the bullet impact speeds ranged from 2 – 6.5 mph and produced target vehicle changes in velocity (Delta-v) of 1.5 – 4.5 mph. Seven human volunteers participated in the testing. Males and females between the ages of 29 – 61 years and in good health were involved. In the study, two test subjects were seated in the target vehicle and one subject drove the bullet vehicle for each of the seven tests. The target vehicle was a 1982 Toyota Celica GT two door hatchback. The vehicle had a rear bumper consisting of a foam core sandwiched between an outer plastic cover and a metal reinforcement bar that was mounted to the bodywork. The bullet vehicle was a 1984 Ford Mustang two door hatchback. The front bumper was mounted to the vehicle upon two isolators. An isolator is a piston and cylinder assembly that will typically compress to absorb energy during an impact and then rebound back to its original position. In this study the coefficient of restitution figures ranged from about 0.3 – 0.5 at impacts between 3.22 kmph (2.01 mph) and 10.46 kmph (6.5 mph).

There is clearly a correlation between increase in impact speed and the decrease in the restitution figure. In simple terms, this is due to more permanent damage occurring at higher impact speeds. An understanding of the restitution values discovered in other research papers provided a starting point for the consideration of restitution values in the present research. It should be remembered that the figure alters not just with impact speed, but the nature of the structures in contact (Braun et al, 2001; Henderson et al, 2009). Two rigid structures coming into collision may provide for a more elastic collision than two soft malleable structures. The latter would provide a more inelastic collision. A more malleable structure being contacted by a rigid structure would also provide for a more inelastic collision. The damage would manifest itself more clearly on the softer structure. With the majority of research coming from the United States of America, a comparison of restitution figures from U.K. vehicles would be of particular interest.

In a previous study, Malmsbury and Eubanks (1994) conducted 49 crash tests using 1981 to 1985 Ford Escorts constructed to North American safety standards applicable at the time of manufacture. Twenty-nine barrier crash tests were conducted at speeds ranging from 0.89 mph (0.4 m/s) to 9.53 mph (4.26 m/s). Twenty car-to-car crash tests were conducted. In these tests a moving vehicle was impacted with a stationary vehicle at speeds from 1.72 mph (0.77 m/s) to 19.6 mph (8.76 m/s).

This review will now only consider the car-to-car crash tests. The results of the twenty car-to-car crash tests are summarised in Appendix A of the Society of Automotive Engineers (SAE) paper. These results were carefully examined for the purpose of this review. Since no information to the contrary is given in the paper, it is assumed that all the tests were front-to-rear impacts. The numerical results from this review are presented in the attached Review Table (Table 1.1). These results are discussed and a comparison made with existing GBB (GBB(UK) Ltd) research data. Although it is stated in the abstract of the SAE (Society of Automotive Engineers) paper that the target vehicles were stationary, Appendix A of the paper shows that for some of the tests the target vehicle had a small initial velocity. From the information given in Appendix A of the SAE paper, it is possible to carry out a momentum conservation check for each test using the values of Delta-v and mass for each vehicle. From this check, a percentage error in momentum conservation has been calculated and is shown in column 3 of the Review Table (Table 1.1).

If the error is positive, it indicates that the momentum gained by the target vehicle is greater than the momentum lost by the bullet vehicle. For example, in test 31 a momentum error of +3% has been calculated. This means that the target vehicle in this test had gained 3% more momentum than the bullet vehicle had lost. This would indicate a small calculation or measurement error in the investigation by Malmsbury and Eubanks (1994). Apart from test 23, all target vehicles were in 3rd gear when the impact occurred. It is assumed that their engines were not running and the hand brake was not applied. In test 23, the gearbox was in neutral. At low speeds, a negative error would have been expected due to the application of 3rd gear in the target vehicles as some of the momentum lost by the bullet vehicle would have been used in overcoming friction between the tyres and road surface rather than increasing the momentum of the target vehicle.

From the summary in the Table 1.1, it can be seen that the momentum balance errors at low speeds are positive rather than negative. The explanation for this is not clear. Possible reasons may have been calculation error, measurement error or the authors may have made some adjustment to the results to allow for target vehicle resistance due to being in 3rd gear. This adjustment could have overcompensated for the resistance leading to a positive momentum error. It is assumed from this review that a momentum error of less than 10% is within reasonable experimental error bounds for these types of tests. Any tests which have an error above 10% should be treated with suspicion and caution. From the Review Table 1.1, it can be seen that tests 24, 18, 37, 26, 21 and 27 have momentum balance errors greater than 10%. The values of the coefficient of restitution have been checked from the velocity data provided in Appendix A of the paper. The restitutions from the paper and those from this review are shown in columns 4 and 5 of the Review Table 1.1. In general, the two values of restitution are in agreement. Any small differences appear to be due to the authors not taking into account the initial velocity of the target vehicle when calculating restitution. The only exceptions are the restitutions for test 38. From the SAE paper (Malmsbury and Eubanks, 1994), the restitution is given as 0.32 but from the velocities given in Appendix A of the SAE paper it is 0.41. The explanation for this difference is not clear. In general, the results confirm the belief that the coefficient of restitution decreases as impact speed increases. Graphs of restitution vs. impact speed have been plotted and are attached at the end of this review. Graph 1 (Figure 1.2) shows the restitutions for the car-to-car tests carried out by Malmsbury and Eubanks (1994). Tests 24, 18, 37, 26, 21, and 27 have been excluded due to their large momentum balance errors. Test 38 has also been excluded due to the discrepancy between values of restitution described previously. Graph 2 includes GBB data and curves based on mathematical equations (correlations) used as a fit for the points. These equations give the coefficient of restitution (c.o.r.) as a function of impact velocity (v). The data points from the SAE paper that correlate well with the GBB data are identified in column 8 of the Review Table 1.1 using the equation c.o.r. = $e^{-0.253v}$.

This exponential equation has been chosen as a best fit for the GBB data points. It can be seen to also give a good fit to some of the lower speed points from the data of Malmsbury and Eubanks (1994). One property of this particular equation is that it gives a restitution of 1.0 when the impact speed is zero. This is a necessary condition for any equation that is an accurate correlation for low speed data.

$$c.o.r = -0.2272\ln(v) + 0.8286$$

This logarithmic equation gives a good fit to the higher speed restitutions of Malmsbury and Eubanks (1994) and the lower speed restitutions that do not fit with the GBB data. Exponential equations were tried but a good fit could not be obtained. The reason why there are two correlations rather than one correlation that fits all the data is discussed in the section dealing with energy. In the paper by Malmsbury and Eubanks (1994), the term 'damage' is defined as panel damage or damage to any safety related part. Deformation, displacement or other damage to the bumper or reinforcing beam is not included within this definition. The Ford Escorts used by Malmsbury and Eubanks (1994) had spring loaded hydraulic impact absorbers situated behind the front and rear bumpers and attached to the chassis (frame rail), as shown overleaf. The impact absorbers required a force of 4 kN to initiate movement and approximately 12 kN was required to reach maximum compression (see Figure 1.1). The maximum stroke of the piston was about 2.5 inches (63.5 mm).

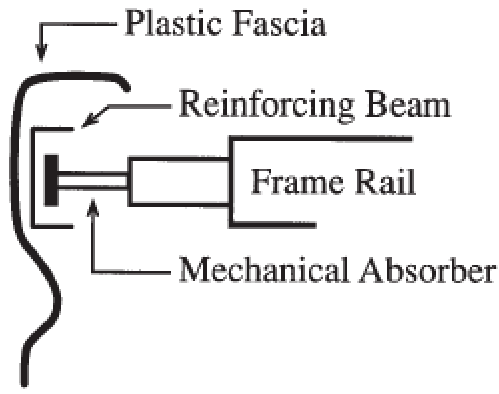


Figure 1.1: Diagram showing how energy is absorbed during a collision

The diagram in Figure 1.1 indicates the bumper structure set up. The plastic fascia is the bumper cover which fastens to the bodywork of the car and provides an attractive cosmetic appearance. This covers the bumper reinforcer which in itself is attached to the shock absorber. It is the reinforcer which gives any 'bumper' its strength. The absorber is fastened directly to body of the vehicle at the end of the chassis rails (the point of greatest strength and rigidity) so there is the right balance of rigidity and elasticity within the system.

Up to 1983, regulations in the USA stated that passenger vehicles should be able to resist impacts up to 5 mph without damage to safety related parts and exterior panels. Hydraulic energy absorbers were introduced to meet the regulations. The regulations were relaxed from 1983 onwards when the impact speed was reduced to 2.5 mph.

When an impact occurs to a vehicle fitted with hydraulic energy absorbers, the initial force of the collision is absorbed by the bumper. Larger forces are transferred to the reinforcing bar fitted behind the bumper. Still larger forces will cause the bumper and reinforcing bar to bend or displace sufficiently to compress the piston of the energy absorber (see Figure 1.1.) These forces will be transferred to the chassis of the vehicle via the absorber mounting brackets. Only when the piston of the energy absorber is completely compressed, at about 12 kN impact force, will panel damage start to occur. From the paper by Malmsbury and Eubanks (1994), permanent damage to panels was found only in tests 27 and 22, which were at the highest speeds. For tests below these speeds 'damage' did not occur as indicated in column 7 of the Review Table 1.1. According to crash testing carried out by GBB, a typical passenger vehicle found on British roads could show panel damage from about 6 mph upwards depending on the make and model. This speed was exceeded in about half the tests carried out by Malmsbury and Eubanks (1994) but panel damage was only found in the last two tests carried out at the highest speeds. The difference is clearly due to the presence of the energy absorber.

Kinetic energy absorbed in the flexing of the bumper and reinforcing bar and in the compression of the spring in the absorber can be recovered during the final phase of the collision following maximum engagement. Kinetic energy expended in causing permanent damage to the bumper and reinforcing bar and converted into heat generated within the energy absorber cannot be recovered. Column 6 of the Review Table 1.1 shows the amount of kinetic energy lost when it is converted into other forms of energy or used to create permanent damage during the collision. Also shown in column 6 of Table 1.1 is the lost kinetic energy as a percentage of the total kinetic energy at the start of the collision.

In a vehicle without hydraulic energy absorbers, the majority of the lost kinetic energy will be used in creating permanent damage. In a vehicle fitted with a hydraulic energy absorber, some of the lost kinetic energy will be dissipated as heat generated within the absorber leaving less kinetic energy to cause permanent damage. The energy stored within the spring of the absorber can be recovered during the latter stage of the collision and will be responsible for an extra component of Delta-v to the bullet and target vehicles. This will raise the coefficient of restitution for these collisions. This effect will be more apparent in higher speed collisions since the absorber springs are more compressed and will restore with a greater force. In lower speed collisions, the effect will be less marked as the recovery of the springs will occur at a lower rate and may even take place outside the time over which the collision occurs. In this case the absorbers will have little influence on the coefficient of restitution.

Of the twenty car-to-car crash tests carried out by Malmsbury and Eubanks (1994), seven should be discarded due to large errors in momentum conservation or inaccuracy in the calculation of restitution. The remaining thirteen crash tests fall into two groups when restitution is plotted against impact speed. Six of the remaining crash tests, mainly in the lower speed range, follow the same trend as the GBB crash test data. Seven of the remaining crash tests follow a different trend showing higher values of restitution. This is due to energy returned to the colliding vehicles from the springs of the hydraulic energy absorbers. The definition of damage used by Malmsbury and Eubanks (1994) does not include damage to bumpers and reinforcing bars.

The hydraulic energy absorbers fitted to the vehicles used by Malmsbury and Eubanks (1994) prevented panel damage up to speeds of about 14 mph. This speed is far greater than the impact speed at which panel damage would be expected in typical passenger vehicles used on British roads. In general, the results from the crash testing carried out by Malmsbury and Eubanks (1994) should not be used in the investigation of collisions on British roads. This is due to the difference in the definition of damage and the influence that hydraulic energy absorbers can have on the value of restitution and on the degree of panel damage.

Other papers worthy of mention in relation to restitution include:
Howard et al (1993), Antonetti et al (1998), Happer et al (2003) and Seigmund et al (1993).

Table 1.1 Results from 20 Car to Car Crash Tests

Review Table									
1	2		3	4	5	6		7	8
Test No.	Impact Speed mph	(m/s)	Mom. Error %	Rest. (paper)	Rest. (review)	Lost K.E. joules	(%)	Dam.	GBB Corr.
31	1.72	(0.77)	+3	0.60	0.60	87	(31)	N	Y
32	2.57	(1.15)	+5	0.53	0.56	173	(27)	N	Y
39	3.51	(1.57)	+6	0.54	0.54	383	(33)	N	N
33	3.80	(1.70)	0	0.41	0.41	595	(43)	N	Y
40	4.07	(1.82)	+3	0.37	0.37	668	(42)	N	Y
19	4.21	(1.88)	+4	0.35	0.35	716	(43)	N	Y
34	4.99	(2.23)	+3	0.44	0.47	786	(33)	N	N
24	5.06	(2.26)	+22	0.27	0.28	819	(34)	N	Y
23	5.08	(2.27)	+2	0.32	0.32	1153	(47)	N	Y
18	5.15	(2.30)	-16	0.31	0.31	1452	(58)	N	Y
35	6.85	(3.06)	+8	0.35	0.36	1605	(36)	N	N
36	7.49	(3.35)	+8	0.38	0.38	2091	(39)	N	N
37	8.34	(3.73)	+15	0.30	0.31	2207	(33)	N	N
38	9.17	(4.10)	-6	0.32	0.41	3753	(47)	N	N
20	9.62	(4.30)	-4	0.33	0.32	4308	(46)	N	N
25	9.95	(4.45)	+9	0.33	0.31	4566	(48)	N	N
26	12.95	(5.79)	+27	0.29	0.29	5172	(32)	N	N
21	14.23	(6.36)	-22	0.35	0.35	12258	(55)	N	N
27	18.93	(8.46)	+14	0.14	0.14	15340	(45)	Y	N
22	19.60	(8.76)	0	0.12	0.12	19113	(53)	Y	N

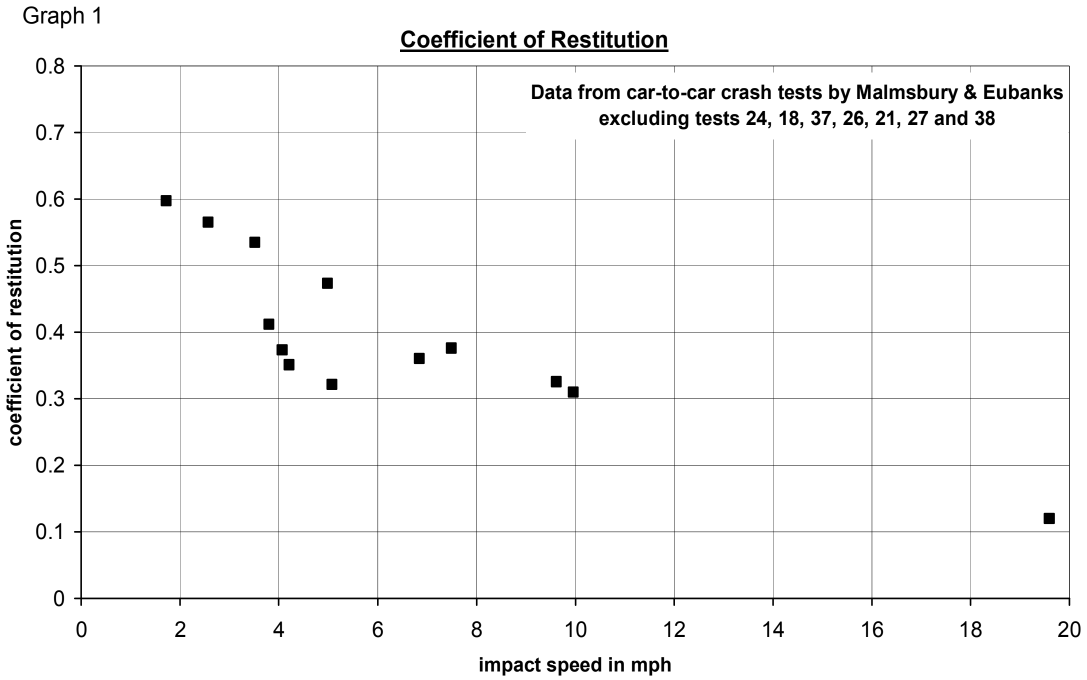


Figure 1.2: Data showing the spread of restitution (taken from Malmsbury and Eubanks, 1994)

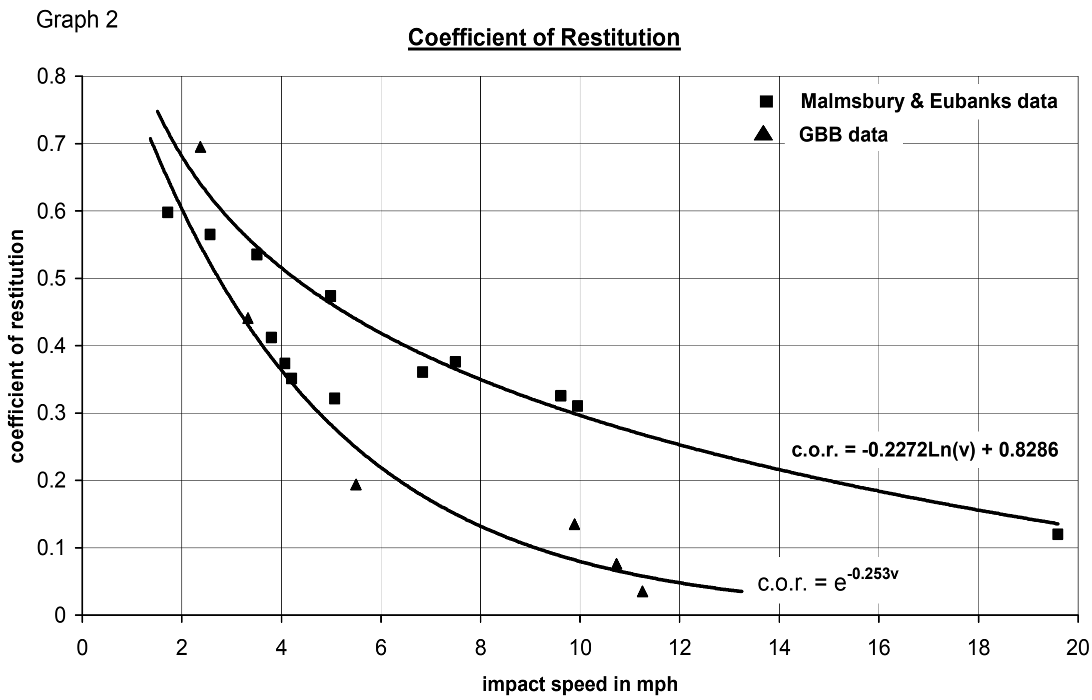


Figure 1.3: Comparison of data from Malmsbury and Eubank (1994) and those from GBB Henderson et al (2009)

Graph 1 in Figure 1.2 shows the spread of restitution figures from Malmsbury and Eubanks (1994).

Graph 2 in Figure 1.3 shows the Malmsbury and Eubanks (1994) figures integrated with GBB data (Henderson et al 2009).

1.5 Injury Threshold

As far back as 1993, detailed published research in the United States of America considered the relation of 'low velocity collisions' (McConnell et al, 1993). At this time the increase in claims for injury in the United Kingdom from such collisions was just beginning to gather pace. In the USA, this had been the situation for some time.

The paper by McConnell et al (1993) began with an explanation that although the classic "whiplash" neck response to rear end collisions and the widely accepted hyperextension/hyperflexion cervical injury mechanism had been extensively written and speculated about (Howard et al, 1999). There have been little human experimental data available, especially for low velocity collisions. The research studied kinematic responses for the head, neck and trunk from tests involving four volunteer test subjects during a series of low velocity collisions. The tests were filmed and the volunteers were fitted with accelerometers. Interestingly, the test protocol was first evaluated by the University of Texas Health Science Center Institutional Review Board. (IRB protocol #9010099006 under DHHS Regulation 46.110[3]) This approved the use of four test subjects from Biodynamic Research Corporation for the test programme. The four volunteers were healthy males aged 45 – 56 years. Pre-testing physical evaluations were undertaken including radiographic imaging of the cervical, thoracic and lumbar regions of their spines.

Tri-axial accelerometers were fitted to the vehicle frames measuring Gx (forward/rearward), Gy (right/left lateral) and Gz (upward/downward) accelerations and a bi-axial array on the vehicle seat back. Contact switch-operated flash units were installed to allow photographic time marking. The test subjects themselves were fitted with tri-axial accelerometers fitted to a bite block, held in place by a normal bite or jaw closure pressure. Similar equipment was fitted to a manikin during the tests. A further bi-axial accelerometer was fitted to a corset like garment which measured Gx and Gz. [Note- the sampling rate for the accelerometers is not stated but appears to be 100Hz.] Photographic equipment using high speed cameras and LED timing light operating at 100 hertz was also used.

The test site was a level section of asphalt paved roadway. Rather than driving the vehicles into collision, a specially constructed ramp was used in order to better control the range of impact speeds. The starting position of the striking vehicle on the ramp was calibrated before each test run. The actual closing speeds and resulting changes in velocity for each vehicle were determined using high speed film, video and electronic speed trap equipment. High speed cameras were used in the vehicles and at fixed site positions. Understandably, the vehicles used were American specified models and comprised of the following: a 1986 Dodge 600 convertible, a 1984 Buick Regal Limited coupe, a 1984 Ford Club Wagon van and a 1984 GMC 1500 pickup truck. There was no evidence of collision structural damage and each was in a roadworthy condition with factory standard parts. The testing protocol apparently required slight modifications to the Ford van (upper portion of left hand ‘B’ pillar and door removed) and GMC pickup (rear window replaced). The head restraints in the coupe and convertible were in the raised position. Factory fitted 3 point seatbelt restraints were used in each test. The vehicles were checked prior to testing and bumper damage found was remedied with the fitting of new parts.

Data from ten manned vehicle to vehicle tests were recorded. The purpose of the testing was to consider kinematic response at the head, neck and trunk to low velocity impacts. The data included measurement of accelerations, displacement-time information from the high speed cameras and slow motion video records of each subject's movement during the collision sequence. Smoothing of the accelerometer data to eliminate 'noise' was undertaken. Mathematical manipulation gave an earth reference based G-time history for a point near the junction of the head and upper cervical spine. The tests were undertaken on two weekends with an 8 day break in between. Four tests were undertaken on days 1 – 2.

These were:

Test 1 – Convertible (Δv -4.81 kph) into Ford van (Δv 3.48 kph) Subject 1 into 2

Test 2 – Pickup (Δv -6.04 kph) into Ford van (Δv 6.45 kph) Subject 4 into 1

Test 3 – Ford van (Δv-3.35 kph) into Pickup (Δv 3.04 kph) Subject 4 into 1

Test 4 – Ford van (Δv -6.75 kph) into Pickup (Δv 6.65 kph) Subject 1 into 4

The tests on days 10 and 11 were:

Test 5 – Coupe (n/a) into Convertible (n/a) Subject 2 into 3

Test 6 – Coupe (Δv -7.82 kph) into Convertible (Δv 8.06 kph) Subject 2 into 3

Test 7 – Convertible (Δv – 9.24 kph) into Coupe (Δv 7.83 kph) Subject 3 into 2

Test 8 – Pickup (Δv -8.21 kph) into Ford van (Δv 6.61 kph) Subject 4 into 2

Test 9 – Pickup (Δv -3.28 kph) into Coupe (Δv 3.93 kph) Subject 4 into 2

Test 10 – Ford van (Δv -7.48 kph) into Pickup (Δv 7.03 kph) Subject 2 into 4

Each test subject had between 3 to 7 vehicle to vehicle test exposures, divided between the striking and struck vehicle. No test subject reported any discomfort during or immediately after any of the test collisions. The conclusions were that substantial Gz direction acceleration occurs and this is associated with both compressive and tensile forces sequentially directed axially through the cervical spine.

These push-pull forces probably represent the injury causation mechanism independent of the commonly described 'whiplash' hypertension/hyperflexion mechanism.

For the rear end collisions within the range of their testing, the classic 'whiplash' mechanism was not evident since there was no hyperextension/hyperflexion observed in any test subject. Despite having experienced no neck movement outside voluntary range limits, three out of four test subjects transiently had very mild, but clinically classic, neck discomfort symptoms.

During the lower energy level 4 kph (2.5 mph) Δv tests, the subject's relatively rearward head motion was similar but much milder and in each case, the back of the head did not reach the head restraint. The injury causation potential was subjectively judged by the physician test subjects to be minimal or non-existent. The very mild discomfort symptoms experienced by three out of four test subjects after multiple exposures, indicated that the 4 – 5 mph Δv for the struck vehicle tests were probably at or near the typical human threshold for very mild, single event musculoskeletal cervical strain injury.

In 1996, Kornhauser (1996) described a study on Cervical Spine Injury. He wrote the paper with the purpose of converting cervical spine injury data into Delta-v quantities and establishing an injury/Delta-v database for 'whiplash', or cervical spine injury in the automotive environment. The paper explains that Delta-v is an input parameter that correlates well with injury thresholds for responses to impulsive loading. Moreover, this is a more convenient method for the accident reconstructionist than the conventional, two-step method in relating injury to the input conditions that caused the injury. This is due to bypassing the response calculation and correlating injuries directly with the Delta-v injury database.

The rear-ender accident involving vehicles with energy absorbing bumpers is also analysed. It was found possible to produce 'whiplash' injuries in cases where there was little or no damage to either of the vehicles involved in the crash. The paper looked at work on Delta-v thresholds for whiplash injuries conducted in the 1940s and 50s. Test data by Mertz and Patrick (1971) using human volunteers and cadavers and Melvin and Weber (1985) were used to summarise injury threshold moments for the 50^{th} percentile male. The 120 Newton-meters was selected for the flexion mode, in the extension mode of rearward bending (the so-called "whiplash" mode). The injury threshold was selected at 57 Newton-metres; and 54 Newton-metres for lateral flexion. In other words, an average human being could withstand those levels of force being applied from a single exposure.

Age, sex, general health conditions, physical size, and skeletal development all affected the impact tolerance of various individuals. For example, females are approximately 10% more flexible than males in extension, and approximately 4% more flexible in flexion. In regards to strength, males are stronger than females by a factor of about 1.5.

In the terms of probability of injury, Schutt and Dohan (1968) reported that women were 4.8 times more likely to receive a whiplash injury than males in urban populations and 1.7 times more likely in rural areas. The paper explains that the introduction of energy absorbing bumpers can result in situations that can confuse the accident reconstructionist. Namely, where individuals can experience cervical spine injury in a rear-end collision, even when there is very little or no sheet metal damage to the vehicles. The data also show that Delta-v depends on the weight ratio of the two vehicles and the energy absorbing rating of the two bumpers. In addition, bumpers that absorb all the collision energy and do not return compressed energy will reduce Delta-v numbers. The concept of differential rebound was introduced by States (1979) who hypothesised that some injuries were explained by the existence of different spring rate characteristics in the main section of the seat back and the head restraint.

As the occupant compressed the seat cushion in the first part of the impact sequence, energy was stored by the seat and head restraint. The result was thought to be that the torso rebounded much faster off the seat than did the head from the head restraint; with the consequence that hyperextension of the neck was produced. This could cause the Delta-v forces transmitted in a rear-end collision to increase substantially. It is conceivable that the upper limit on Delta-v between head and torso could be double the struck vehicle's Delta-v. The paper concluded that the reconstructed Delta-v could provide evidence that an accident was severe enough to have been the cause of injuries to the vehicle occupants. However, for calculated Delta-v below the 50th percentile injury thresholds given, the reconstructionist must rely on the biomechanics community to provide data on divergences from the threshold data.

Varying factors about the occupants influence injury thresholds considerably, but quantitate data are very sparse in terms of Delta-v thresholds and the paper urged biomechanics researchers to generate more quantitative data on the Delta-vs leading to cervical spine injury. The final observation was that "it is apparent that the injury threshold is above 8 km/hr, even for subjects with mild pre-existing spinal degeneration" Schutt and Dohan (1968).

In 2001 Braun et al (2001) prepared a paper entitled "Rear-End Impact Testing with Human Test Subjects". In this study low speed rear-end aligned bumper-to-bumper impact tests were conducted. The bullet vehicle impact speeds were 2 – 6.5 mph. This produced speed changes (Δv) between 1.5 – 4.5 mph. Seven human volunteers, female and male in the age group 29 – 61 years were involved in the testing. All participants were considered to be in good health prior to the start of the testing. Two test subjects were present in the target vehicle and one person drove the bullet vehicle for each of the seven tests. Occupant kinematic response was monitored by video tape and test subjects were interviewed immediately post impact to record subjective impressions. The collisions resulted in restitution figures between 0.3 – 0.5 and the time of collisions ranged between 0.09 – 0.124 seconds.

There were three objectives to the crash testing, these were:-

A) Firstly, it adds to the human exposure database by testing human volunteers in low speed rear-end impacts at a level that was at or below the level associated with no significant risk of injury.

B) The second was to subjectively describe and characterize the severity of the impact that was experienced by the occupants. (This was in addition to characterizing impacts in terms of delta v or peak acceleration.)

C) The third objective was to evaluate the vehicle dynamic response to low speed rear-end impacts. They were also interested in considering the effects of a driver having the foot brake applied compared to no braking effort applied.

Test 1 resulted in the target vehicle experiencing a speed change of 1.5 mph. This was considered a trivial impact by the occupants. There was a slight bump with no significant noise or noticeable forward displacement of the vehicle. The target vehicle was pushed forwards 25 cm and the vehicles were touching at rest. Neither test subject experienced any symptoms of discomfort or pain.

Test 2 was a speed change of 3 mph. Interestingly, this impact was significantly more forceful in nature and was near the limit of what both subjects associated with head accelerations near to the limit of that experienced in daily activities. One of the subjects noted contact with the head restraint. The target vehicle was pushed forwards 38 cm and the vehicles were touching at rest. Neither test subject experienced any symptoms of pain or discomfort immediately following the test.

Test 3 resulted in a speed change of 3.9 mph. The impact was quite forceful and was accompanied by a crashing sound at impact, noted by the subjects. Both subjects were displaced rearwards into contact with the head restraints. The contact is described as 'noticeable'. Both subjects considered the severity of impact to have produced accelerations above that experienced in daily activity. Interestingly, neither experienced pain or discomfort immediately following the test.

Test 4 resulted in a speed change of 4.5 mph. The impact was described as before, with both subjects making contact with the head restraints. Additionally, the driver's foot came off the brake and the vehicle rolled forward a considerable distance before the brake was reapplied.

Again, neither party experienced any pain or symptoms of pain or discomfort immediately following the test.

Test 5 was a collision with a speed change of 2.6 mph. Both subjects noted that their heads were displaced rearwards into the head restraint. No pain or discomfort was felt immediately following the test.

Test 6 resulted in a speed change of 4.5 mph. Both subjects made contact with the head restraints and considered the severity of the impact exceeded forces or accelerations experienced in daily activity.

Test subject A noted a transient headache immediately following the test which lasted several minutes and then went away.

Test 7 was a collision with a speed change of 4.1 mph. The impact was considered 'quite forceful' and generated a significant crashing sound. There was a noticeable impact with the head restraint. Both subjects considered that the collision provided accelerations above those experienced daily. Test subject B's foot came up off the brake. Neither subject experienced any pain or discomfort immediately following the test.

The conclusions from the testing are that with speed changes of 4.5 mph, normally seated healthy adults with adequate head support can tolerate such changes without significant risk of injury.

Collisions which result in speed changes of 3 mph or less could reasonably be related to activities of daily living. The forces on the head, neck and torso were considered by the subjects to be within the range experienced in daily activity. Speed changes of 3 mph or above resulted in the subjects making contact with the head restraint. Below 3 mph there was either no contact or contact was not discernible.

Restitution values for the test ranged between 0.3 – 0.5.

The impact durations ranged from 0.09 – 0.124 seconds.

Peak acceleration of vehicles was between 1.5 – 2.7 times higher than the average acceleration.

Forward displacement of the target vehicle was a poor indicator of the nature of the collision in terms of impact severity.

Vijayakumar et al (2006) undertook a study involving a number of bumper car tests. The Δv of the target vehicles ranged from 2.4 – 3.7 mph. The collisions resulted in peak vehicle accelerations of 1.2 – 6.9 g.

GBB is an independent organisation which was set up to investigate car crashes.

In 2005 Sintra Engineering of Canada, a company of a similar type to the forensic research company GBB, carried out a statistical analysis of all available staged crash testing and real world collisions where reliable data was available. The results were published in SAE Technical Paper 2005-01-0296 (Moss et al, 2005). The findings are presented in the form of an equation and a graph produced by the analysis of over 200 collisions (see Figure 1.3). Due to the numbers involved, these results are statistically significant and cannot be dismissed lightly.

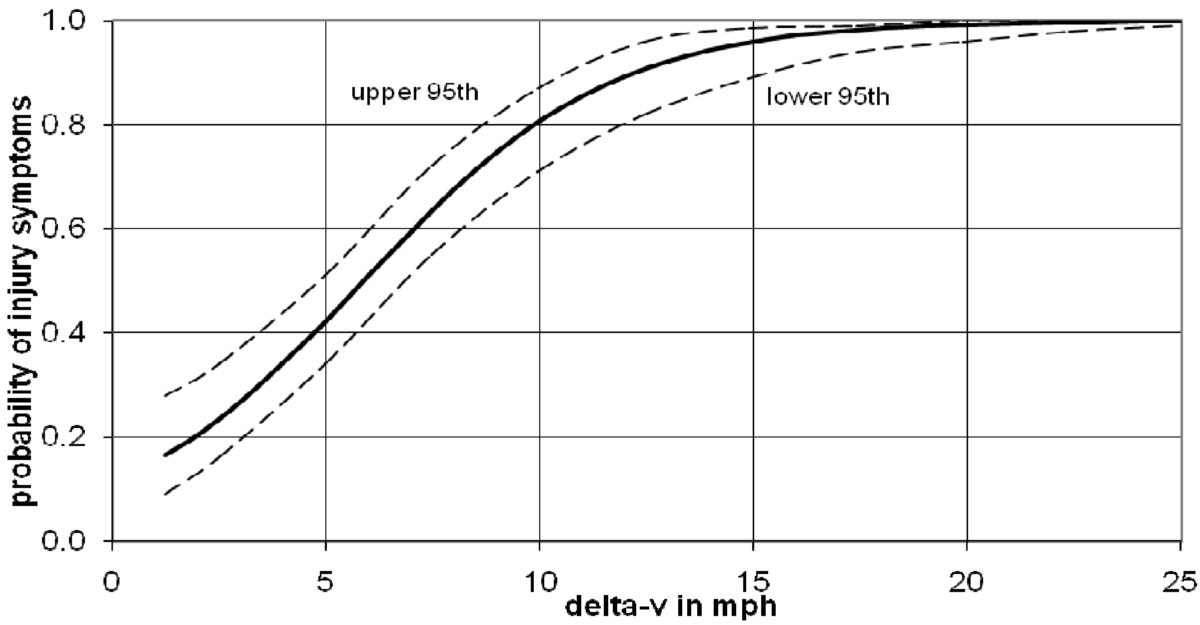


Figure 1.3: Relationship between the probability of injury/symptoms and delta-v in mph following SINGLE EXPOSURE REAR IMPACTS – taken from SAE Technical Paper 2005-01-0296)

The main features of this graph are as follows:

The scatter of data points that make up the graph in Figure 1.3 are low as 90% of all points and they are contained within the upper and lower 95th percentile bands.

The injury symptoms are WAD grades 1 and/or 2 as defined by the Quebec Task Force on Whiplash Associated Disorders.

WAD grade 1 = only neck complaints such as pain, stiffness or tenderness.

WAD grade 2 = neck complaints and musculoskeletal signs.

The threshold value of Delta-v is 5.87 mph. This is the value of Delta-v where the probability of injury symptoms is 50%.

The vehicle occupants included in the study cannot be taken as representative of the general population or of any specific group within the general population. On the other hand, the vehicle occupants, who were in staged and real world collisions, cannot be considered to be totally unrepresentative. If the curve is extrapolated down to a Delta-v of 0 mph, a probability around 0.1 is predicted. This, of course, cannot be correct, as the vehicle would not be moving. This anomaly can possibly be explained by the placebo effect, exaggeration and mistaken diagnosis (Castro et al, 2001). It should also be noted that not all the occupants were examined by a medical expert following their collisions. Thus, at low values of Delta-v, the curve becomes unreliable. Conversely, as Delta-v increases towards the threshold, the curve must become more reliable as genuine injury becomes more likely.

It is not intended by the author of this thesis that a probability should be given for any particular value of Delta-v. The intended use is that if a value of Delta-v is above 5.87 mph, then it can be stated that, on the balance of probabilities, injury symptoms are likely to have occurred. If a value of Delta-v is below 5.87 mph, then it can be stated that, on the balance of probabilities, injury symptoms are unlikely to have occurred. If an occupant is claiming a whiplash injury with symptoms greater than WAD 2, then, for an otherwise healthy occupant, their Delta-v should have been greater than 5.87 mph.

In an attempt to produce a more realistic representation of the probability at low values of Delta-v, an alternative curve can be introduced as shown in the following graph (Figure 1.4).

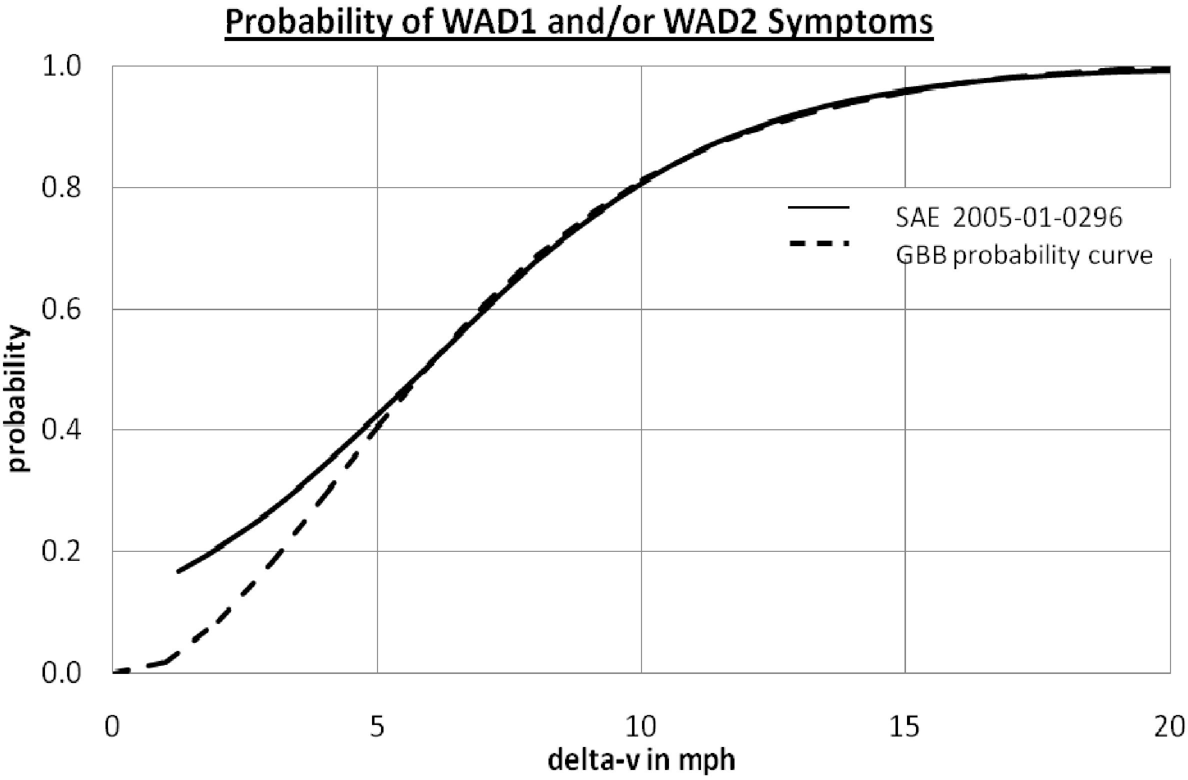


Figure 1.4: Graph showing the probability of WAD1 & WAD2 vs. the delta-v in mph (taken from Moss et al, 2005)

The GBB probability curve is not based on crash testing data but it has been chosen to be more realistic for low values of Delta-v (as at 0 mph there is no probability of occupant movement) while still producing the same threshold as the SAE curve. Above the threshold, the two curves are nearly identical.

The equation for the SAE curve is:

$$p = \left[1 + e^{(2.0489 - 0.3488\Delta v)}\right]^{-1}$$

The equation for the GBB curve is:

$$p = 0.00000010252\Delta v^6 - 0.0000090164\Delta v^5 + 0.00031222\Delta v^4 - 5.2370E\text{-}03\Delta v^3 +$$

$$0.038886\Delta v^2 - 0.016312\Delta v$$

From both research and real world collisions, it has been established quite clearly that in a collision between vehicles of similar mass, occupants in the struck or target vehicle are at a greater risk of injury than occupants in the striking or bullet vehicle (Bailey et al, 1995). It is believed that the reason for this is that occupants in the struck vehicle are subjected to a particular acceleration/deceleration mechanism, often called the whiplash mechanism. This mechanism will cause disparity in the accelerations of the head and chest of an occupant which can lead to injury if the disparity is of sufficient magnitude. Occupants in the striking vehicle are subjected to a deceleration mechanism which does not cause such large disparities in the accelerations of the head and chest and therefore these occupants are less likely to be injured for the same value of Delta-v.

Historically, research into adverse symptoms resulting from rear-end collisions have been correlated against the change in speed or Delta-v of the struck vehicle. Delta-v (Δv) is an easily measurable quantity and given that most collisions take place over a similar period of time, Delta-v will also be a measure of the accelerations and forces experienced by the occupants of the struck vehicle (Castro et al, 1997; Braun et al, 2001; Brault et al, 2004; Henderson et al, 2009).

GBB (UK) Ltd, a private Company based in Burnley Lancashire, has carried out a number of full-size, rear-end collisions with instrumented vehicles and occupants. From these tests, correlations between acceleration disparities of the head and chest and Delta-v have been established for occupants of both bullet and target vehicles. These correlations are presented in the following graphs {CT = crash test}(see Figure 1.5 and 1.6).

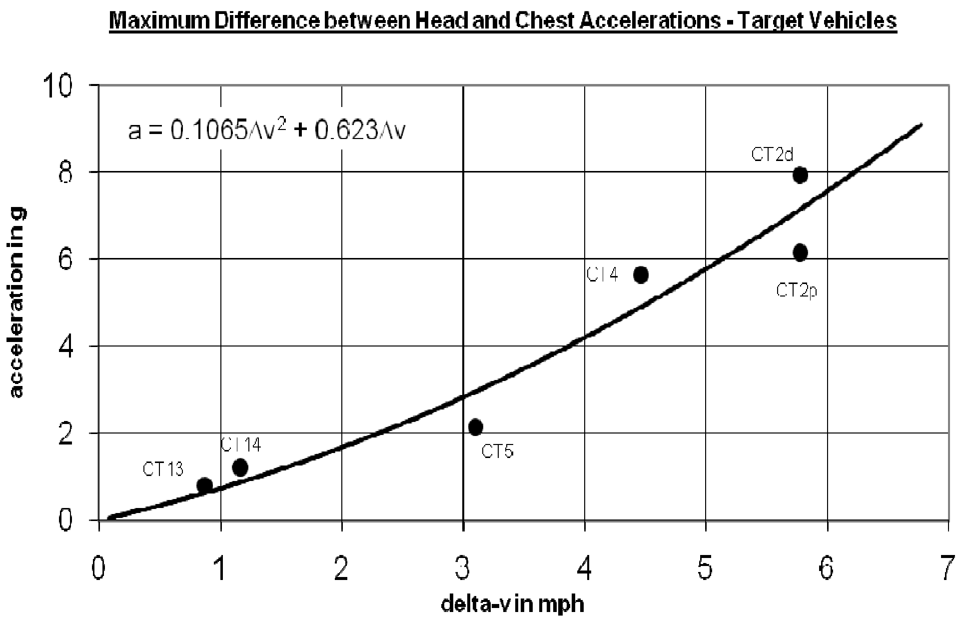


Figure 1.5: Relationship between the acceleration and delta-v in mph showing the max. difference between the head and chest accelerations

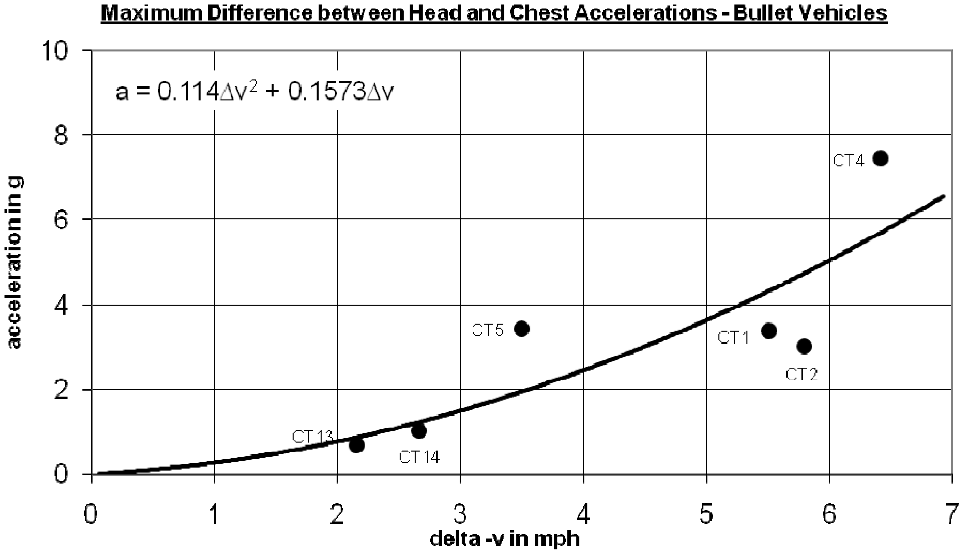


Figure 1.6: Relationship between the acceleration in g and delta-v in mph showing the max. difference between the head and chest accelerations

Tables 1.2 and 1.3 show the analysis of the results.

For the target vehicles, the data points are fairly close to the trend line. The correlation test shows a goodness of fit at about 92%. For the bullet vehicles, the points do not indicate such a good correlation with rather more scatter than in the target vehicle graph. The correlation test produces a 68% goodness of fit. More data points are required to give greater authenticity to the trend line.

It can be clearly seen from the above two graphs (see Figures 1.5 and 1.6) that the maximum difference between head and chest accelerations is greater for occupants in a target vehicle than it is for occupants in a bullet vehicle. This offers a plausible explanation in terms of occupant movement of the increased risk of injury to occupants in the target vehicle, (Bailey et al, 1995). Bumper car tests suggested the maximum pulse was 4.9g in 55.7 msec. This was defined as the envelope of safety for the human volunteers. (Balasubramanian et al, 2009).

Table 1.1 Correlation Test for Target Vehicles

	DeltaV	Max Disparity	Term 1 $(x_i-\bar{x})(y_i-\bar{y})$	Term2 $(x_i-\bar{x})^2$	Term3 $(y_i-\bar{y})^2$
	0.88	0.80	8.38	7.00	10.05
	1.17	1.19	6.55	5.55	7.73
	3.10	2.15	0.77	0.18	3.31
	4.46	5.62	1.54	0.87	2.72
	5.77	6.14	4.87	5.04	4.71
	5.77	7.92	8.87	5.04	15.60
Mean	3.53	3.97			
Σ			30.99	23.68	44.12
				r	0.96
				r^2	0.92

Table 1.2 Correlation Test for Bullet Vehicles

	DeltaV	Max Disparity	Term 1 $(x_i-\bar{x})(y_i-\bar{y})$	Term2 $(x_i-\bar{x})^2$	Term3 $(y_i-\bar{y})^2$
	2.25	0.85	5.06	4.59	5.58
	2.72	1.03	3.65	2.80	4.76
	3.57	3.38	-0.14	0.68	0.03
	5.55	3.55	0.39	1.34	0.11
	5.83	3.05	-0.23	2.06	0.03
	6.44	7.41	8.59	4.19	17.63
Mean	4.39	3.21			
Σ			17.33	15.66	28.13
				r	0.83
				r^2	0.68

From a close examination of the acceleration data for occupants in target vehicles, it appears that the maximum disparity between accelerations of the head and chest occurs when the acceleration of the chest has returned to zero and the head is close to its peak value of acceleration. In other words, the chest is about to decelerate while the head is still accelerating.

The following graph below in Figure 1.7 contains the trend lines for both target and bullet vehicles.

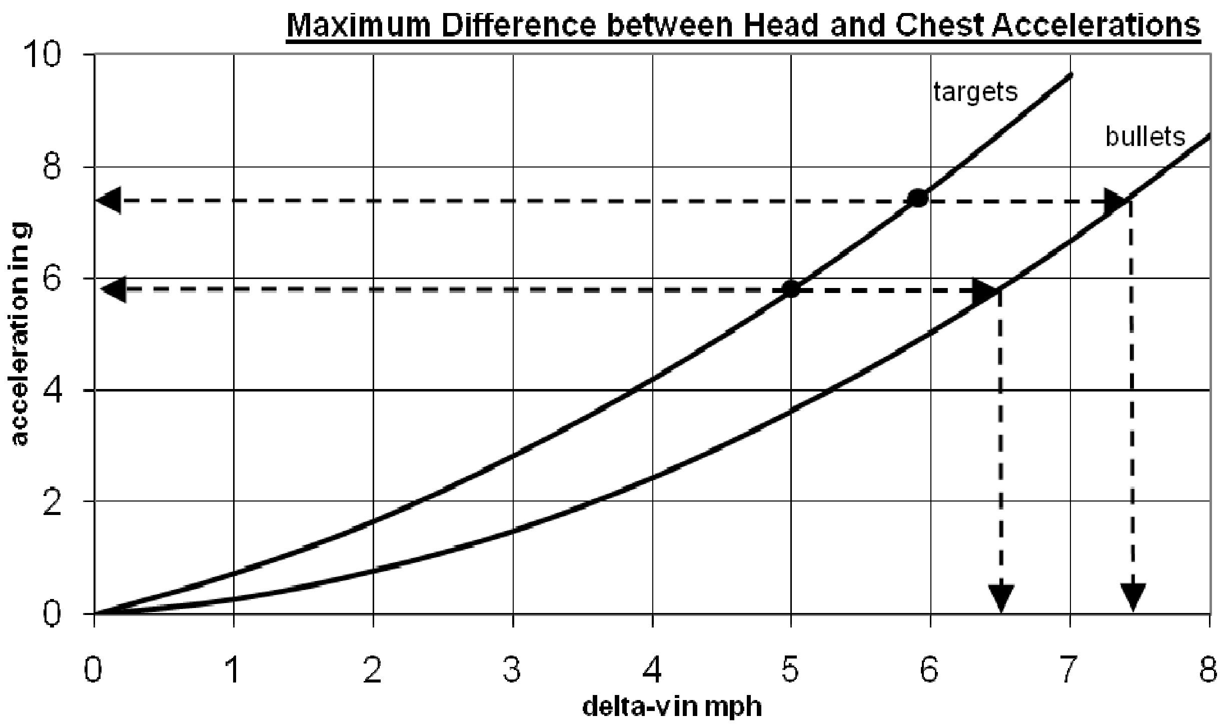


Figure 1.7: Relationship between acceleration in g and delta-v in mph showing the difference between bullet and target vehicle

An important result that is unique to GBB can be obtained from this graph.

A not insignificant proportion of injury claims are made by occupants in bullet vehicles (source: Association of British Insurers). The graph in Figure 1.7 allows an injury threshold for bullet vehicle occupants to be determined based on the same criterion that is applied to occupants in target vehicles.

The data shows that at a threshold Delta-v of 5 mph, the graph indicates that the maximum difference between head and chest accelerations is 5.8 g. From the bullet vehicle curve, the same value of 5.8 g is achieved at a Delta-v of 6.5 mph. This would be the threshold value for bullet vehicles (see arrows at Figure 1.7).

Alternatively, by taking the threshold value of 5.87 mph predicted by Moss et al (2005), a maximum difference between accelerations of the head and chest of 7.3 g is indicated. From the bullet vehicle curve, the same value of 7.3 g is achieved at a Delta-v of 7.4 mph. This would be the threshold value for bullet vehicles.

In summary, the results from GBB over the last few years have clearly shown the available conservative values of target and bullet vehicle thresholds of 5 mph and 6.5 mph, respectively. Recent studies show more accurate thresholds based upon the statistically significant data provided in the SAE paper combined with research data obtained by GBB. In this case the target and bullet vehicle thresholds are 5.87 mph and 7.4 mph, respectively (Fig 1.7 above).

1.6 Working Hypothesis

This project tests the hypothesis that low speed change collisions following vehicle collisions always result in occupant injury.

1.7 Aims and Objectives

Having been involved in collision reconstruction over a period of years, it was evident that there is little or no research from the United Kingdom which is directly relevant to the problems encountered in understanding 'low speed change' collisions. The collisions were referred to as 'low speed collisions' or 'minimal impact collisions'. Therefore, a number of aims were outlined for the proposed research:

1. To understand the interaction of motor vehicles in different collision layouts.

2. To study the movement of the occupants of those vehicles in great detail and to understand the levels of acceleration experienced during the collision phase.

3. To design and build a simulator capable of replicating the speed changes encountered during rear end collisions.

4. To consider the research against similar or related international studies.

5. To analyse the data and write up the MSc by Research thesis.

6. Publish the work in peer reviewed journals where possible.

As the research developed, it was hoped that an understanding of these types of collisions and their effects upon the occupants involved would also enhance knowledge in the proposed area which in turn may reduce frequency of injury and reduce costs to the Motor and Insurance Industries.

Chapter 2

Materials and Methods

2.1 Materials

2.1.1 Roadworthy Motor Vehicles

Purpose designed and built collision simulator

Vericom DAC 3000 accelerometric data recorder

Crossbow 10 g accelerometers

Crossbow 25 g accelerometers

Sony HDR-HC3 high speed camera

Sony DCR-SR37 high speed camera

Skidman data recorder

Garmin GPS

2.2 Methodology

2.2.1 Background: In order to improve understanding on low speed change collisions, the project embarked upon a lengthy study of low speed collisions starting in 2003, instigating a number of crash tests with colleagues in an attempt to consider a likely threshold at which 'whiplash' type injuries occurred. A number of previous studies suggested a threshold of 5 mph, the resultant change in velocity for a struck vehicle in a rear-end collision (McConnell et al, 1993; Szabo et al, 1994; Castro et al, 2001).

2.2.2 General Procedure: In accordance with the Declaration of Helsinki, prior to testing, test subjects were asked to complete a questionnaire relating to general health and to confirm their involvement in research. Whilst the intention was not to cause injury, any research clearly did pose such a risk and each test subject had to be made acutely aware of such a situation. A copy of the questionnaire and disclaimer is shown at Appendix 1. The project received ethical clearance from UCLAN Ethics Committee.

Testing carried out in 2003 was relatively primitive as the recording equipment was not sophisticated enough to provide full data for each collision. However, what could be obtained were the impact speeds and subsequent calculations of post impact velocities, amounts of damage, effects upon occupants and identification of the stages of a collision. The impact speeds were checked against radar and the collisions were filmed. In March 2005 a number of 'roll into' tests were undertaken, and in June 2005 further full scale testing was completed.

2.3 Crash Testing in 2005

The June 2005 testing was completed using different vehicles in a variety of tests. The recording equipment that was used consisted of Vericom VC3000 units placed in vehicles and external accelerometers placed on occupants of the vehicles.

A detailed analysis of one of the tests (Crash Test 2) was undertaken and the different measured parameters are shown below. These include (A) the crash test number and (B) the vehicle details and (C) the target vehicle:

Crash Test Number 2 (CT2)

Crash Layout: Front to rear impact

Bullet Vehicle Speed: 11.1 mph

Target Vehicle Speed: 0 mph

Vehicle Details

Bullet Vehicle

Number: 2

Make: Vauxhall

Model: Carlton

Kerb weight: 1166 kg

Driver: Paul Brooks

Passenger: Ian Law

Target Vehicle

Number: 1

Make: Toyota

Model: Celica

Kerb weight: 1135 kg

Driver: Eric Taylor

Passenger: Dan Bradshaw

2.3.1 Crash Layout

The Toyota Celica was an automatic transmission vehicle which was stationary with the handbrake applied and the gear lever in neutral mode. The vehicle was fitted with the Vericom VC 3000 data recorder, and the driver and passenger were each fitted with external 25 g and 10 g accelerometers at the head and chest, respectively. The Vericom unit fitted to the target vehicle had a guaranteed accuracy up to ± 2 g. Beyond this value, the readings were less reliable but this would have little effect on velocity and displacement values that were integrated from the acceleration data. The sampling interval of the accelerometers was 0.01 seconds.

In contrast, the Vauxhall Carlton was an automatic vehicle and was driven at a steady speed of 10 mph as indicated upon the speedometer of the vehicle. It was driven into the rear of the Toyota and the brakes were not applied at any stage until the vehicle came to a complete stop after the collision.

The speed of the Vauxhall was checked by radar and found to be 11 mph. (Note radar showed full increments of 1 mph.) Accelerometer data from the Carlton indicated an impact speed of 11.1 mph. This was the value used in calculations.

2.3.2 Driver Instrumentation

The driver was fitted with two accelerometers. A 25 g accelerometer was fitted on the forehead and a 10 g fitted to the chest. Figure 2.1 below shows the positioning of the accelerometers and their orientation.

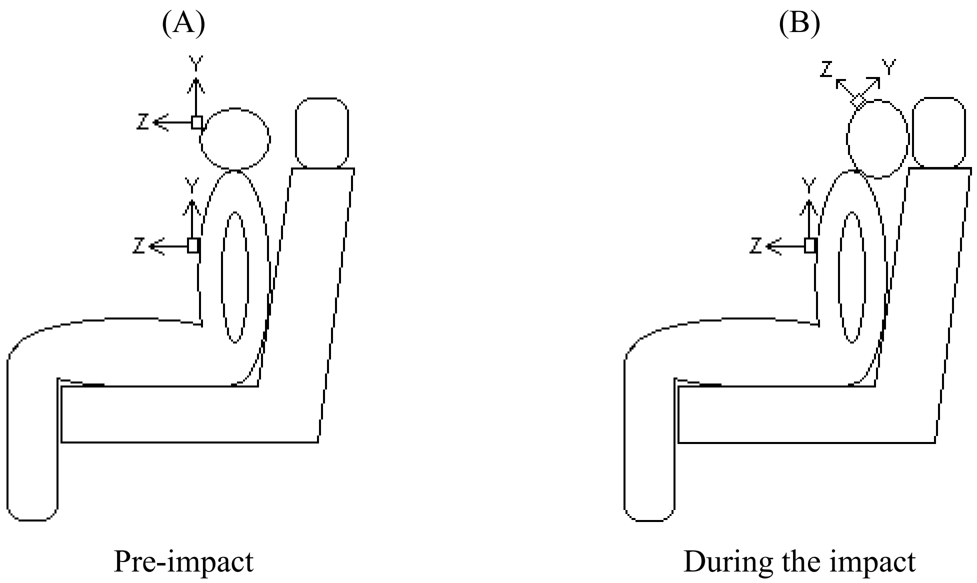


Figure 2.1: Diagrams in the figure showed (A) pre-impact and (B) during the impact following an early stage of collision at GBB.

The body of an occupant was able to experience an impact force through the seat (Figure 2.1A). The body would accelerate under the action of this force but the motion of the head would lag behind that of the body during the early stages of a collision. This lag in turn would cause the head to rotate and the orientation of the accelerometers to change as shown in Figure 2.1B above.

Later on during the impact, the rotation of the head might be in the other direction as forces transferred to the head through the neck structure would cause the head to accelerate past the body. It should be noted that the graphs of head accelerations shown below had not been corrected for changes in orientation. The maximum acceleration experienced by the head would be the resultant of accelerations in the individual axial directions.

2.3.3 Simulator Testing

In addition to the 'full size testing' programme, it was felt that a series of simulated tests would assist greatly if the time of the collision could accurately be replicated. If then the speed of impact could be replicated, it would be possible to increase the occupant study numbers dramatically. The simulator testing programme commenced in 2005. Figure 4.5 shows the testing protocol.

The applicant designed the rig based upon a piece of gymnasium equipment. It was noticed that a leg exercise machine consisted of a seat upon a track where resistance of the weights was used to push the occupant to a rest position. Use of the leg muscles pushed the seat up the track. It was the belief that in reverse a seated vehicle upon a track could, with the use of falling weights, be accelerated to given speeds, thus:

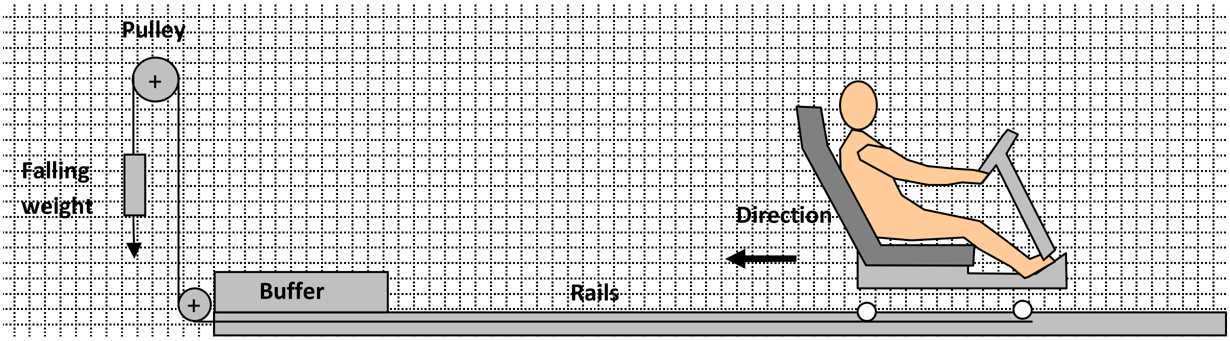


Figure 2.2: A diagram showing the testing protocol.

In such a configuration, the occupant movement would be akin to the movement of the occupant of the target vehicle involved in a rear end collision. A local company constructed the equipment to the applicant's design and a seat from a Toyota Carina was used. A mounting point for the accelerometer was positioned at around steering wheel height so that when held, the occupant position was similar to the driver's position. Mounts for the feet were also added to consider the effects if occupants had their feet on the vehicle control pedals in any given collision scenario. A seat belt was also fitted.

An image of the finished equipment is shown below in Figure 2.3:

Figure 2.3: A photograph showing the whiplash simulator which replicates collisions of given speed changes.

2.3.4 Daily Activity

Using the same accelerometer placements, everyday activity such as sitting in a variety of chairs, stalling a vehicle and numerous others were undertaken with the research subject asked to undertake the task in a normal relaxed manner.

2.3.5 Statistical Analysis

All data are presented as original graphs or tables. Correlation tests use Pearson product-moment correlation coefficient.

Chapter 3

Results

3.1 Target Vehicle

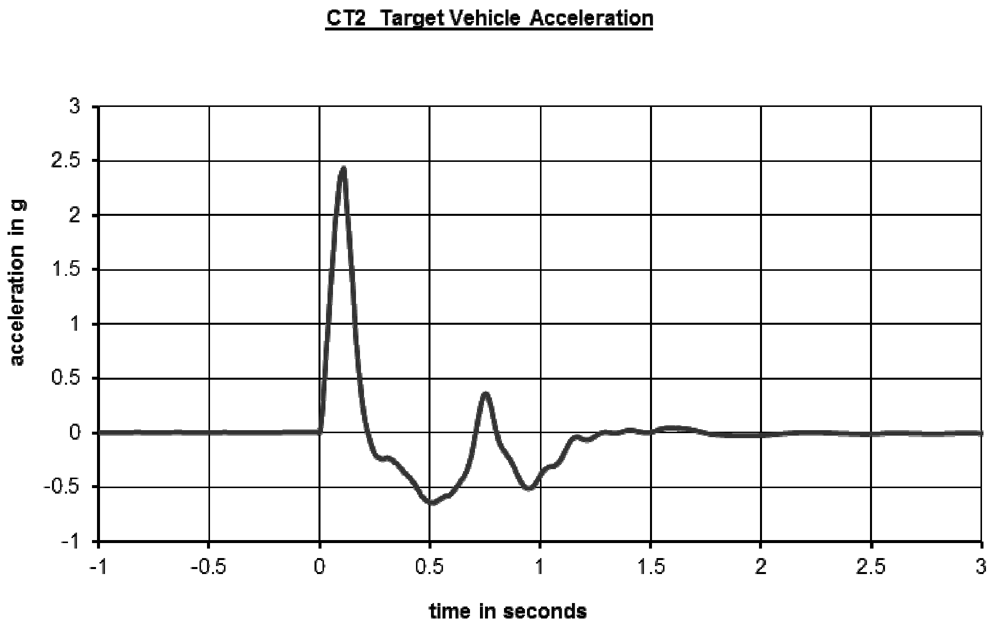


Figure 3.1: Time course graph (in seconds) showing target vehicle accelerations in g. This graph is typical of 10-15 such different experiments undertaken in this study.

The timescale of the accelerometer was adjusted so that the impact started at 0 seconds. The acceleration reached a peak of 2.43 g at 0.11 seconds. As explained in Chapter 2 (Materials and Methods), this is probably an underestimate maximum value of acceleration experienced by the target vehicle. The impact ended at 0.22 seconds when the acceleration returned to below zero reaching maximum at 0.5 seconds. At this point the vehicles disengaged.

A second impact between the bullet and target vehicles occurred as indicated by the second peak of acceleration at 0.75 seconds (see Figure 3.1). This occurred because the bullet vehicle did not brake during the first collision and the engine continued to run and driving the vehicle forward into a second small collision with the rear of the target vehicle. The periods of negative acceleration occur as the target vehicle slows down following each impact. The vehicle reached zero acceleration after 1.2 seconds following collision.

It is commonly accepted, and indeed taught, that a rear-end collision can occur in around 1/10 of a second. This was frequently observed during the experiment. This was also noted in previous crash testing. It was also observed that other than direct contact injury, occupant injury occurs from the acceleration applied in a very short space of time. In other words, it is the time from 0 mph to the time of peak acceleration (g) that appears to be important.

From Figure 3.1, it can be seen that the whole of this collision from start of impact to the end of impact took just 0.22 seconds, with the vehicle accelerating throughout up to 5.97 mph, but the peak acceleration phase occurred in 0.11 seconds.

During this time course experiment, the Toyota accelerated from 0 to 2.43 g in 0.11 seconds. This equates to a velocity change of around 4 mph, giving an average acceleration of about 16 m/s^2 or 1.63 g. The results from this figure are above the threshold reaching 6 mph after 0.2 seconds. This time of around 0.1 seconds was found throughout all the tests undertaken in the testing programme and this is consistent with previous studies over the past 8 years. In a collision with a total velocity change of 5 mph, during the first 0.1 seconds or thereabouts, a vehicle (as in this test) would reach 4 mph, and in the following 0.1 seconds or thereabouts would accelerate from 4 mph to 5 mph.

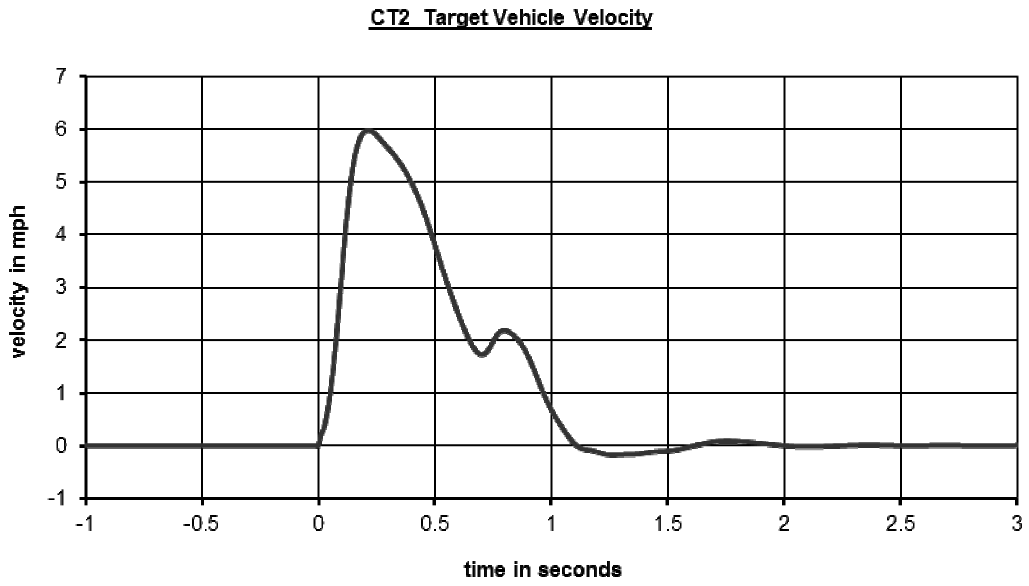


Figure 3.2

Figure 3.2: Time course changes in Target Vehicle Velocity in CT2 experiment. This is typical of 15-20 similar tests. Note the rapid increase in velocity and the gradual decrease within 1 second of the experiment.

The velocity of the target vehicle increased throughout the collision and reached a maximum of 5.97 mph (2.67 m/s) at 0.22 seconds at the point when the vehicles disengaged (Figure 3,2). A smaller peak of just over 2 mph (0.9 m/s) at about 0.8 seconds is due to the second impact between the bullet and target vehicles. The bullet vehicle came to rest about 2 seconds after the start of the main impact.

The data from the collision were compared to a mathematical momentum exchange calculation. This was done for a number of reasons; namely a) to see if momentum was conserved, b) to see if the vehicles had a 'common post impact velocity' and c) to see if the effects of elasticity affected the results. The results are shown overleaf in Table 3.1.

Table 3.1 A momentum calculation showing impact velocity, post impact velocity and post impact velocity of the struck vehicle.

Impact Velocity	Theoretical Common Post-Impact Velocity	Post Impact Velocity of Struck Vehicle from Test
11.1 mph	5.67 mph	5.97 mph

A momentum calculation, assuming a totally inelastic collision, gave a theoretical common post impact velocity of 5.67 mph. The test result gave a post impact velocity for the struck vehicle of 5.97 mph. These results indicate that it is not inaccurate, in this type of collision, to assume that it is totally inelastic for the purposes of calculation. The difference of 0.3 mph will be either due to elasticity within the collision, experimental error or a combination of the two factors.

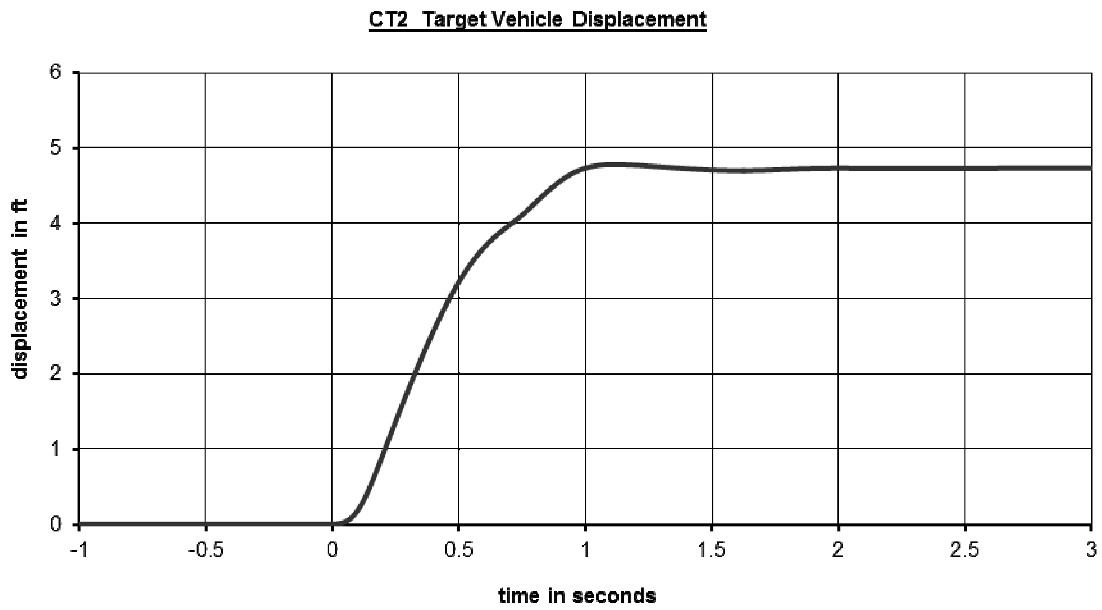


Figure 3.3

Figure 3.3: Time course graph showing target vehicle displacement in the experiment. This graph is typical of several 9-15 such different experiments.

Figure 3.3 shows the time course of displacement of the target vehicle following an impact. The results reveal that the impact caused the target vehicle to move forwards a total distance of 4.7 feet (1.4 m). This value is consistent with the target vehicle slowing down due to the application of its hand brake.

3.2 Driver Accelerations (24.5 sec to 26 sec)

The time course data in Figure 3.4 is included to give an overview of the accelerations experienced by the driver's head and chest. More detailed graphs are shown and discussed in the next section. Due to the sensitivity of the accelerometers, data displayed beyond 25.3 seconds on the time scale is down to normal movement of the occupant.

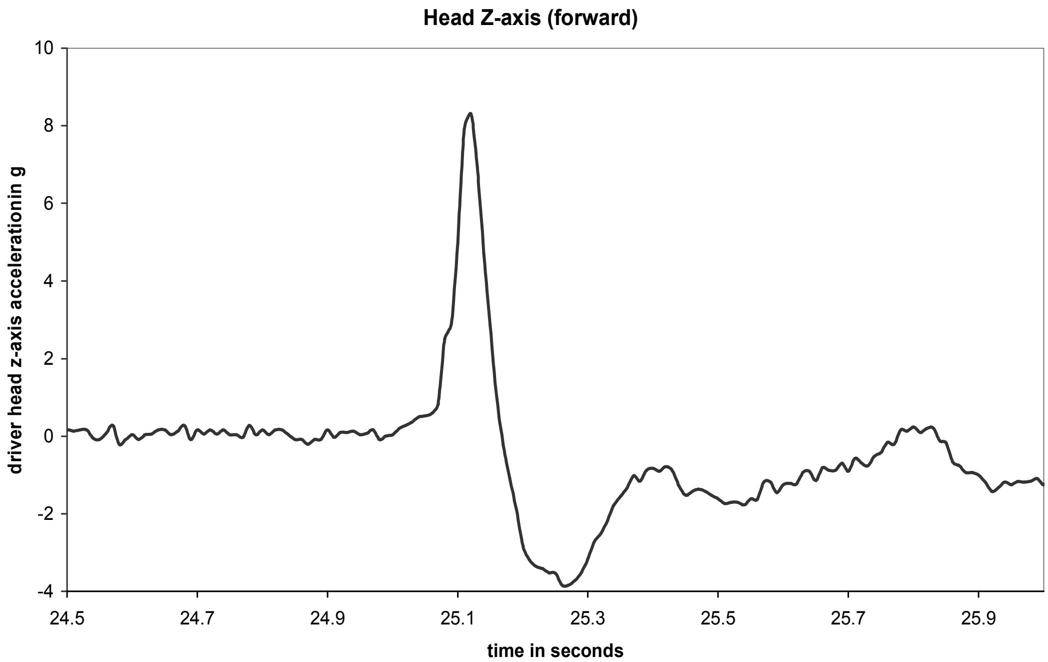
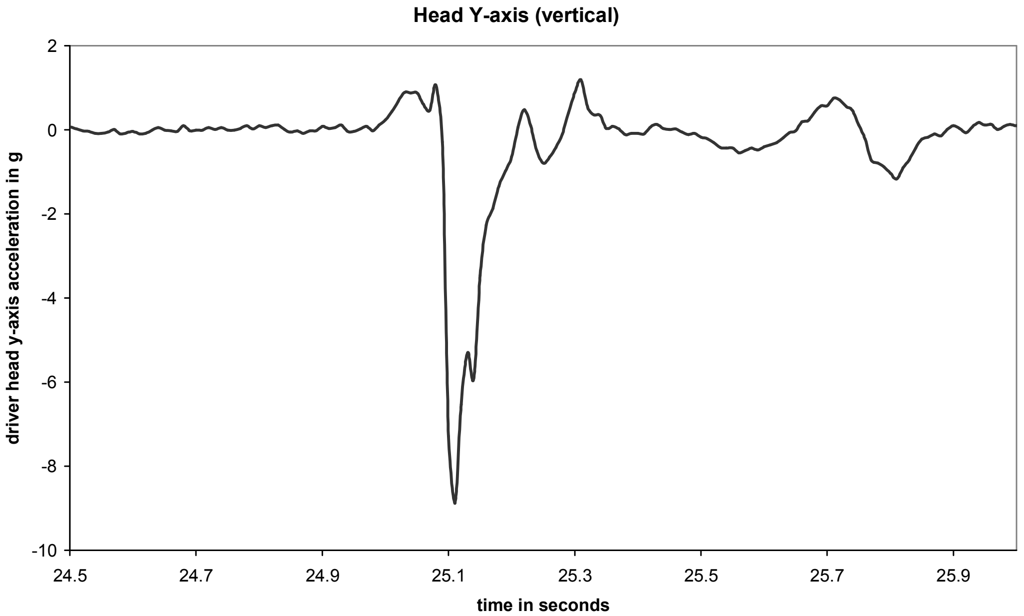


Figure 3.4

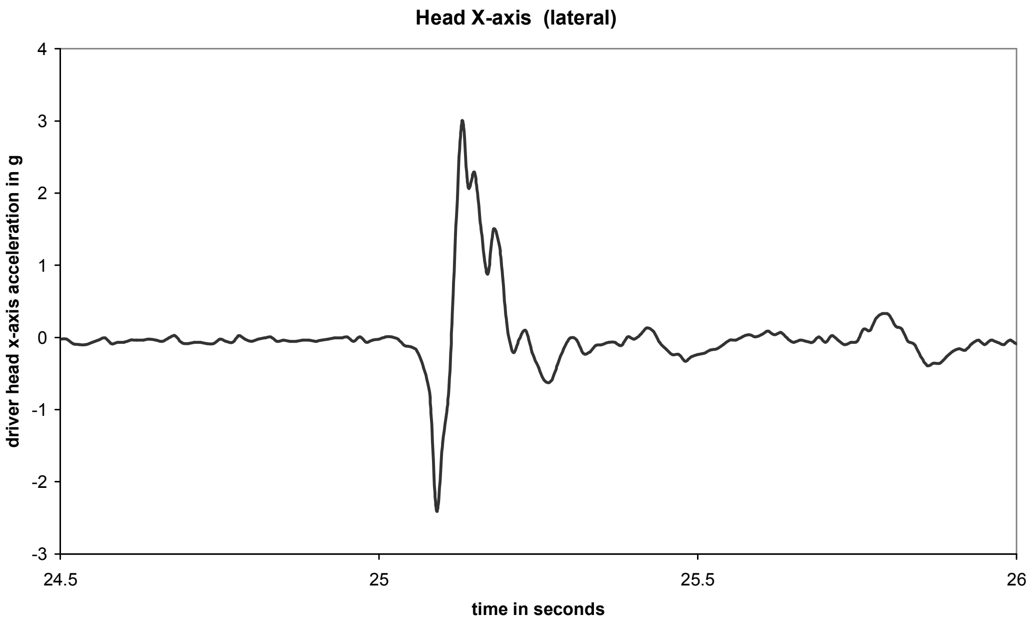
Figure 3.4: Time course of accelerations experienced by driver's head and chest during a low speed change collision. This graph is typical of 5-10 such different experiments. Note the head impact acceleration at time 25 seconds (0.1 secs after impact).

The Graphs in Figure 3.5 (A to E) show accelerations for head and chest in different axes.

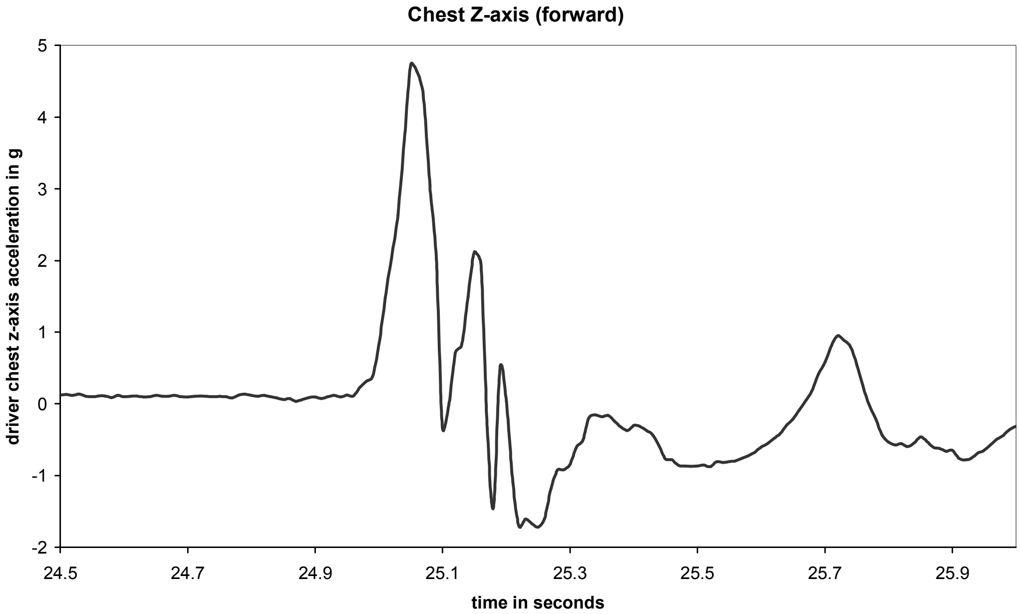
(A)



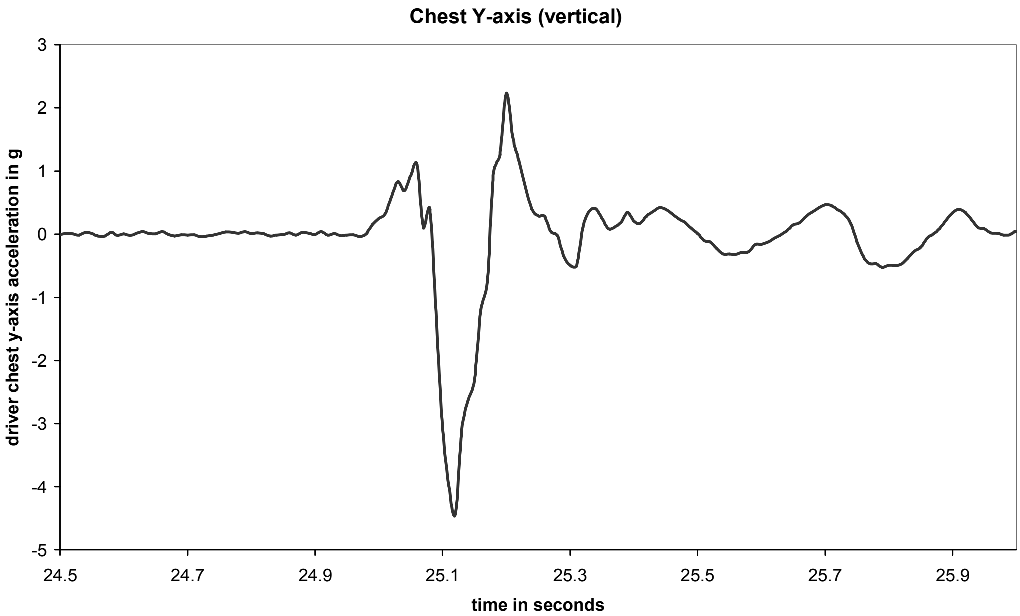
(B)



(C)


Chest Z-axis (forward)
driver chest z-axis acceleration in g
5
4
3
2
1
0
-1
-2
24.5
24.7
24.9
25.1
25.3
25.5
25.7
25.9
time in seconds

(D)


Chest Y-axis (vertical)
driver chest y-axis acceleration in g
3
2
1
0
-1
-2
-3
-4
-5
24.5
24.7
24.9
25.1
25.3
25.5
25.7
25.9
time in seconds

(E)

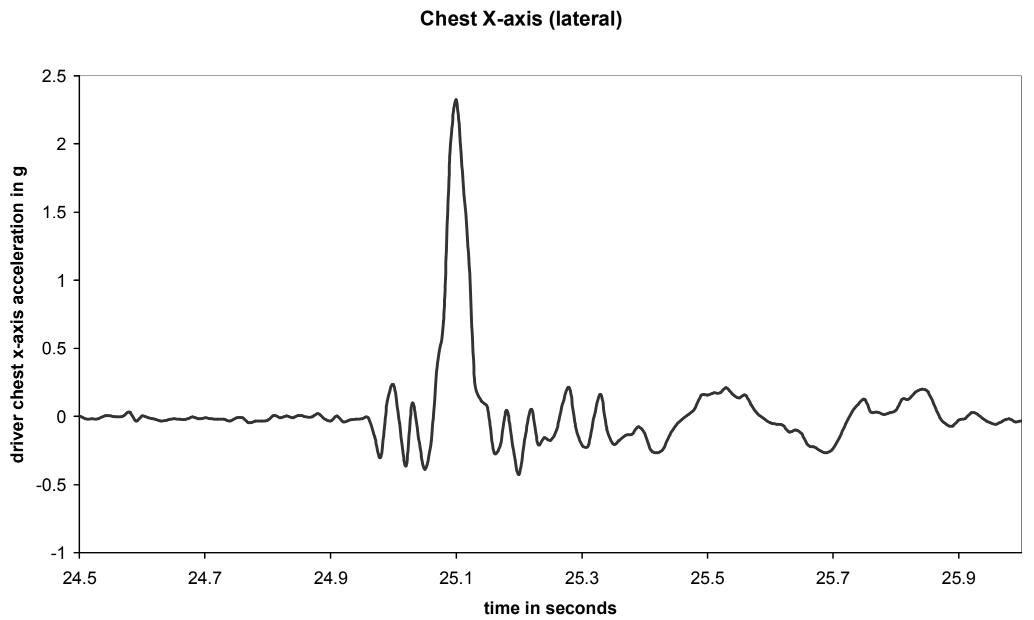


Figure 3.5: Some typical graphs (A-E) showing time course of acceleration experienced by the Driver's head and chest.

3.3 Driver Accelerations (-0.1 sec to 0.5 sec)

The timescale of the accelerometer was adjusted so that the impact started at 0 seconds.

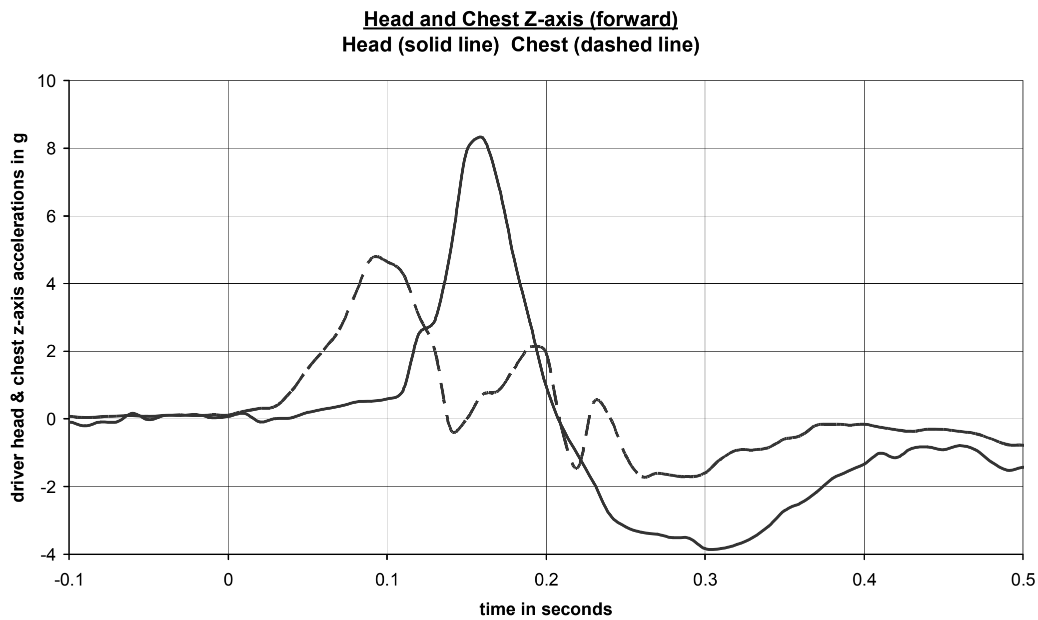


Figure 3.6: Time course changes in driver's head and chest accelerations during a low speed collision experiment. Typical of 10 such different experiments.

Figure 3.6 shows the time course of movements of the driver's head (solid line) and chest (broken line) during a low speed change collision. The results show that maximum positive and negative accelerations for both the head and chest. Typically the values were:

Maximum positive head acceleration = 8.3 g at 0.16 sec.

Maximum negative head acceleration = -3.8 g at 0.30 sec.

Maximum positive chest acceleration = 4.7 g at 0.09 sec.

Maximum negative chest acceleration = -1.7 g at 0.26 sec.

From Figure 3.6 it can be seen that the forward acceleration of the chest increased slowly at first as the initial effect of the impact was cushioned by the seat. The acceleration then rose rapidly towards its maximum of 4.7 g. After this point, acceleration of the chest decreased, probably due to the restraint of the seat belts.

Figure 3.6 also shows that up to about 0.1 seconds the difference in the accelerations of the head and chest were significant with the chest experiencing the greatest acceleration. The chest moved forwards a greater distance than the head over this period of time. The difference in forward movement between the head and chest caused shear and tensile forces to be transmitted to the head via the neck structure. As a consequence of these forces, the head rotated backwards and began its own period of acceleration in the forward direction. At about 0.11 seconds the head came into contact with the head restraint. This produced a rapid rise in the rate of increase of acceleration of the head. The head then moved beyond the chest such that the chest now lagged behind the head.

Moreover, in Figure 3.6 it can also be observed that the effect of this was that the head now applied a force to the chest that caused a rise in chest acceleration leading to the second peak of chest acceleration at about 0.19 seconds. Also, in accordance with Newton's Third Law, the chest applied a retarding force to the head that gave rise to the downward slope of the head acceleration between its peak at 0.16 seconds and about 0.21 seconds. During this phase the head rotated in the opposite sense to that achieved earlier at the start of the collision. Beyond 0.21 seconds, the forward accelerations of the head and chest were predominantly negative as by this time, the collision was coming to an end and vehicle braking became the dominant force.

From the description given above, based on actual accelerometer data, it is clear that there is a complicated relationship between the motion of the head and chest during this type of collision. Disparities in the motion of the head and chest have to be accommodated within the neck structure and it is not surprising that beyond a certain threshold of impact velocity the neck structure is unable to accommodate such differences without injury.

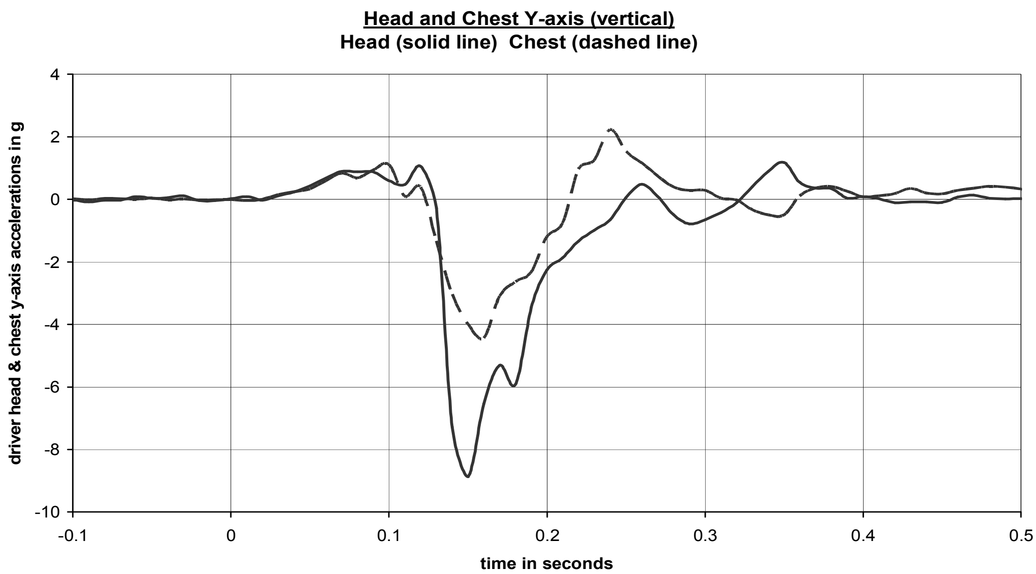


Figure 3.7: Time course changes in driver's head and chest accelerations in the vertical plane during a low speed collision experiment. Typical of 10 such different experiments.

Figure 3.7 shows the time course effect of acceleration on the movement of the driver's head (solid line) and the chest (broken line) during a typical low speed change collision test. The two tracks in Figure 3.6 show negative readings indicating that acceleration in an upward direction has occurred. From the graph it was possible to calculate the maximum positive and negative accelerations for the head and chest. The data presented below included:

Maximum positive head acceleration = 1.2 g at 0.35 sec.

Maximum negative head acceleration = -8.9 g at 0.15 sec

Maximum positive chest acceleration = 2.2 g at 0.24 sec.

Maximum negative chest acceleration = -4.4 g at 0.16 sec

Vertical accelerations of the head and chest can have a number of causes. These are:

(i) The angle at which the seat and seat back are adjusted can cause the seat to propel the occupant in an upward as well as forward direction during the course of a collision.

(ii) Due to the complicated structure of the human body and the way that it is seated within a vehicle, forward and vertical accelerations are not independent i.e. they are coupled. Thus, acceleration in a forward direction can inevitably lead to acceleration in a vertical direction. The opposite is also true.

(iii) If the point at which impact forces enter the target vehicle is above or below the centre of gravity of the target vehicle, then impact moments can be generated that can give rise to vertical accelerations.

(iv) Asymmetry in the construction and strength of the target and/or bullet vehicle can cause the impact forces to change direction as the collision progresses. This can give rise to vertical accelerations.

From the graphs in Figure 3.7, it can be seen that head and chest vertical accelerations were in phase and followed a very similar pattern to each other. Thus, peak head and chest negative accelerations occurred at about the same time. Since the head had the greater acceleration, it would have had the greater displacement indicating that the neck had been stretched in a vertical direction in a time interval from about 0.14 seconds up to about 0.32 seconds.

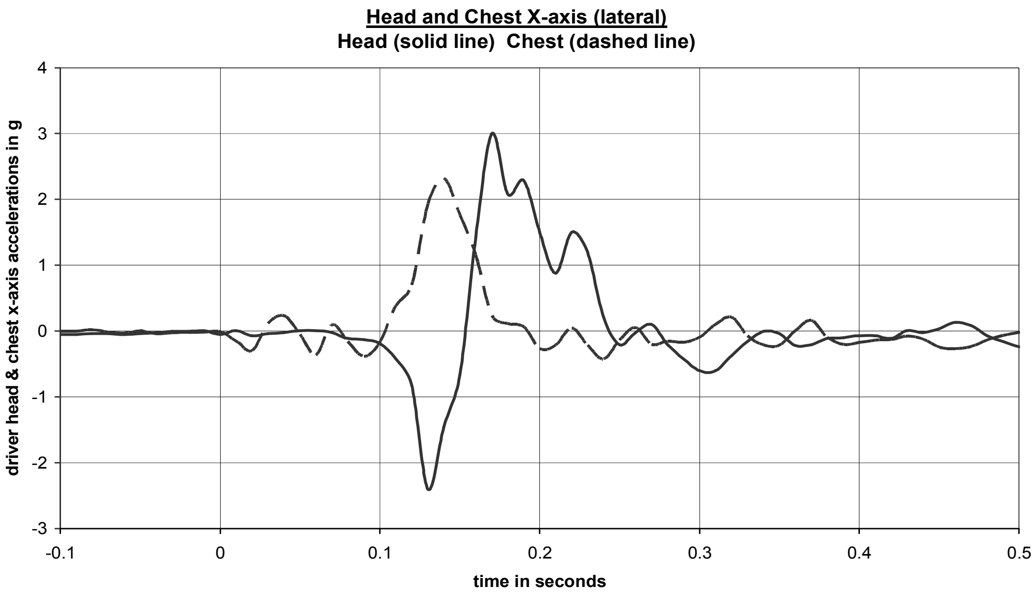


Figure 3.8: Time course changes in driver's head (solid line) and chest (broken line) x-axis acceleration following a low speed change collision. This experiment is typical of 12-15 such different experiments.

Figure 3.8 shows a typical experiment of the time course changes in the movement of the driver's head (sold line) and chest (broken line) following a low speed change collision. From the graph it is possible to calculate both the maximum and minimum negative head and chest lateral accelerations, details of which are shown below.

Maximum positive head acceleration = 3 g at 0.17 sec.

Maximum negative head acceleration = -2.4 g at 0.13 sec.

Maximum positive chest acceleration = 2.3 g at 0.14 sec.

There was no significant negative lateral acceleration of the chest.

The graphs in Figure 3.8 indicate that despite the main collision impulse being in a forward direction, it was still possible to get some significant lateral accelerations. Lateral accelerations of the head and chest can be due to a number of causes. These included:

(i) Asymmetry in the positioning of the seat relative to the centre-line of the vehicle.

(ii) Asymmetry in the positioning of the occupant at the time of the collision.

(iii) If the point at which impact forces enter the target vehicle is to the left or right of the centre of gravity of the target vehicle, then impact moments will be generated that will give rise to lateral accelerations.

(iv) Asymmetry in the construction and strength of the target and/or bullet vehicle can cause the impact forces to change direction as the collision progresses. This can give rise to lateral accelerations.

The graphs of lateral accelerations in Figure 3.8 indicate that movement of the chest was only in one direction while movement of the head was to the left and to the right.

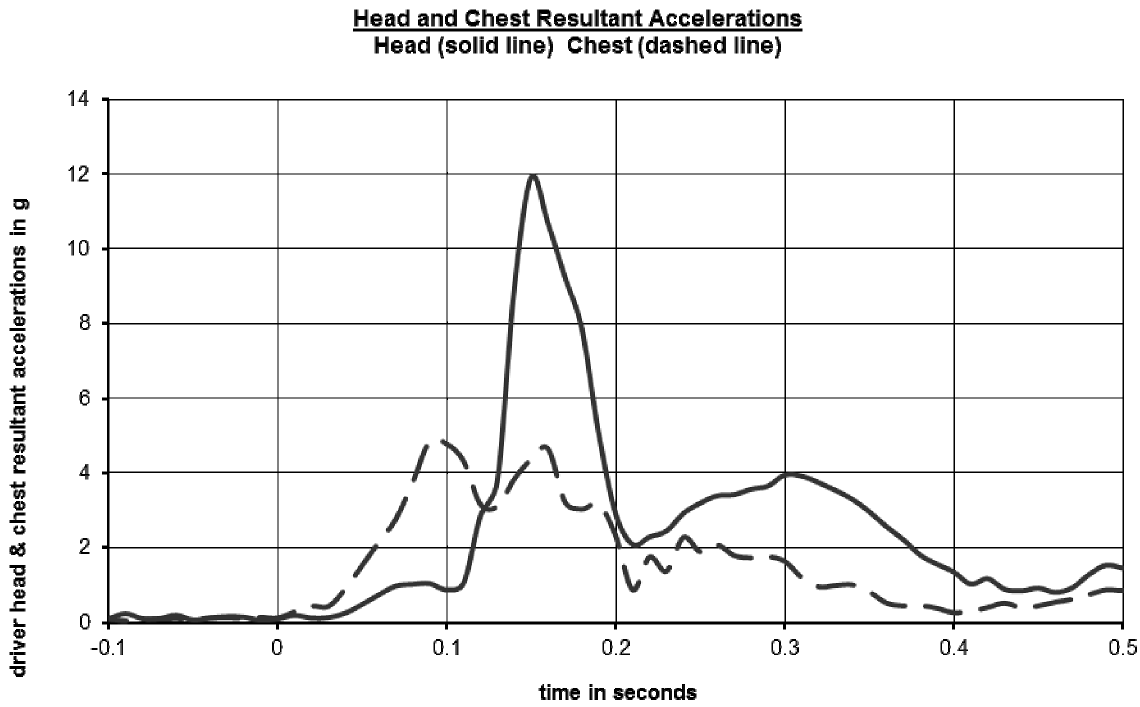


Figure 3.9: Time course changes in a driver's head (solid line) and chest (broken line) movement (resultant acceleration) following a low speed change collision. This experiment is typical of 5-6 such different experiments.

The graphs in Figure 3.9 shows the effect of combining accelerations in the x, y and z directions to give overall or resultant accelerations of the head and chest. The resultant accelerations can be calculated using the formula:

$$a_r = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

where a_x, a_y and a_z are accelerations in the x, y and z directions.

The resultant acceleration of the head showed two peaks. One of 11.9 g at 0.15 seconds and the other lesser peak of 3.9 g at 0.31 seconds. The resultant acceleration of the chest also showed two peaks. The first of 4.8 g at 0.09 seconds and the second of 4.6 g at 0.16 seconds.

The maximum resultant head acceleration of 11.9 g is due almost exclusively to the peaks of acceleration in the forward and vertical directions which occur at about the same time (Figure 3.9).

3.4 Details of Damage to Vehicles

(A) Bullet Vehicle

Vehicle Number: 2 (Vauxhall Carlton)

Firstly, it is of paramount importance to examine the vehicle damage following a low speed change collision. Figure 3.10 and Figure 3.11 show examples of the bullet vehicle and target vehicle. From Figure 3.10 it can be seen that the front area concerned with this collision included:

- Front bumper collapsed in centre
- Bumper hangers still intact
- Front nearside headlight broken on mounts
- Front offside headlight smashed and pushed down
- Bonnet slightly distorted to nearside

Figure 3.10: An example of damage to the front part of a typical bullet vehicle following a 10 mph + collision, typical of 5-6 such different experiments.

(B) <u>Target Vehicle</u>

Vehicle Number: 1 (Toyota Celica)

Figure 3.11 shows the damage occurred to the target vehicle following an 11 mph collision (10 mph +). From Figure 3.11, it can be see that the main areas concerned with this collision included:

- Rear bumper cover at offside wrap-round moved forward slightly
- Offside lights cluster showed induced forward displacement

- Same with centre section caused by forward movement of bumper cover
- Gap at nearside rap-round section to wing is 13 mm as is gap at offside
- Seam joint at boot floor to rear panel, "trough" at joint deepened forward of main impact site.
- Spare wheel well forward of "A7" in number plate flattened
- Rear panel pushed forward into centre with wheel well
- Slight bowing of carrier/reinforcer apparent when bumper was removed

Figure 3.11: An example of damage to the rear end of a typical target vehicle.

3.5 Post-impact Symptoms of the Occupants

The Tables 3.2 and 3.3 show the time course of injuries for the driver and passenger.

Table 3.2: Time course of injuries suffered by the Driver

TIME	PHYSICAL SYPTOMS
Immediate post impact	Momentary disorientation.
0 to 24 hours	No obvious symptoms.
After 30 hours	Pain behind left kidney (stiff/sore).
30 to 48 hours	Pain continuing and disturbed sleep.
After 48 hours	Stiff neck, slight restriction to neck rotation.
Day 3	Discomfort during the night. Stiff back in the morning easing after a bath. Neck problem gone.
Day 4	Stiffness in lower back in the morning – quickly eased off.
Day 5	Slight ache in back after full day's work.
Medication	Three ibuprofen during first 48 hours.
Restricted activities	Unable to play golf on Friday 3rd of June – two days after the collision.

Table 3.3: Time course of injuries suffered by the Passenger

TIME	PHYSICAL SYPTOMS
Immediate post impact	Disorientation, shocked, shaken, feel a bit sick.
0 to 10 minutes	Still shaken. Still feel sick.
10 to 30 minutes	Still shaken. Sickness going. Slight headache.
Within 1 hour	Slight headache.
Within 6 hours	Slight headache.
Within 24 hours	Slight ache around shoulders. Neck no worse than having been to the gym.
After 24 hours	None.

The results in Tables 3.2 and 3.3 show the time course changes in the injuries (physical symptoms) experienced by the driver and the passenger of the target vehicle, respectively. The data clearly show that both the driver and the passenger experienced slightly different reactions with the different symptoms occurring over time. The injuries were more severe for the driver compared to the passenger. Interestingly, the driver was of slight build in comparison to the heavy build of the passenger. This collision was not one to be considered 'low speed change' by the nature of the struck vehicle's actual speed change being above 5 mph. Despite this, long term follow up revealed no further symptoms.

3.6 Crash Testing 2005

3.6.1 Head and Chest Acceleration

The results of the recent study have shown that an impact velocity of 11.1 mph can give rise to a Delta-v (Δv) of 5.97 mph for the target vehicle. This is within 0.3 mph of a theoretical common post-impact velocity and validates current methodology when investigating collisions of this nature. Accelerometer readings for the target vehicle show a linear rise to maximum acceleration in 0.11 seconds and a total collision time of 0.22 seconds. Accelerometers attached to the head and chest of the target vehicle driver recorded significant accelerations in all three axial directions. The highest accelerations occurred in the forward (8.3 g) and upward (-8.9 g) directions. They were of similar magnitude and occurred at the same time thus indicating that they were probably part of the same acceleration mechanism acting on the head of the driver. During this time, the head of the driver was accelerating from a position lagging behind the chest towards a position in front of the chest. To achieve this, the head would require a significantly higher acceleration than the target vehicle. The maximum acceleration acting on the head of the driver was 11.9 g. This was primarily the resultant of the maximum accelerations in the forward and upward directions. It is believed that a key feature contributing to injury in this type of low speed, rear-end impact is the distance between the head of the driver and the head restraint at the time of impact. If the head was resting on the head rest at the time of the impact, the lag between the head and chest would be minimised and the magnitude of the subsequent acceleration phase when the head accelerates past the chest would be reduced. Similar results have been reported by other researchers in the area.

Adaptive head rests that move into position behind the head at the moment of impact are thought to have made a significant contribution to the reduction in whiplash injuries in vehicles where they are installed. The occupants of the target vehicle, in particular the driver, experienced some symptoms following the collision. From these symptoms, it is reasonable to conclude that this impact was in the region of a threshold. By this it is meant that an impact velocity slightly greater than that experienced would have led to more serious symptoms and possibly injury that would require the attention of a medical practitioner. The results of this crash test tend to support the opinion that a general threshold for whiplash type injury is 5 mph. These results are in agreement with other previous studies.

The paper CT2/2005/1 was produced as an internal GBB (UK) Ltd report [Henderson (2005)] and a copy was sent to Sintra Engineering in Canada. The only query raised related to evidence of a secondary impact which was caused by the target vehicle slowing post impact more quickly due to having the hand brake applied. The paper has also been specifically requested by our peers in the United Kingdom. No comments were forthcoming. CT2/2005/1 has been used for a number of years and can be considered to be one of the foundation or cornerstones upon which the rest of the research was built. The information obtained related to live occupants using vehicles recovered from UK roads, months before they were used in the crash tests and also involved longer term follow ups in relation to any possible symptoms. Symptoms in the target vehicle subjects were resolved by day 6. No further symptoms have been observed and therefore, ongoing symptoms post day 6 were nil. In terms of the bullet vehicle, the vehicle and occupant accelerations are shown in Figure 3.12 overleaf:

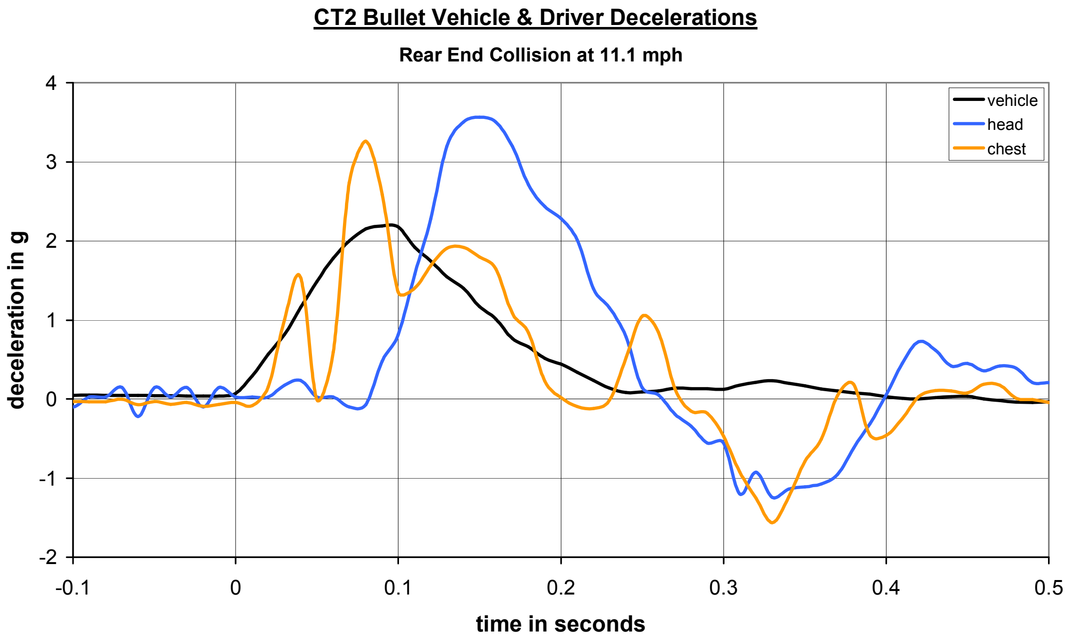


Figure 3.12: Bullet Vehicle and Driver Decelerations from Crash Test 2 (taken from Henderson et al, 2005)

It is interesting to note that the average vehicle acceleration was -1.1 g whilst the peak acceleration was -2.11 g. (This compares with 2.4 g in the lighter target vehicle.) The peak acceleration at the head was -3.56 g, whilst at the chest it was -3.26 g. Whilst this thesis concentrates on the movement in the target vehicle primarily, it would be remiss not to comment upon the bullet vehicle subject movements. What is of immediate note is that peak acceleration is considerably less at both head and chest. The maximum disparity between the peaks is 0.3 g compared to 4.7 g in the target vehicle subjects. There is greater synchrony between the head and chest movement with the result that when peak head acceleration occurs, the chest is still accelerating and the difference between the two is around 1.5 g. In the target vehicle the difference is in the region of 6 g+. Cases of reported injury in the bullet vehicle are considerably less than that of the target vehicle for any given collision layout. This is not surprising given the results above. It goes some way towards explaining why the occupants of bullet vehicles are frequently aghast at the suggestion of occupant injury in low speed change collisions in the target vehicle.

The other rear end collisions from the 2005 series of tests followed a similar trend as highlighted above, the results for which are reproduced in Figure 3.13 below:

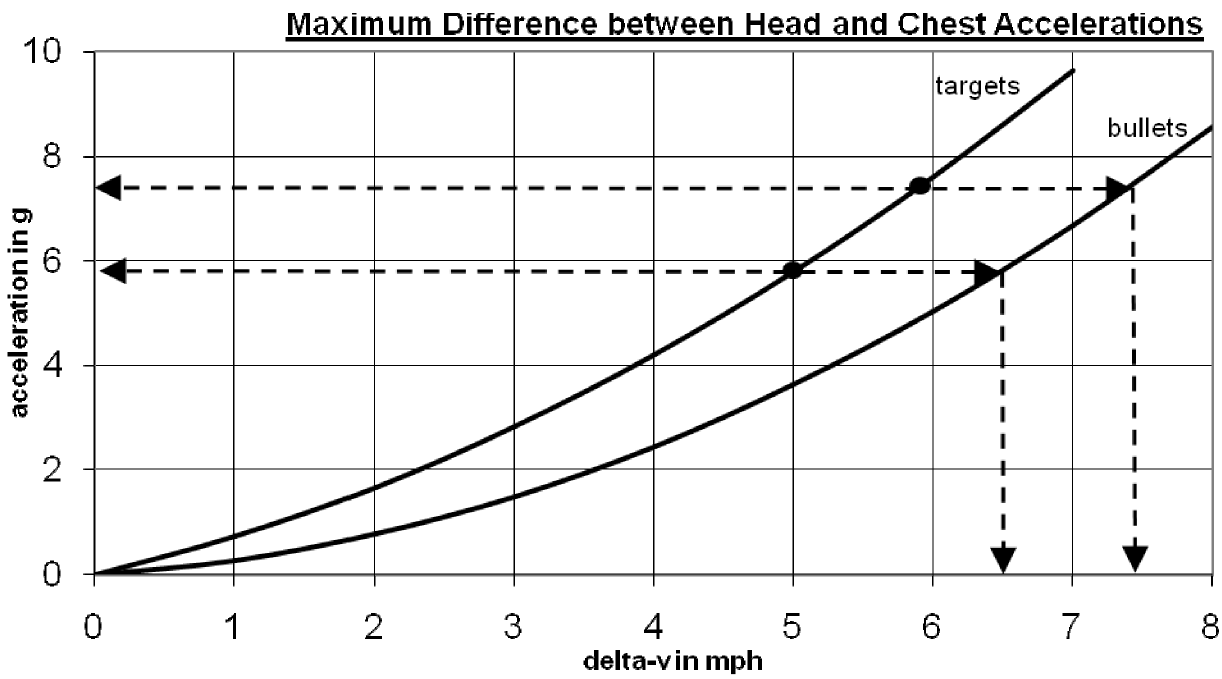


Figure 3.13: Head and Chest Acceleration Disparities Crash Testing (taken from Henderson et al, 2005)

3.6.2 Occupant Movement

Now that the accelerations experienced in Crash Test 2 were known, actual consideration of the movement of the occupants coupled with the acceleration data was considered. A visualisation of the movement was considered to be the best way to explain to the lay person what actually happens -

The movement of an occupant in the target or struck vehicle is quite different to the movement of an occupant in a bullet or striking vehicle.

Strictly speaking, due to the difference in movements, it is only the occupant of a struck vehicle that can suffer a true whiplash injury. The occupant in a striking vehicle may suffer some other form of soft tissue injury but it is widely believed that such injury occurs at a higher value of Delta-v than that which may lead to a whiplash injury. These results compared well with those previously reported.

3.6.3 Target Vehicle

Hyperextension (over-extension) injury to the neck is often the result of being struck from behind, as by a fast-moving vehicle in a car accident. The mechanics of whiplash injury are thought to be as follows: The victim may be first pushed or accelerated forward, pushing the body forward, but the head remains behind momentarily, rocking up and back, and some muscles and ligaments may be stretched or torn. These muscles, in a reflex action, contract to bring the head forward again, to prevent excessive injury. There may be overcompensation when the head is travelling in a forward direction as the vehicle decelerates. This may rock the head violently forward, stretching and tearing more muscles and ligaments. From www.medterms.com.

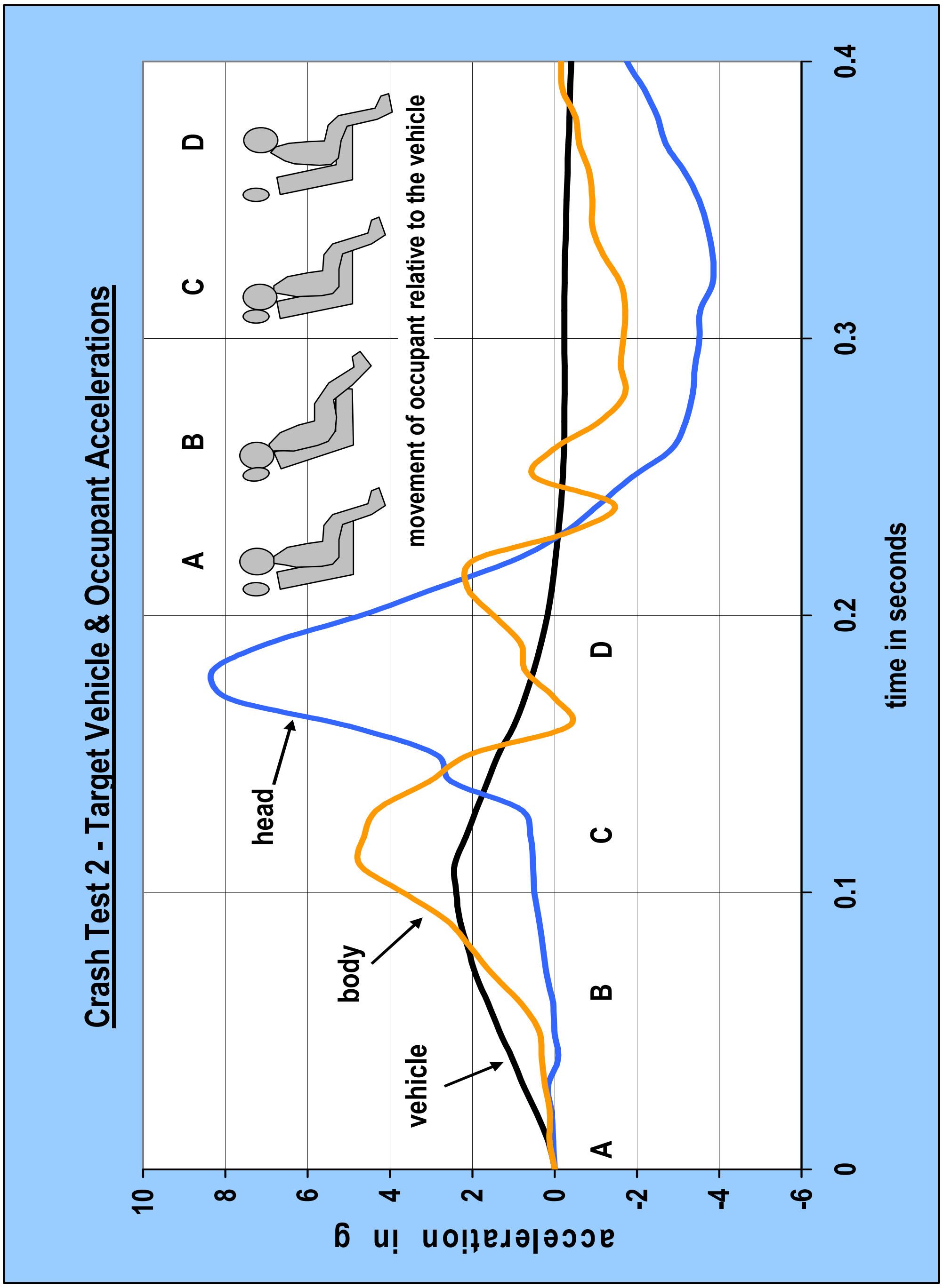


Figure 3.14: This figure shows the relationship between Target Vehicle and Occupant Accelerations with Graphics Crash Test 2

The accelerometer data from the target vehicle in Crash Test 2 is shown in Figure 3.14 above. Included are diagrams showing the movement of the front seat occupant at various stages throughout the collision.

At point A initial contact between the bullet and target vehicles has just occurred. Accelerations of the vehicle, body and head have not yet started and so Diagram A shows the occupant in their normal seated position. At point B the vehicle has been accelerated in a forward direction by the impact. Impact forces can only be transferred to the body of the occupant by the seat but at this point the seat is unable to transfer much force and so the body, along with the head, will move backwards relative to the seat. Between points B and C the seat back has stiffened due to compression and it is now able to transfer the force of the collision to the body of the occupant. The body will now accelerate in a forward direction relative to the seat. The movement of the head will lag behind that of the body as the neck and head restraint are unable to provide sufficient force to allow the head to move with the body. Thus, the head will rotate in a rearward direction relative to the body. At point C the body has its maximum forward acceleration and is moving faster than the seat. The body is coming away from the seat back. The head of the occupant has hardly moved from its previous position at B and at this point the rearward rotation of the head is at its maximum. Between points C and D forces in the neck of the occupant and possibly from the head restraint are of sufficient magnitude to cause the head to accelerate rapidly in a forward direction. At point D the acceleration of the head is at its maximum while the acceleration of the body is close to zero. At this point and beyond, the head will accelerate rapidly past the body and will rotate in a forward direction. The whiplash mechanism is believed to be triggered by the relative motion of the head and body that occurs between points C and D.

A sequence of photographs, marked i to vi, taken from Crash Test 1 from 2003 is shown below to illustrate occupant movement in a target vehicle.

Crash Test 1 2003. Rear-end impact between two identical Ford Escorts. Impact speed is 8 to 9 mph resulting in a Delta-v of around 5 mph with a coefficient of restitution of about 0.13.

i) Just before the impact - note the position of the rear tyres relative to the white line.

ii) Just after the initial impact. The head and chest have moved backwards relative to the car.

iii) The body sinks further into the seat and the head contacts the head restraint.

iv) The body and head move forward as their accelerations exceed that of the car.

v) Near the end of the collision the point of maximum forward head movement is reached.

vi) The head returns towards its normal driving position.

The images i) to vi) show occupant movement in the struck vehicle.

3.6.4 Bullet Vehicle

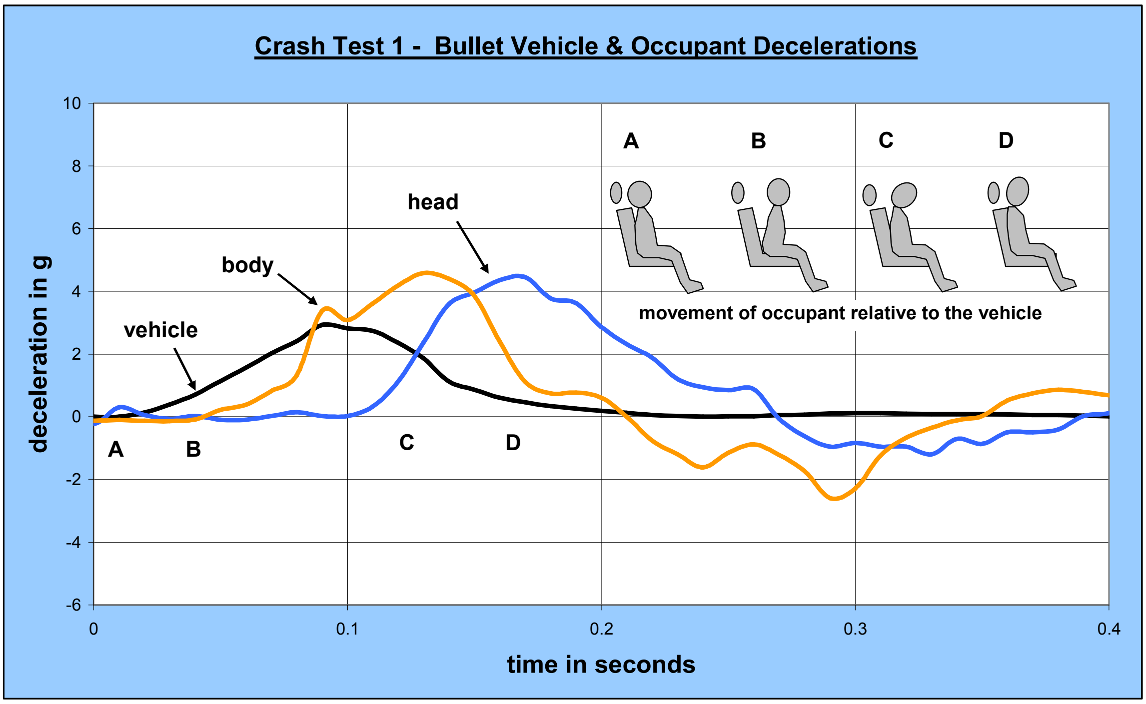


Figure 3.15: Relationship between the Bullet vehicle and occupant decelerations

The accelerometer data from the bullet vehicle in Crash Test 1 of 2005 is shown in Figure 3.15 above.

At point A initial contact between the bullet and target vehicles has just occurred. Accelerations of the vehicle, body and head have not yet started and so Diagram A in Figure 3.15 shows the occupant in their normal seated position.

At point B in Figure 3.15 collision forces have caused the vehicle to start decelerating (slowing down). The body and head of the occupant will continue to move forward at their original speed.

Between points B and C in Figure 3.15 the body will start to slow down due to force received from the tightening seat belt and by the feet of the occupant from the floor of the vehicle.

At point C in Figure 3.15, the deceleration of the body is at its maximum and the body has now returned towards the seat. On the other hand, the head has barely started to slow down and this results in forward rotation of the head relative to the body.

Between points C and D in Figure 3.15 sufficient tension has built up in the neck of the occupant to cause the head to decelerate.

At point D in Figure 3.15 the vehicle has all but ceased its deceleration. The body still has some small deceleration and is moving rearwards relative to the seat. The head has its maximum value of deceleration and is moving back towards alignment with the body.

A sequence of photographs, marked vii - xii taken from Crash Test 4 from 2005 is shown overleaf to illustrate occupant movement in a bullet vehicle. This was a rear-end impact between a Rover Metro (bullet) and a Vauxhall Cavalier.

Impact speed was 11.8 mph resulting in a Delta-v of 6.4 mph for the bullet vehicle with a coefficient of restitution of about 0.06.

vii) Just after the initial impact. Damage is occurring and the vehicle is decelerating.

viii) As the vehicle decelerates, the occupant continues moving forward relative to the vehicle.

ix) Further forward movement of the occupant's head and body as the vehicle decelerates.

x) The head is now at its maximum forward position. The safety harness is restraining the body of the occupant. Note the distance between the head and steering wheel.

xi) Near the end of the collision the head moves rearwards relative to the car.

xii) The head returns towards its normal driving position.

Images vii) to xii) show bullet vehicle and occupant decelerations.

Full details of the vehicles used and the collision scenarios from the 2005 series of tests can be found in Appendices 3 and 4.

3.7 Simulator Testing

The simulator research followed the same format as the full size crash testing insofar as the Helsinki protocol was followed and all subjects were volunteers aware of any potential risks. The simulator was set such that the impact speed was less than 3 mph and the delta v also less than 3 mph where possible (allowing for rebound). As mentioned earlier, one of the important factors for the simulator testing was to make sure the time of the collision accurately reflected the time of a rear end collision. Initially, the time of the collision using the simulator was too short. This was rectified using a foam damper attached to the striking area of the rig itself.

The graph below in Figure 3.16 shows the time scale from Crash Test 6 from 2009.

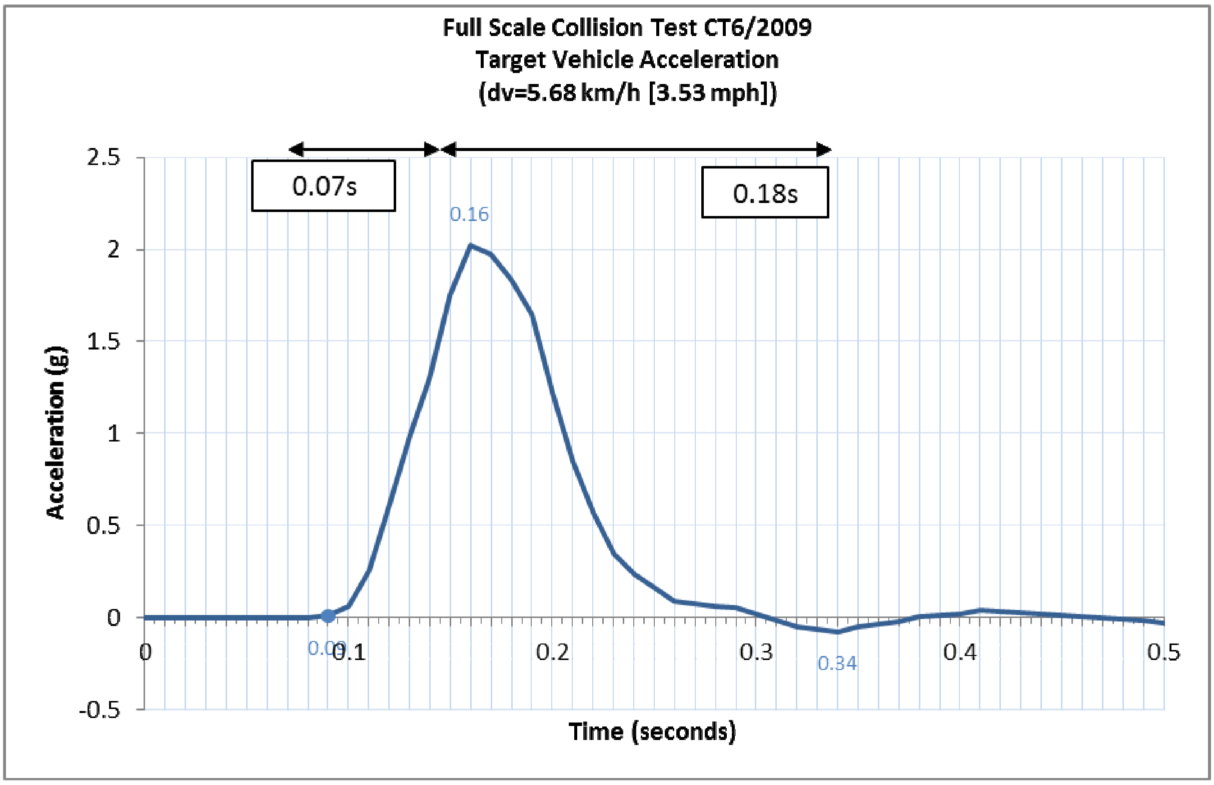


Figure 3.16: Time course graph showing a full scale collision test.

This can be compared to the graph in Figure 3.17 from one of the simulator tests shown below:

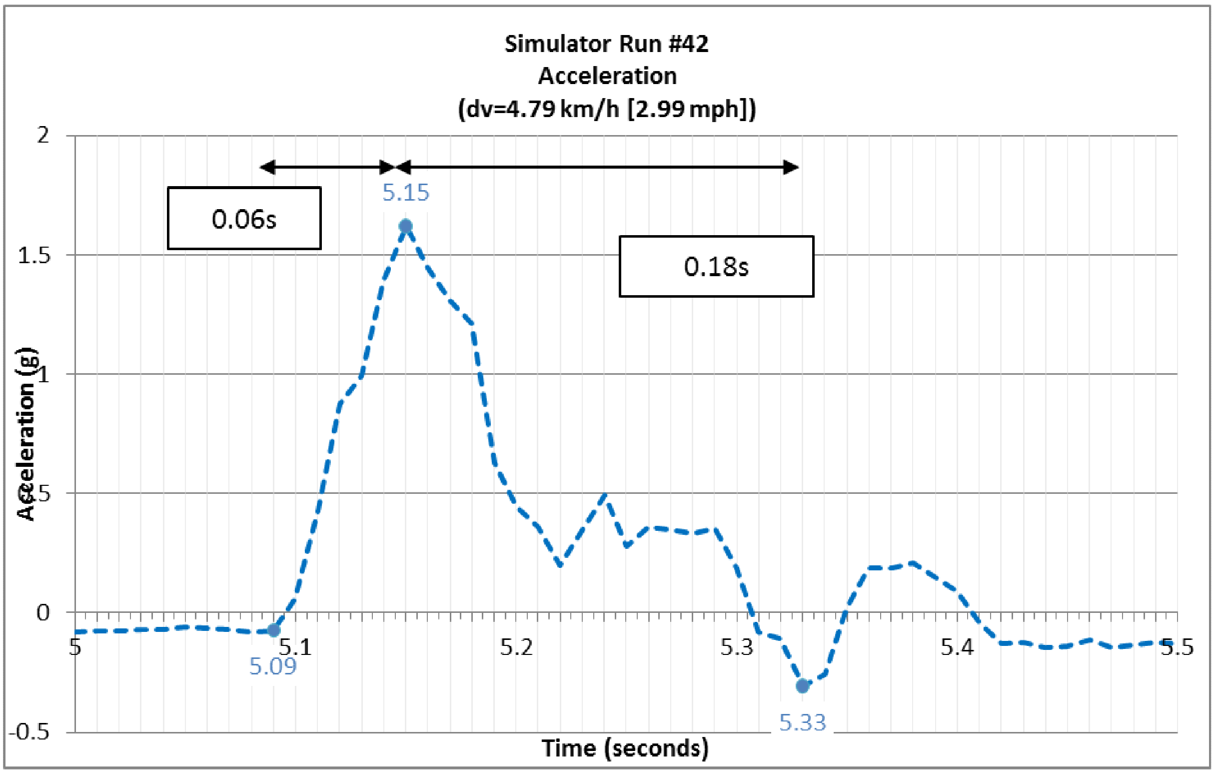


Figure 3.17: Time course graph showing a simulator run test.

The smaller acceleration peaks are from rebound of the sled with the fixed rig. The data from the simulator research up until 2009 can be found at Appendices 5 and 6. A graph in Figure 3.18 shows the accelerations of the simulator in runs 2 – 27, and the head and chest accelerations from those tests can be found at Appendix 5.

The obvious point to note is that only test numbers 8 and 24 provided head accelerations above those of the chest. In other words, a positive disparity.

Test 8 was an error insofar as the peak head acceleration was recorded at 3.61 g and the peak chest acceleration was 4.34 g. From data this was 3.87 and 3.41 g, respectively.

Test 24 was a test that the candidate personally undertook. Test 23 was undertaken immediately before whilst in a normal seated position. Test 24 was then undertaken but in a position where the head was placed firmly against the head restraint. The test produced a positive disparity of around 1 g. This was direct acceleration of the head, akin to being struck to the head and this led to stiffness at the base of the skull with a slight headache. All symptoms had resolved within 6 hours. All other tests failed to provide a positive disparity. Mild 'symptoms' including 'surprise', 'shaken but no discomfort' and 'mild discomfort at back of chest – cleared within 10 minutes' were noted (Henderson et al, 2005). See Appendix 5.

An Orthopaedic Surgeon from Run 14 recorded symptoms as 'Forehead pain 3/10 cleared within 5 seconds. Within 10 minutes, dull ache in region of shoulders resolved within 6 hours'. Examination of that test run indicated higher levels of acceleration at both head and chest. It also highlighted a longer time lapse of 0.1 seconds between the peak accelerations compared with the norm of 0.03 – 0.04 seconds. If one considers that test in isolation the delay between the peak accelerations led to the largest disparity between them. That is logical as the chest would have been approaching the end of its acceleration phase when the head was at its peak whereas normally the peak head acceleration occurred slightly before the end of the chest acceleration phase. Even a relatively large disparity provided mild transient symptoms (Henderson et al, 2005). See Appendix 5.

It is clear that in most tests, the initial impact provided a shock to the system and in some cases a light jolt. It should be noted that the 'occupant and seat mass' was much closer to the mass of the rig than that of occupants in a car to car collision. The results of the first batch of simulator testing showed that impacts up to 3 mph did not provide a positive head acceleration compared to chest acceleration. Consequently, only minor transient symptoms were noted. Long term follow up enquiry (1 week) indicated that no symptoms were present. Indeed, 6 hours seems to have been the longest asymptomatic period (Henderson et al, 2005). See Appendix 5.

In the second batch of tests 25 – 42, numbers 29 – 30 involved contact with the body accelerometer being positioned at the lower back, hence a small positive disparity between its acceleration and the head's. (The lower back always provides the lowest level of acceleration of the three measured points.)

Test 31 provided a positive disparity of 1 g. The test subject had his head resting on the head restraint.

Test 32 provided a positive disparity of 0.27 g. Interestingly, the test subject was the same individual who was of slight build (neck girth – 38 cm).

Test number 33 provided a small disparity of 0.36 g and together with 34 and 35 was actually undertaken whilst holding a cup of water to see if any would be spilled. Probably not the best arrangement for consideration of occupant accelerations! That was not their intention.

No symptoms were recorded during the second phase of simulator testing. An overview of the simulated tests indicated the average peak head acceleration was 2.66 g and the average peak chest acceleration was 3.05 g. In line with other international studies, the simulator research clearly showed that a speed change of 3 mph within a rear end collision sequence as a one off incident was well within human tolerances.

The simulator accelerations for simulator tests 2 – 27 are shown overleaf:

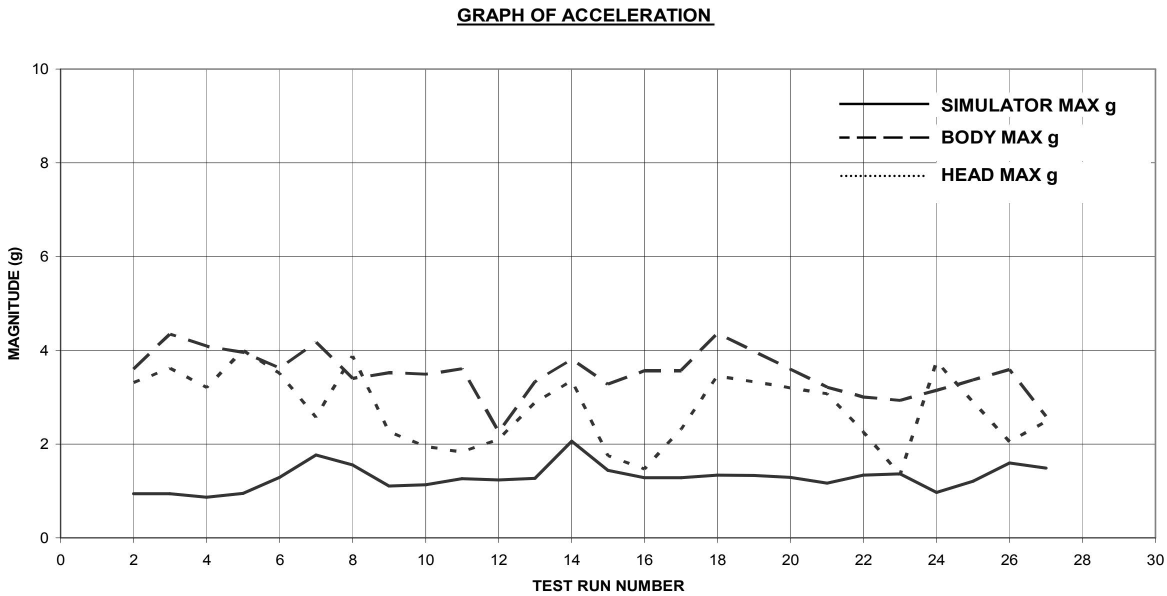


Figure 3.18: Head and chest acceleration figures from simulator programme

3.8 Crash Testing 2009

The crash testing programme of 2009 was undertaken during August of that year with 13 different collision scenarios.

Of those, seven (Tests 2 -7 & Test 13) were squarely aligned rear end shunts with impact speeds between 1.2 mph – 13.8 mph.

Test 1 was a squarely aligned rear end shunt with vehicles of largely differing mass involving a Citroen ZX and a single decked bus.

That test was subject of a presented paper at the ‘International Congress on Traffic Accident Investigation’ held in Shanghai, China in November 2009. A copy of the published paper is appended at the end of the thesis in the ‘published papers’ section.

Test numbers 8 and 9 were collisions involving only the exterior mirrors of a Ford Focus and a Volvo 960. Test 8 was undertaken to see the effects of mirror to mirror contact with vehicles in opposing directions (one stationary) such that the mirrors folded as designed.

Test 9 was a repeat but with contact between the vehicles in the same direction, again with one stationary, such that the mirror on the stationary Volvo was forced in the opposite direction to its design.

Those tests were subject of a published paper with ‘Impact’, the journal of the Institute of Traffic Accident Investigators. The paper was published in winter 2009 (Henderson et al, 2009).

A copy of that paper is appended in the ‘published papers’ section at the end of this thesis.

Test numbers 10, 11 and 12 were a series of side impacts, two being dynamic and the other being a collision into the side of a stationary vehicle.

Focussing on the rear end collisions, it was relevant to consider the following crash tests: CT2, CT5, and CT6 of 2009 (referred to as Test1, 2 and 3).

CO-ORDINATE SYSTEM - The acceleration axis system was in accordance with SAE J1733-Sign Convention for Vehicle Crash Testing. In relation to the vehicle the positive X, Y and Z axes were forwards, rightward and downward respectively.

VEHICLES - Two vehicles were used over the three tests. The first, a 2000(X) registered Alfa Romeo 156 T-Spark four-door saloon, 1747 cc petrol, manual (VIN: ZAR932000011*****) had an unladen mass of 1230 kg. The second, a Ford Focus 1.6L circa 1998-2002 five-door hatchback, petrol, manual (VIN: WFOAXXWPDAYL*****) had an unladen kerbside mass of approximately 1180 kg (Glass's Guide).

For Test 1 the Alfa Romeo was used as the bullet vehicle and the Ford as the target. For Tests 2 and 3 the configuration was reversed with the Ford becoming the bullet and the Alfa Romeo the target vehicle.

The reason for exchanging vehicle roles is that as part of other research the Ford Focus had been subjected to a 10 mph collision in between Tests 1 and 2. To avoid issues with alterations in elasticity it was decided that the roles of the vehicles be swapped.

Both vehicles were fully inspected before testing to determine any previous damage or repairs. The bumper systems were dismantled before testing and then again after each test. The bumper systems were unmodified, standard fitments to these vehicle models. Replacement bumper reinforcers were available if any damage was found that might alter the crash characteristics. The replacements were not required.

The unmodified seats and seatbelt systems were used in each vehicle.

Impact speeds were selected that would produce a change in velocity for the struck vehicle that would test the findings of the applicant's original research and investigate the region of 0 to 3 mph and slightly beyond.

The impact speeds were 1 mph, 3 mph and 6 mph which were calculated to produce speed changes of 0.9 mph, 2.2 mph and 3.6 mph.

The bullet vehicle was driven by a volunteer along a flat concrete surface into an aligned impact with the target vehicle. This method was employed because of its similarity with real-world collisions. Allowing the bullet to be driven into the target, rather than free-wheeled, gave better control over alignment, and it also allowed the driver of the bullet vehicle to be analysed, by accelerometers and video footage, for further research.

The target vehicle was in neutral with the handbrake disengaged. The positional lamps were illuminated as part of a separate university test running in conjunction with our own investigations.

Impact speeds were judged by the driver of the bullet vehicle using GPS.

A dual axis accelerometer and data logger (Vericom VC3000DAQ) was affixed to the approximate lower centre of the windscreen of both vehicles. Occupant accelerations were measured by tri-axis accelerometers. A 10 g unit (Crossbow model CXL10Lp3) strapped across the centre of the chest and a 25 g unit held against the centre of the forehead by elastic webbing (Crossbow model CXL25Lp3). Data acquisition was made by the Vericom 3000DAQ mounted within the vehicle using a sample rate of 100 Hertz.

Figure 3.19 below shows the acceleration results for the three tests.

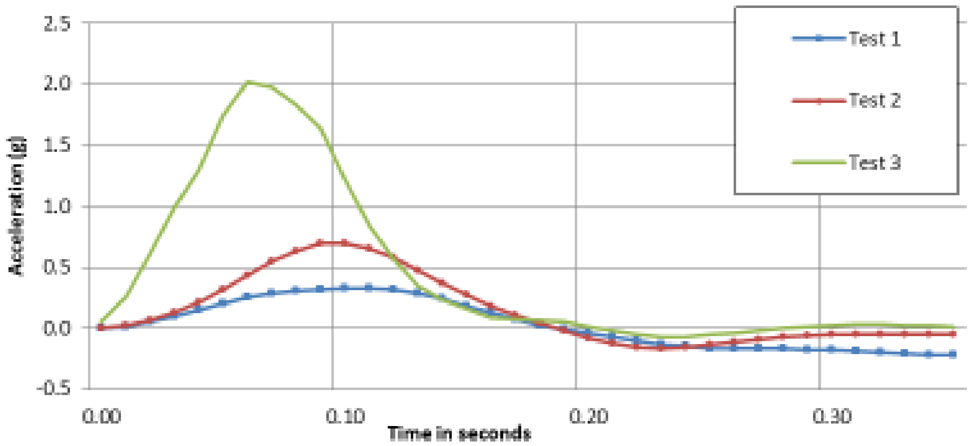


Figure 3.19: Collective acceleration results

Figure 3.20 below shows the speed change for the target.

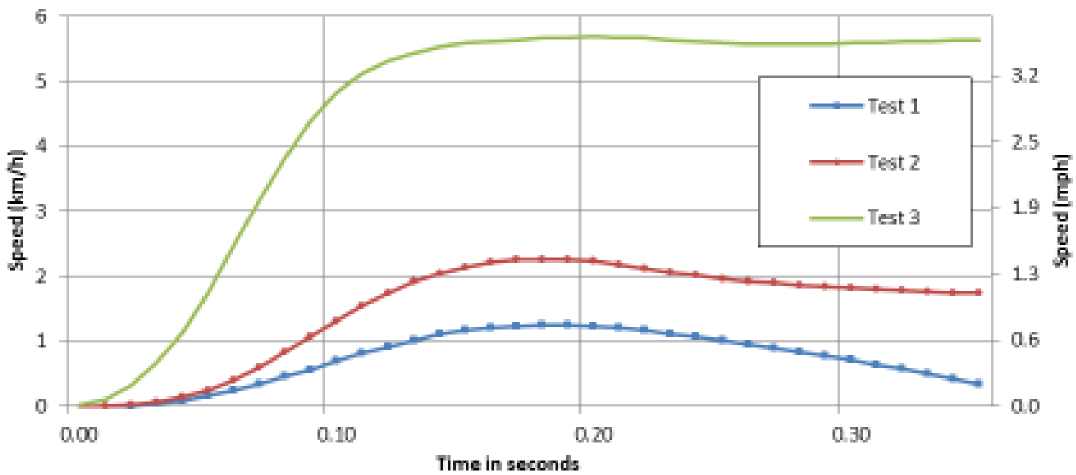


Figure 3.20 Target vehicle speed changes

What is obvious from the above testing is that, not surprisingly, the higher the impact speed, the higher the resultant speed (delta-V) or speed change of the struck vehicle.

The higher the speed change, the greater the acceleration of the struck vehicle.

More important perhaps is the time at which peak acceleration occurs. The greater the acceleration, the sooner peak g occurs. This implies that for the vehicle occupants not only is there a higher acceleration to endure, but it occurs in a shorter time, thus increasing the peak force applied. (This is often referred to in the USA as the jerk. Conversely, at lower speeds, the mechanical action required to trigger the whiplash mechanism is not available. Lower acceleration results in a longer time frame.

Interestingly, in cases studied in recent years where the speed change is below 3 mph, the occupants describe being 'jolted forwards then backwards'. This was unusual as the occupant movement relative to the vehicle ought to be rearwards. However, in video footage with such speed changes, the relative rearward movement between head and chest could not be detected. The disparity of movement between the head and the chest was so small that it required accelerometer data for it to be exposed. What was seen in the video footage was that the synchronous movement of the head and chest in the rearward direction was slight and dwarfed by the movement in the forward direction. The lower levels of acceleration within an extended time frame seem to preclude the rearward movement which is required to trigger the whiplash mechanism.

The target vehicle occupant accelerations are shown overleaf:

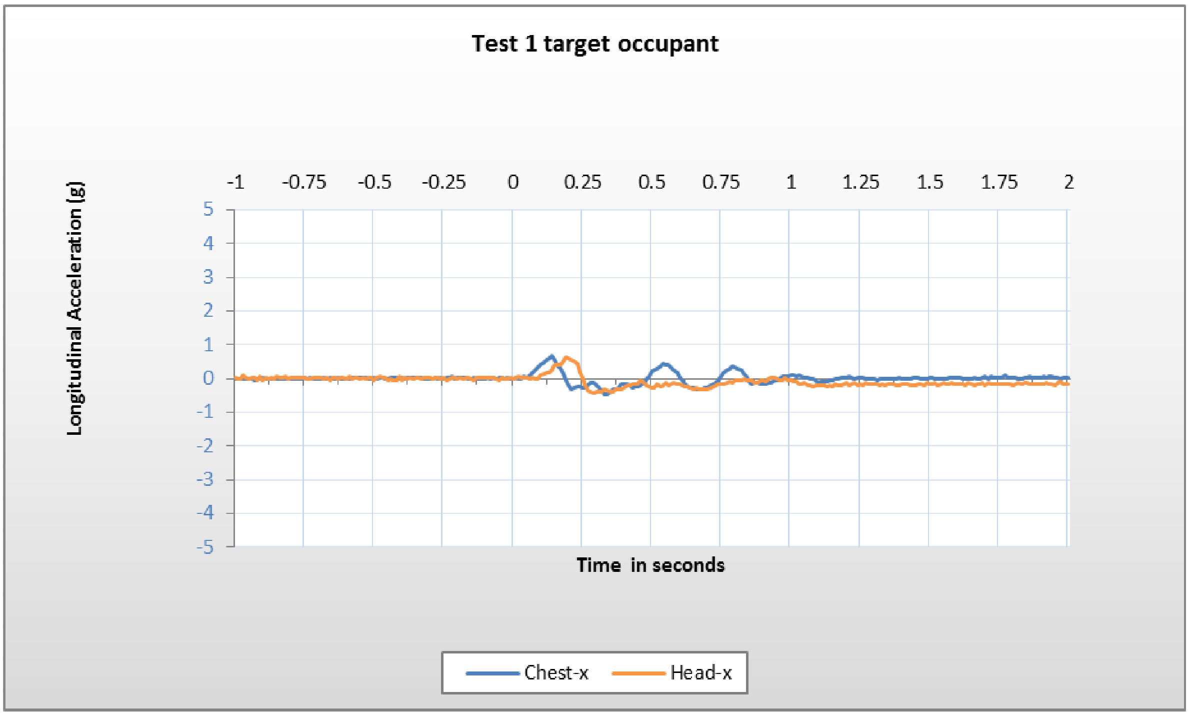


Figure 3.21: Test 1 target vehicle occupant acceleration

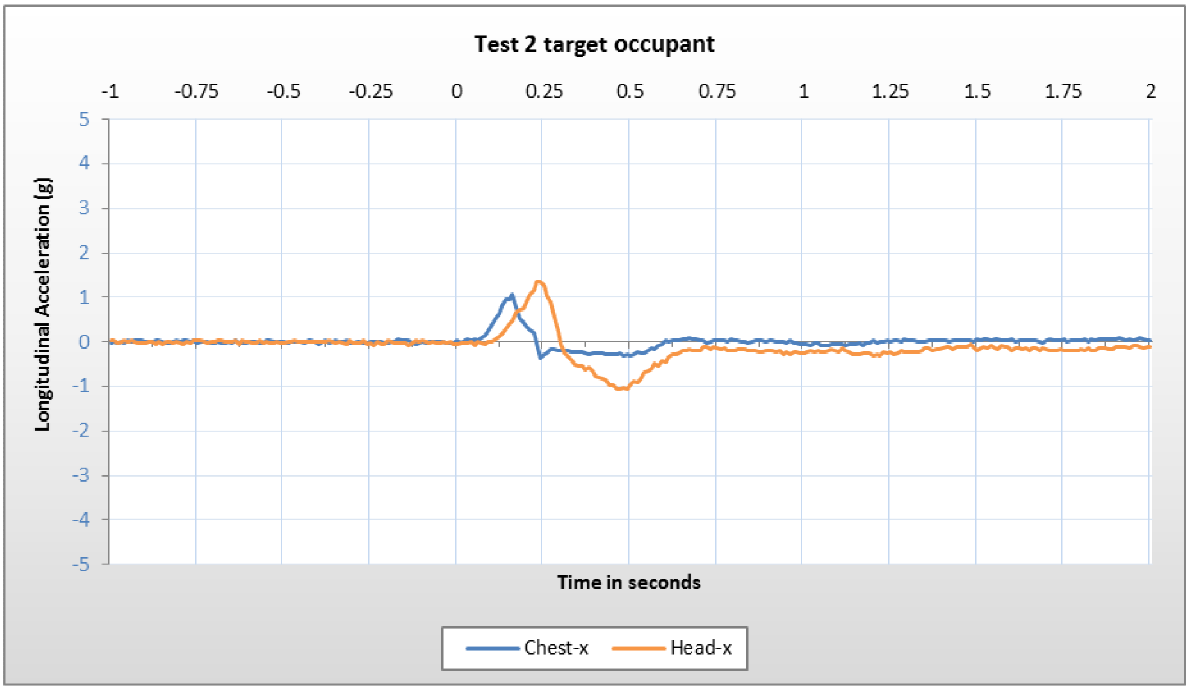


Figure 3.22: Test 2 target vehicle occupant acceleration

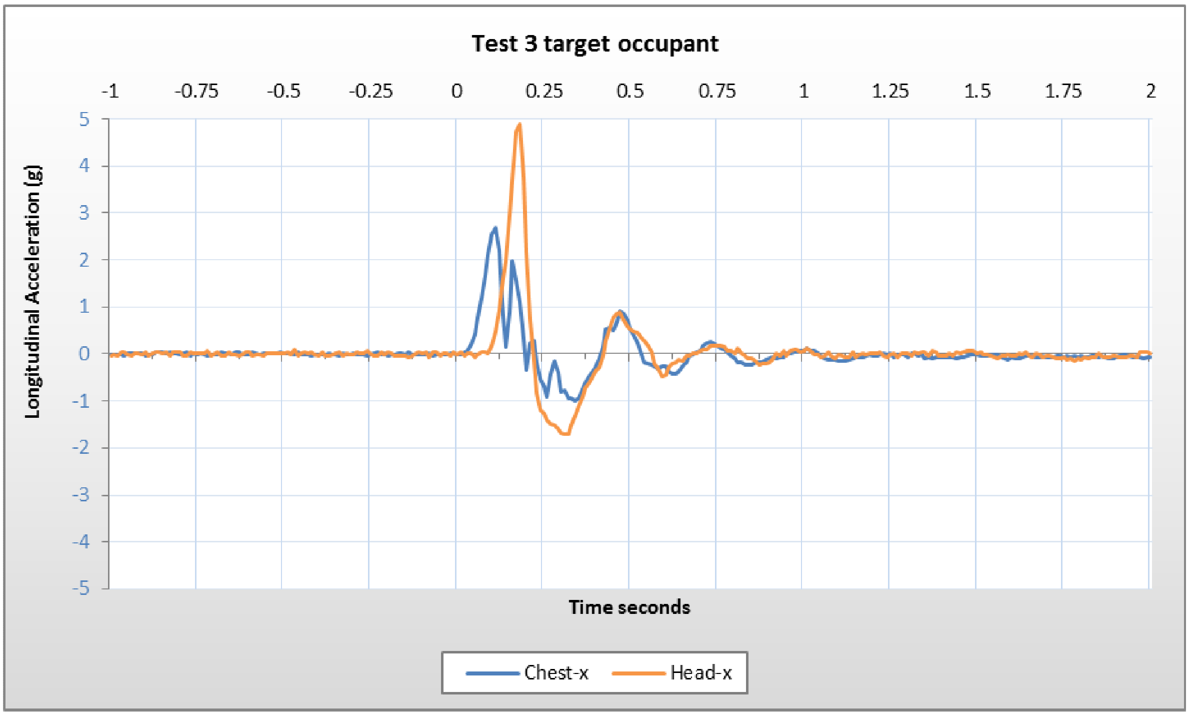


Figure 3.23: Test 3 target vehicle occupant acceleration

A review of the three tests above clearly shows the relationship between increased closing speed and the increased acceleration of occupants. What it also shows and it is a truly obvious point, is that there will always be a disparity between head and chest acceleration at the point that the head acceleration reaches its peak. This is due to the delay in movement between the chest and the head – typically 0.03 – 0.04 seconds. What is also the case is that the disparity increases with the closing speed of the collision.

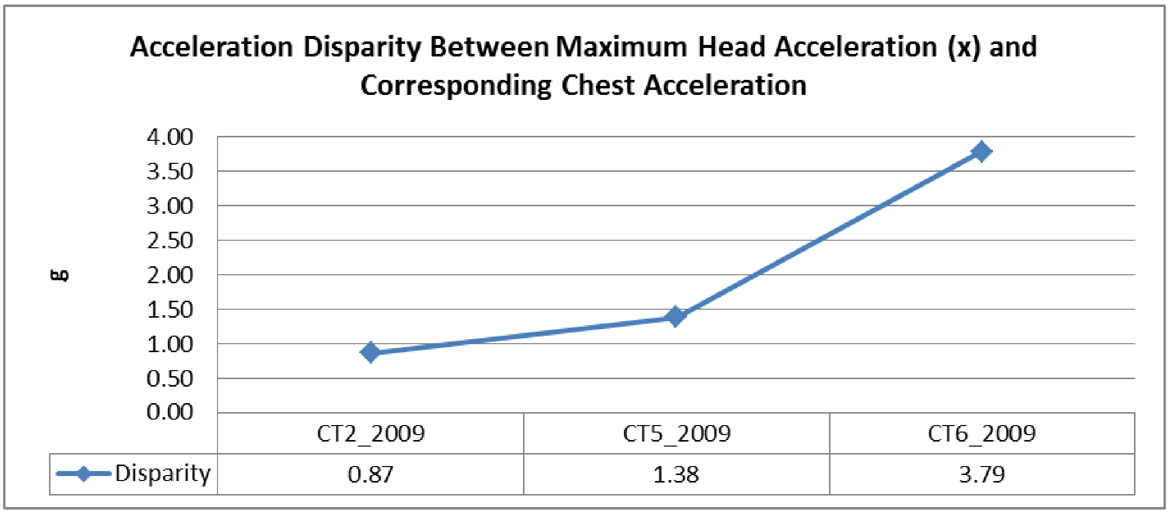


Figure 3.24: Head/chest disparity graph

The disparity graph presented earlier in relation to 2005 testing was added to following the 2009 tests. It is shown below:

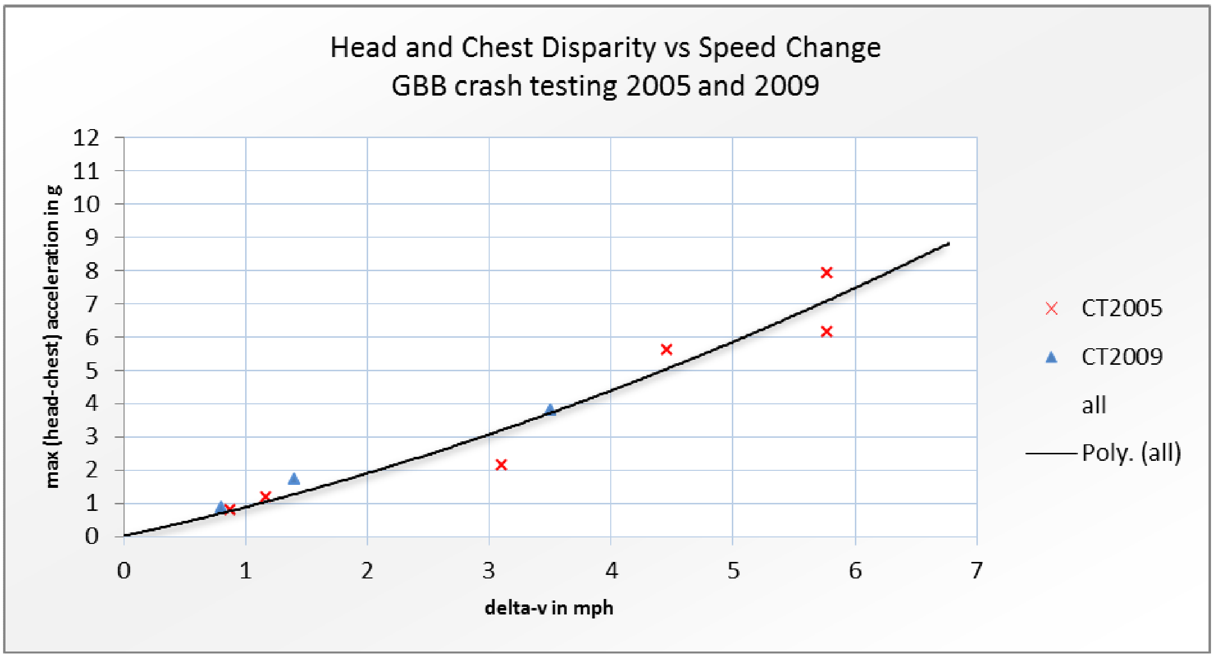


Figure 3.25: Head/chest disparities amalgamation from 2005 and 2009 Crash Tests

What can be seen to be happening now is there is an increase in the number of maximum disparity figures at low level (2 g and below) with speed changes of 3 mph below, occasionally at slightly above 3 mph too.

A correlation test (Table 3.1) result of 93% shows that including the test results from 2009 serves to increase the correlation of the data and gives an improved goodness of fit.

Table 3.1 Correlation test including the 2005 and the 2009 data.

	DeltaV	Max Disparity	Term 1 $(x_i-\bar{x})(y_i-\bar{y})$	Term2 $(x_i-\bar{x})^2$	Term3 $(y_i-\bar{y})^2$
	0.88	0.80	5.39	4.42	6.57
	1.17	1.19	3.94	3.29	4.72
	3.10	2.15	-0.14	0.01	1.47
	4.46	5.62	3.33	2.18	5.09
	5.77	6.14	7.74	7.77	7.71
	5.77	7.92	12.92	7.77	21.50
	0.8	0.86	5.47	4.77	6.27
	1.4	1.72	2.60	2.51	2.70
	3.5	3.79	0.22	0.27	0.18
Mean	2.98	3.36			
Σ			41.47	32.98	56.22
				r	0.96
				r^2	0.93

Figure 3.26 shows the results of the 2005 and 2009 plus those from the rear impact simulator. The correlation in results falls slightly to 0.81% (Table 3.2) but with speed changes of 3 mph and below there is now a small cluster of acceleration disparities below 2 g.

Logic would dictate that the low level acceleration disparity plays a part in the lack of injury in collisions with such speed changes.

The rhetorical question the applicant posed is whether or not that was the whole story?

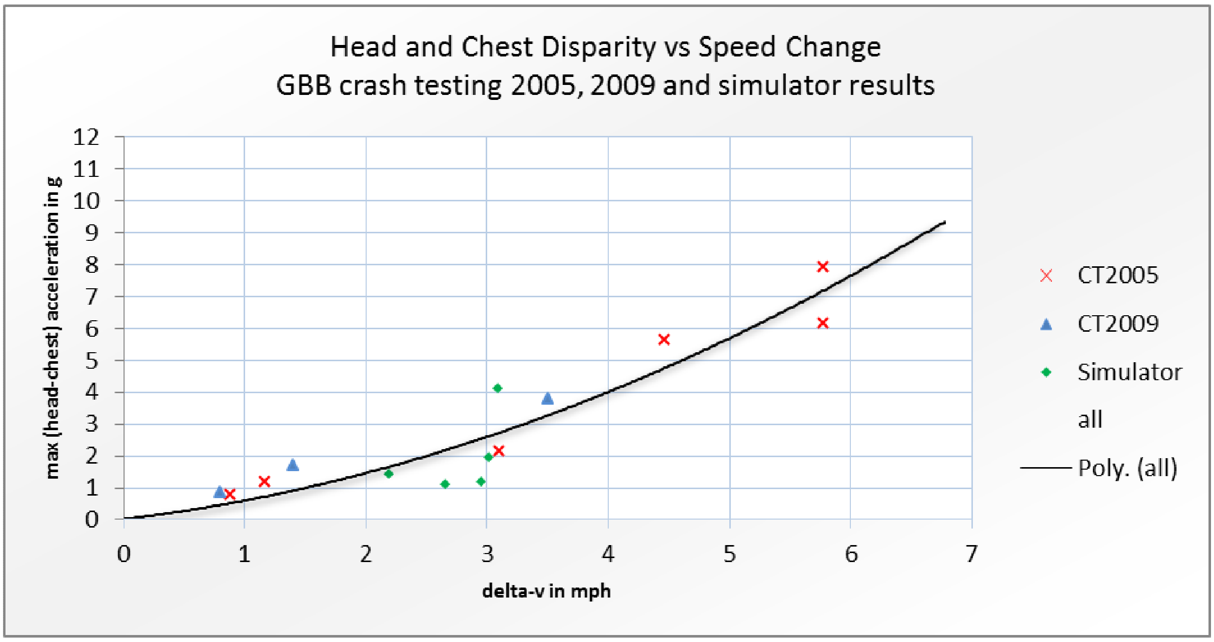


Figure 3.26: Head/chest disparity vs Speed change

Table 3.2 Correlation test on the 2005, 2009 and the simulator data.

	DeltaV	Max Disparity	Term 1 $(x_i-\bar{x})(y_i-\bar{y})$	Term2 $(x_i-\bar{x})^2$	Term3 $(y_i-\bar{y})^2$
	0.88	0.80	4.19	4.13	4.25
	1.17	1.19	2.91	3.03	2.79
	3.10	2.15	-0.13	0.04	0.51
	4.46	5.62	4.27	2.40	7.61
	5.77	6.14	9.37	8.17	10.75
	5.77	7.92	14.69	8.17	26.40
	0.8	0.86	4.23	4.46	4.01
	1.4	1.72	1.73	2.28	1.30
	3.5	3.79	0.55	0.35	0.86
	3.02	1.96	-0.10	0.01	0.81
	2.19	1.42	1.04	0.52	2.08
	3.09	4.1	0.22	0.03	1.53
	2.95	1.2	-0.06	0.00	2.76
	2.66	1.11	0.44	0.06	3.07
Mean	2.91	2.86			
Σ			43.33	33.65	68.74
				r	0.90
				r^2	0.81

In the collisions reviewed thus far, the applicant considered the difference in peak accelerations at the head and chest, the time of the peaks, the nature of the movement and the maximum disparity at peak head acceleration time.

Considering again the three tests above, the actual disparities between peak head and chest accelerations were -0.04 g, 0.29 g and 2.18 g, respectively. These in turn manifested themselves at peak disparity as 0.87 g, 1.38 g and 3.79 g, respectively.

Those levels of instantaneous disparity were easily accommodated. Indeed, figures above those were also easily accommodated with no symptoms whilst others provided minor transient symptoms. The same might not be said if the upper levels were endured for prolonged periods.

The applicant was interested to see the range of acceleration at the head compared to the chest in the tests above.

- In Test 1 (CT2/2009) the head varied between 0.63 g and -0.35 g (Range – 0.98 g)

- In Test 2 (CT5/2009) the head varied between 1.36 g and -1.07 g (Range 2.43 g)

- In Test 3 (CT6/2009) the head varied between 4.88 g and -1.71 g (Range 6.59 g)

The acceleration range typically occurs over a time of around 0.2 – 0.3 seconds. In isolation it is difficult to understand the magnitude of such movement.

3.9 Daily Activity

In order to make comparisons of any type between low speed change rear end collisions and daily events, it was necessary to consider a whole range of activities. These included:

1. Being bumped into by a person walking at normal speed (approximately 50% overlap) [The graph is shown at Appendix 8]
2. Jumping off a low chair (for example after changing a light bulb etc) [Appendix 9]
3. Stalling a vehicle [Appendix 10]
4. Driving forwards up a kerb [Appendix 11]
5. Reversing into a kerb [Appendix 12]
6. Getting out of a chair quickly [Appendix 13]
7. Flopping into a chair [Appendix 14]

The list could be of infinite length in reality. A common sense approach had to be applied and it may be that other daily activities could be monitored as part of future research.

Being bumped into revealed a head acceleration range of 0.88 g, a maximum disparity at peak head acceleration of 0.58 g and a disparity in peak accelerations of 0.45 g.

Jumping from a small chair of 49 cm height revealed a head acceleration range of 2.2 g with an instantaneous maximum disparity of 1.76 g. Peak acceleration of 1.93 g was recorded at the head and 1.59 g at the chest. The disparity between peaks was 0.34 g. (Note – this was forwards/backwards only. The up/down acceleration was considerably greater than a 3 mph speed change collision.)

Stalling a vehicle could produce a head acceleration range of 0.8 g with an instant maximum disparity of 0.87 g. The peak head acceleration was 0.42 g and the peak chest acceleration was 0.9 g. The disparity between peaks was in favour of the chest.

Driving up a kerb produced a peak acceleration at the head of 1.48 g. The maximum disparity was 0.82 g. Peak head acceleration was 0.87 g and the peak chest acceleration was 0.42 g.

Reversing slowly into a kerb produced a peak acceleration of 1.3 g with an instantaneous maximum disparity of 0.42 g. The peak head acceleration was 0.73 g with peak chest acceleration at 0.47 g allowing a disparity of 0.26 g.

Getting out of a chair quickly produced a head acceleration of 1.36 g with a peak maximum disparity of 0.97 g. The peak head acceleration was recorded at -0.77 g with the chest recording -1.4 g. The disparity was 0.63 g.

Flopping into a chair produced a head acceleration range of 0.88 g with a maximum disparity of 1 g. The peak head acceleration was 0.48 g and the chest 0.1 g.

Other activities such as jogging etc. produced similar values in the forward/backward plane but considerably greater accelerations in the up/down plane.

Chapter 4

Discussion & Conclusions

4.1 Discussion

The number of reported minor injury cases resulting from road traffic collisions appearing before the courts in the United Kingdom was in excess of 500,000 in 2007. Over 430,000 of the claims presented to the Courts were for 'whiplash' injuries. Whiplash is a mechanism for injury and it is acknowledged that the term almost exclusively relates to soft tissue injury. The United Kingdom is referred to as the whiplash capital of Europe, with 75% of personal injury claims being for whiplash. It has been felt for some time that the number of reported injury cases cannot all be legitimate. There is a large number which falls under the category of 'Insurance Fraud' and the Transport Select Committee has been considering for a number of months how to tackle this problem. The applicant has personally provided assistance to the Chair of the Committee.

The Quebec Task Force (Spitzer et al 1995) defines whiplash as 'an acceleration-deceleration mechanism of energy transfer to the neck'. If a road traffic accident (RTA) occurs where this mechanism is present and the resulting forces applied to the neck are sufficiently large, a 'whiplash' has taken place. Thus whiplash can be thought of as a bio-mechanical phenomenon leading to a probability of soft tissue injury.

In an accident which results in an injury, such as a broken bone, diagnosis is easily and unambiguously achieved. However, soft tissue injury, such as that resulting from a whiplash mechanism of sufficient amplitude, is notoriously difficult to diagnose to a degree of certainty sufficient to satisfy a Court of Law. Further expert evidence is often required in cases of a disputed RTA. This evidence will inevitably centre on the vehicle or vehicles involved in the collision. By a process of thorough investigation and evaluation following the principles of classical physics, most notably Newton's Laws of Motion, an opinion can be formed regarding the movements of the vehicles over the course of the collision and as a result the magnitude of the whiplash mechanism and the likelihood of a soft tissue injury.

It is not acceptable for a medical expert to give an opinion on a 'whiplash' injury without some explanation as to why and how the injury falls into that part of the injury spectrum and the range of expert opinion, nor is it acceptable for an expert to contend that no injury has occurred based solely on the low-velocity impact argument. There is a middle ground which allows that, when all the evidence is considered for an individual case, the injury prognosis can be determined within a reasonable range of expert opinion to the standard of proof required for civil litigation.

Prior to the start of the applicant's research, up-to-date information relating to 'low speed change' collisions, particularly within the United Kingdom, was almost non-existent. It was considered that new research was required to better understand the movement of vehicles and occupants in such collisions. In order that the research remained independent, no external funding was sought. Full-size crash testing and simulator testing programs were undertaken to better understand the effects of a range of vehicle speed changes on occupant accelerations within the time scale of typical vehicular collisions. The results of these test programs have illuminated the link between vehicle movements and the movements of occupants during a collision and in particular the disparity in the accelerations of the head and chest which are central to the whiplash mechanism as defined by the Quebec Task force.

The most common RTA leading to whiplash claims is a front-to-rear impact, where a bullet or striking vehicle runs into the back of a stationary target or struck vehicle. The classic whiplash mechanism is experienced by occupants in the target vehicle as it is pushed forward as a result of the collision. These types of collisions were thoroughly investigated in the applicant's research for a range of vehicle masses and impact speeds. This research has proved to be of particular significance as live instrumented occupants (volunteers) were used throughout the programs allowing first-hand assessment of accelerations to the head and chest and any resulting symptoms and injury.

One of the major aims of the crash testing the applicant carried out in 2005 was to monitor the accelerations of the head and chest of occupants in bullet and target vehicles. Not unexpectedly, the accelerations changed in magnitude and sign throughout the course of a collision. Of particular interest was the maximum difference or disparity between the accelerations of the head and chest as the applicant thought that this should give a good indication of the magnitude of the energy transfer mechanism to the neck leading to a whiplash type of injury as described earlier. For the front-to-rear crash tests, it was found that the maximum disparity between head and chest accelerations increased as delta-v increased. Results for occupants in the target vehicle are shown in Figure 1.5. A simple quadratic correlation represents the trend of the data points. Results for occupants of the bullet car are shown in Figure 1.6.

From a comparison of Figures 1.5 and 1.6, it is clear that, for a given value of delta-v, the maximum disparity between the head and chest is smaller for a bullet vehicle occupant than it is for a target vehicle occupant. This result implies that soft tissue injury probability should be less for bullet vehicle occupants than it is for target vehicle occupants assuming no individual variation in the occupants.

Thus, from the applicant's crash testing a clear link has been forged between the mechanical behaviour of the colliding vehicles, namely delta-v, and the bio-mechanical behaviour of occupants, namely the maximum disparity between accelerations of the head and chest.

There exists a perceived international threshold for injury of 5 mph (delta-v). This relates to the change in speed experienced by the target vehicle due to a rear-end collision. The inference is that above this threshold the whiplash mechanism has sufficient magnitude to cause the soft tissue injury known as whiplash and below this threshold there is insufficient energy transfer to the neck to cause injury. However, research has shown that these conclusions are not always so clear-cut.

The 5 mph threshold is not without merit as it does appear from the applicant's research that the probability of a whiplash type injury increases significantly above 5 mph. A non-linear increase is not unexpected as whiplash is an energy transfer mechanism and the energy available in a collision (kinetic energy) increases as the square of the bullet vehicle speed. For example, in 2005 the applicant carried out a crash test that was intended to produce a change in speed of the target vehicle of 5 mph (Henderson 2005). The crash actually resulted in a change in speed of 5.97 mph. Injury did occur with symptoms of strain and headache lasting up to five days. For obvious reasons this was the only crash test carried out above the 5 mph threshold. All other crash tests that were subsequently carried out were below a change in speed of 5 mph. None of these resulted in injury or significant symptoms. These no-injury results are extremely important as many claims for injury are very often made for low-speed collisions that are well below the 5 mph threshold.

The results from the applicant's crash testing are consistent with those published in SAE Technical Paper 2005-01-0296 (Moss et al, 2005). In the applicant's opinion, this paper is of particular importance as the authors base their conclusions on a statistically significant number of collisions that have passed through a rigorous filtering process. A major conclusion from this paper is that above a threshold of 5.87 mph (delta-v), injury is likely on the balance of probabilities. Below 5.87 mph injury is unlikely.

As indicated earlier, the whiplash mechanism can be defined as an acceleration-deceleration mechanism of energy transfer to the neck. Thus disparity between accelerations of the head and chest as measured during crash testing is of some interest. From the applicant's research, at the 5 mph (delta-v) threshold, an acceleration disparity of 5.8 g was measured for an occupant in the target vehicle (Figure 1.7). At the 5.87 mph threshold indicated by Moss et al, the disparity increased to 7.3 g.

In their paper, "Human Occupant Motion in Rear-End Impacts", Judson et al measured accelerations of dummy occupants in five low-speed collisions providing delta-v values from 1.0 to 5.1 mph. Acceleration differentials were provided by accelerometers positioned at the head and thorax. At a delta-v of 5.1 mph, the maximum acceleration differential was 7.3 g which is above my 5 mph value but in agreement with my 5.87 mph value. One female volunteer was used by the Judson study whereas I used male volunteers so it is likely that some of the differences can be explained by physical differences in the volunteers tested.

A number of other groups have tested the resistance human volunteers to injury in low-speed front-to-rear collisions. Most of the volunteers were not instrumented so no information on acceleration disparities are available. However, almost all groups identify an injury threshold in the region of a 5mph change in speed of the target vehicle. Typical of these is the testing carried out by Braun et al (2001) in their paper "Rear-End Impact Testing with Human Test

Subjects" One of their conclusions was that normally seated healthy adults with adequate head support can tolerate delta-v's of 4.5 mph.

The applicant's research indicates that for an occupant in a bullet vehicle to achieve a disparity of 5.8 g and 7.3 g, speed changes of 6.5 mph and 7.4 mph respectively would be required for the bullet vehicle. It is thought that these differences between target and bullet vehicle occupant thresholds are due to the way in which occupants move within their respective vehicles. If disparity between the accelerations of the head and chest are an indication of the magnitude of the whiplash mechanism, then these results have some utility as they suggest higher threshold values for any bullet vehicle occupants that are claiming soft tissue injuries. No other contemporary research involving bullet vehicle occupants is available with which these results can be compared.

Another important result from my crash testing research was the correlation found for the coefficient of restitution (c.o.r.) for a collision between two vehicles of a type found on U.K. roads. The applicant's company, GBB(UK)Ltd. was, and probably still is, the only investigative company in the UK that has a working correlation based on its own research.

An appropriate value of restitution is often a matter of dispute between experts working for claimant and a defendant. A higher value of restitution confers a higher change in velocity of the colliding vehicles as elastically deformed structures recover their shape in the latter stages of contact between the vehicles. A lower value of restitution implies that a greater proportion of the deformation that occurs during a collision is plastic or inelastic in nature and will remain as observable damage after the collision has ended.

Based on the principles of physics, the coefficient of restitution should tend towards zero at increasing collision speeds due to the increasing proportion of plastic damage compared with elastic deformation. For converse reasons, the coefficient of restitution should converge towards unity as the collision speed decreases and collisions become more elastic. The applicant's crash testing research has produced the correlation c.o.r. = $e^{-0.253v}$ (or c.o.r. = exp (-0.253v)) where v is the collision or closing speed of the two vehicles in mph.

A number of groups (Howard et al., 1994, Malmsbury et al., 1994. and Antonetti. 1998), all based in the U.S.A., have carried out practical research to determine restitution values in both barrier collisions and vehicle-to-vehicle collisions. In general, the results confirm the trend of restitution values decreasing from unity towards zero as impact speeds increase. Due to the complex nature of vehicle constructions and differences between makes and models, there is significant scatter in results. Different structures and materials within a particular vehicle participate more and more in the collision as impact speeds increase. In a collision between a 'hard' vehicle and a 'soft' vehicle, the coefficient of restitution as well as the time period over which the collision occurs will be controlled by the softer vehicle but not in a simple way. The softer vehicle will of course sustain the greater deformation although, in accordance with Newton's Third Law, the forces experienced by each vehicle are equal in magnitude but opposite in direction at all points in time throughout the collision.

The research carried out by Howard et al., Malmsbury et al. (1994) and Antonetti (1998) resulted in restitution verses closing velocity data points that were in general above those correlated by the applicant's research. For example, data produced by Howard et al was correlated in their paper by the third order exponential c.o.r. = 0.5992exp $(-0.2508v + 0.1934v^2 - 0.001279v^3)$ where, in this case, v is the closing velocity in m/s. There is considerable scatter around the correlation and a correlation of this type becomes non-physical as the collision speed approaches zero since it predicts a restitution tending towards 0.5992 rather than unity.

The work carried out by Malmsbury and Eubanks (1994) as described in their 1994 paper, featured a relatively large number of front-to-rear collisions. The purpose of their research was not explicitly to find restitution values, but from their results restitution values could be calculated. Of thirteen validated crash tests, six were well-modelled by the GBB correlation and the remaining seven were significantly different. These seven could be modelled by the different correlation c.o.r. = -0.2272ln(v) +0.8286. Physically, this is less satisfactory than the GBB correlation as it does not tend towards unity as impact speed approaches zero. A comparison of these correlations is shown in Figure 1.3. The applicant has recently carried out more crash testing and it remains to be seen whether the latest results will support the correlation currently in use.

It is important to note that the research carried out by Howard et al (1994)., Malmsbury et al (1994) and Antonetti (1998) was with vehicles available in the U.S.A. some with rigid bumper types, some with isolators in the bumper structure and others with foam. The differences between vehicles available in the U.S.A. and in the U.K. may to some extent account for differences in restitution results and their resulting correlations.

A large number of whiplash claims are made in the lower range of impact speeds between zero and 3 mph. To provide a significant amount of accurate data within this speed range without having to resort to actual vehicle collisions, a rig was designed to simulate front-to-rear collisions. The simulator rig was specifically designed to allow easy measurements of head and chest accelerations over an accurately measured range of impact speeds as described in section 2.3.3.

Using the simulator, a series of tests were undertaken with velocity changes between 1.8 and 3.1 mph. An accelerometer mounted on the simulator gave the impact speed and all occupants were fitted with accelerometers at the head and chest. In a series of simulator tests carried out at around 3 mph, average maximum accelerations applied to the head and chest were recorded as 2.93 g and 3.46 g respectively resulting in an average difference or disparity of 0.53 g. For comparison, a difference of 3.6 g was recorded during an actual crash test with a velocity change of nearly 6 mph. These results indicate the rapid non-linear increase in the disparity between head and chest accelerations as the velocity change (delta-v) of a target vehicle increases and a consequent increase in the magnitude of the whiplash mechanism. Occupant symptoms were recorded and monitored and a follow-up period of up to two years was embarked upon, thus meaning this research was the most lengthy of its type.

A number of tests were carried out where instrumented volunteers performed a range of everyday activities. Disparities between head and chest accelerations were measured and correlated with the applicant's simulator testing. In this way, very low speed collisions, where there are often claims for whiplash type injuries, can be likened to everyday activities.

Vijayakumar et al (2006) carried out a comparison of low-speed rear-end collisions using fair-ground bumper cars with activities of daily living. They carried out instrumented tests on hopping, rope skipping, falling into a chair, running with an abrupt stop and bumper car rides. This group found that head accelerations, upper neck loads and moments determined from the bumper car collisions were comparable to or lower than those experienced by healthy adults during vigorous activities. These are in agreement with the applicant's findings.

The inference from the applicant's research and from the findings of Vijayakumar et al (2006) is that if a litigant is not injured during daily activities, why should they be injured in an equivalent very low speed collision? It is of course up to a Court to make a final decision.

Finally, it is the applicant's opinion, based on his research, that beyond a speed change of 5 mph, the risk of injury due to the whiplash mechanism is high. The risk between 3 mph and 5 mph is a grey area that would benefit from further exploration and speed changes below 3mph indicate minimal risk of injury.

4.2 Conclusions and Recommendations

A. From full size crash testing, it was found that rear end collisions from start to finish typically take of the order of 0.2 seconds, with maximum acceleration taking place in the first 0.1 seconds.

B. Speed changes of 5 mph within the typical time frame of a rear end collision have generally been considered to be the 'threshold' of human occupant injury tolerance. It was found that speed changes at this level produced considerably greater levels of acceleration than any normal daily activity and provided peak instantaneous disparity acceleration levels way above those.

C. Whilst international opinion seems to be in favour of a proposition that 5 mph is an injury threshold, one should err on the side of caution despite transient symptoms being recorded as the true legacy of testing within that speed change range, after a lengthy follow up period.

D. Closer consideration of the tests with speed changes in the 3 mph or less bracket revealed surprisingly similar levels of acceleration, duration of movement, delay between chest and head movement and perhaps more importantly maximum acceleration disparity levels. At 3 mph or less the typical maximum head/chest disparity was around 2 g. Whilst this in itself has no obvious meaning to the lay person, the reality is that such movement is hardly discernible to the occupant and no effect was felt.

E. No symptoms lasting beyond a few minutes (including psychosomatic symptoms) were recorded. Again, a lengthy follow up programme was followed. When one considers that merely sitting in a firm chair can produce a disparity of 1 g without any consideration then this is not surprising.

F. Analysis of the numerous tests of varying types that the applicant has undertaken leads him to the conclusion that there is no one type of 'everyday activity' test that accurately replicates a rear end collision. The simulator and crash tests are the only way to accurately measure accelerations and understand what actually happens during a collision.

G. Different daily activities provided greater levels of acceleration in the up/down plane but not the forward/backward plane. Some exercises provided greater levels of acceleration all round. Clearly there is an element of up/down movement in a rear end collision, but the over-riding element is the rearward and then forward motion of the head in relation to the movement of the chest and that could not be replicated fully.

H. It is apparent that speed changes in the region up to 3 mph generally provide maximum instantaneous acceleration disparities in the X axis (backward/forward) of around 2 g. Such a level is easily tolerated by human occupants and in reality is only just discernible.

I. Given that light activities provide accelerations just below such level and that some common exercises provide accelerations above it, it would be fair to conclude that speed changes in the 3 mph range provide an experience similar to that encountered in daily activity.

J. It seems that disparities in the 4 g range can also be tolerated as a 'one off' event without anything other than mild transient symptoms being presented. Whilst this is outside the normal range of the light activities, the applicant would argue that this lends support to the conservative view in relation to the 2 g disparities.

K. Bullet vehicle occupant accelerations are considerably less than target vehicle occupant accelerations for any given low speed collision.

In conclusion, the results of this lengthy study have clearly shown that low speed collisions can cause injury to both driver and passengers as well as damage to the vehicles. In this extended follow up study those injuries, including those experienced outside a 5 mph speed change range, were of a transient nature. The lower speed of the collision, then the lower the resultant speed change in either vehicle. The lower the speed change the lower the resultant acceleration of occupants. Further studies are required to find out the effect of medium to high speed collisions.

4.3 Scope for Future Studies

It is anticipated that design or purchase of a crash test dummy would allow consideration of occupant movement in higher speed collisions having compared dummy movement in low speed change collisions initially. Such data could be rapidly gathered and the application of simulation could be added to full size crash testing.

Application of animation technology to the occupant movement is planned to provide clearer detail of such movement. Predictive simulation is expected to follow on from such developments.

Damage patterns in vehicles will continue to be studied, particularly as vehicle design alters.

Chapter 5

References

Antonetti, V. W., (1998) “Estimating the Coefficient of Restitution of Vehicle-to-Vehicle Bumper Impacts”, SAE 980552.

Anderson, B., Kress, T., Hungerford, J. and Richards, S., (2007) “Bumper Paint Damage in Low Speed Impacts”, SAE 2007-01-0728.

Bailey, M. N., Wong, Bing C. and Lawrence, J. M., (1995) “Data and Methods for Estimating the Severity of Minor Impacts”, SAE 950352.

Balasubramanian, S., Seacrist, T., Maltese, M. R., Arbogast, K, B., Hopely, T., Constans, E., Sterner, R., Tanji, H. and Higuchi, K., (2009) “Head and Spinal Trajectories in Children and Adults Exposed to Low Speed Frontal Acceleration”, SAE 2009-09-0263.

Braun, T. A., Jhoun, J. H., Braun, M. J., Wong, B. M., Boster, T. A., Kobayashi, T. M., Perez, F. A., Hesler, G. M., (2001) “Rear-End Impact Testing with Human Test Subjects”, SAE 2001-01-0168.

Brault, J., Smith, T., Wheeler, J. and Siegmund, G., (2004) “Cervical Muscle Response to Rear-End Automobile Collisions: Implications for Injury”, IRCOBI Conference, Austria, September 24.

Castro, W, H., et al (2001) “No Stress – No Whiplash? Prevelance of ‘Whiplash’ Symptoms following exposure to a placebo rear-end collision”, Int J Legal Med. 114(6) ,316-322.

Castro, W, H., Schligen, M., Meyer, S., Weber, M., Peuker, C. and Wortler, K., (1997) “Do ‘whiplash injuries’ occur in low-speed rear impacts?”, Eur Spine J., 6(6):366-375.

Cheng, P. H., Tanner, B. C., Chen, H F., Durisek, N. J. and Guenther, D. A., (2005) “Delta V, Barrier Equivalent Velocity and Acceleration Pulse of a Vehicle During an Impact”, SAE 01-1187.

Cheng, P. and Guenther, D., (1989) “Effects of Change in Angular Velocity of a Vehicle on the Change in Velocity Experienced by an Occupant during a Crash Environment and the Localised Delta V Concept”, SAE 890636.

Chirwa, E, C., (1999) “Vehicle Crashworthiness Design: The world experience and future in space travel safety”. Keynote paper – Proceedings of the Russian Academy of Sciences, Transport Division, 2nd International Conference on Progress in Transportation Systems, Edited by Shekhovsov V. V., Volgorad, Russia, pp. 20 – 30.

Chirwa, E, C., (2005) Keynote Speech, “The impact Loading of Lightweight Structures” Conference, WIT Transactions on Engineering Sciences, Costao Do Santinho, Florianopolis, Brazil, 8th – 12th May 2005.

Chirwa, E, C., (2009) Keynote Speech. “Product reliability in crashworthiness”, INFATS 111 Programme, 6th International Forum of Automotive Traffic Safety and Seminar for Impact Biomechanics and Injury Prevention Conference, Xiamen University of Technology, Xiamen, Fujian Province, China, 1st – 4th December 2009.

Emori, R. I. and Horiguchi, J., (1990) “Whiplash in Low Speed Vehicle Collisions”, SAE 900542.

Dubois, R., McNally, B., DiGregorio, J. and Phillips, G., (1996) “Low Velocity Cat-to-Bus Test Impacts”, Accident Reconstruction Journal.

ECE Regulations – Uniform Provisions Concerning The Approval Of Vehicles With Regard To Their Front And Rear Protective Devices (Bumpers etc.) E/ECE/324.

Fay, R., Raney, A. and Robinette, R., (1996) “The Effect of Vehicle Rotation on the Occupants’ Delta V”, SAE 960649.

Happer, A. J., Hughes, M. C., Peck, M. D. and Boehme, S. M., (2003) “Practical Analysis Methodology for Low Speed Vehicle Collisions Involving Vehicles with Modern Bumper Systems”, SAE 2003-01-0492.

Henderson. B., (2005) “Report on a Full-Size Crash Test”. GBB Internal Report CT2\2005\1

Henderson. B. (2006). “Putting the 5mph Injury Threshold to the Test”. Whiplash - Personal Injury Law Journal. Sept. 2006: p12.

Henderson. B. and Hoyes, P. (2009). “A Study of Human Kinematic Response to Low Speed ‘Rear End’ Impacts Involving Vehicles of Largely Differing Masses”. International Congress on Traffic Accident Investigation, Shanghai.

Henderson. B. and Hoyes, P. (2009). “A Study of Extreme Partial Collisions”. Impact – The Journal of the Institute of Traffic Accident Investigators. 17/3:4-7

Henderson. B. and Hoyes, P. (2010). “Is the Threshold for Injury a 3mph speed change in a Rear End Collision?” Forensic Science Society Spring Conference April 2010.

Howard, R. P., Bomar, J. and Bare, C., (1993) “Vehicle Restitution Response in Low Speed Collisions”, SAE 931842.

Howard, R. P., Harding, R. M. and Krenric, S. W., (1999) “The Biomechanics of ‘Whiplash’ in Low Velocity Collisions”, SAE 1999-01-3235.

Husted, D. C., Niss, D. J. and Heverly, D. E., (1999) “The Appropriate Use of ‘Delta V’ in Describing Accident Severity”, SAE 1999-01-1295.

Judson, B., Welcher, J., Szabo, T., Voss, D., (2001) “Human Occupant Motion in Rear-End Impacts: Effects of Incremental Increases in Velocity Change”, SAE 2001-01-0899.

Kerkhoff, J. F., Husher, S. E., Varat, M. S., Busenga, A. M. and Hamilton, K., (1993) “An Investigation into Vehicle Frontal Impact Stiffness for Reconstruction”, SAE 903899.

Kornhauser, M., (1996) “Delta-V Thresholds for Cervical Spine Injury”, SAE 960093.

Malmsbury, R., Eubanks, J., (1994) “Damage and/or Impact Absorber (Isolator) Movement Observed in Low Speed Crash Tests Involving Ford Escorts”, SAE 940912.

Mansour, R. and Romilly, D., (2011) “Application of Energy Absorbing Foam to the Seat Base to Mitigate Whiplash Injuries in Rear-End Collisions”, SAE 2011-01-0271.

McConnell, W. E., Howard, R. P., Guzman, H. M., Bomar, J. B., Raddin, J. H., Benedict, J. V., Smith, H. L. and Hatsell, C. P., (1993) “Analysis of Human Test Subject Kenematic Responses to Low Velocity Rear End Impacts”, SAE 930889.

Melvin, J. W. and Weber, K., (1988) “Review of Biomechanical Impact Response and Injury in the Automotive Environment”, DOT/HS 807 042.

Mertz, H, J. and Patrick, L. M., (1967) “Investigation of the Kinematics and Kinematics of Whiplash”, SAE 670919.

Moss, R., Bardas, A., Hughes, M., and Happer, A., (2005) “Injury Symptom Risk Curves for Occupants Involved in Rear End Low Speed Motor Vehicle Collisions”, SAE Technical Paper2005-01-0296, 2005, doi:10.4271/2005-01-0296.

Robinette, R. D., Fay, R. J. and Paulsen, R. E., (1994) “Delta-V Basic Concepts, Computational Methods and Misunderstandings”, SAE 940915.

Schmidt, B., Haight, W., Szabo, T. and Welcher, J., (1998) “System-Based Energy and Momentum Analysis of Collisions”, SAE 980026.

Schutt, C. H. and Dohan, C. F., (1968) “Neck Injury to Women in Auto Accident”, Journal AMA, 206, 2689-2692.

Siegmund, G. P. and Williamson, P. B., (1993) Road Safety Conference VIII June 1993, Saskatoon, Saskatchewan.

States, J. D., (1979) “Soft Tissue Injuries of the Neck”, SAE 790135.

Spitzer WO, Skovron ML, Salmi LR, Cassidy JD, Duranceau J, Suissa S, Zeiss E., (1995) Scientific monograph of the Quebec Task Force on Whiplash-Associated Disorders: “Redefining “whiplash“ and its management”. Spine 1995;20(8S):1S-73S.

Starks, I., Henderson, B., Hall, M. and Wade, R. (2007). “Does the Low Back Displace Significantly in Low Velocity Rear Impact Shunts?” J. Injury.11:330

Starks, I., Henderson, B., Hall, M. and Wade, R. (2007). “Is the Threshold for Injury Really a Delta-V of 3mph?” J. Injury.11:331

Starks, I., Henderson, B., Hall, M. and Wade, R. (2009). “Does Whiplash Occur in Low Velocity Rear Impact Shunts?” European Federation of National Associations of Orthopaedics and Traumatology (10th Congress), Vienna.

Szabo, T., Welcher, J., Anderson, R. and Rice, M., (1994) “Human Occupant Kinematic Response to Low Speed Rear-End Impacts”, SAE 940532, 1994.

Tumbas, N. S. and Smith, R. A., (1988) “Measuring Protocol for Quantifying Vehicle Damage from an Energy Basis Point of View”, SAE 880082, 1988.

Vijayakumar, V., Scher, I., Gloeckner, D. C., Pierce, J., Bove, R., Young, D. and Cargill, R., (2006) “Head Kinematics and Upper Neck Loading During Simulated Low Speed Rear-End Collisions: A Comparison With Vigorous Activities of Daily Living”, SAE 2006-01-0247.

Wade, R., Henderson, B. and Simpson, I. (2007). “Deconstructing a Collision”. Whiplash - Personal Injury Law Journal. March 2007: p6.

Chapter 6

Presentations and Publications

The following presentations and publications have been based on this study. They are attached as appendices 7.15 to 7.21.

1. Henderson, B. (2006). “Putting the 5mph Injury Threshold to the Test”. Whiplash - Personal Injury Law Journal. Sept. 2006: p12.

2. Wade, R., Henderson, B. and Simpson, I. (2007). “Deconstructing a Collision”. Whiplash - Personal Injury Law Journal. March 2007: p6.

3. Starks, I., Henderson, B., Hall, M. and Wade, R. (2007). “Does the Low Back Displace Significantly in Low Velocity Rear Impact Shunts?” J. Injury.11:330

4. Starks, I., Henderson, B., Hall, M. and Wade, R. (2007). “Is the Threshold for Injury Really a Delta-V of 3mph?” J. Injury.11:331

5. Starks, I., Henderson, B., Hall, M. and Wade, R. (2009). “Does Whiplash Occur in Low Velocity Rear Impact Shunts?” European Federation of National Associations of Orthopaedics and Traumatology (10th Congress), Vienna.

6. Henderson, B. and Hoyes, P. (2009). “A Study of Human Kinematic Response to Low Speed ‘Rear End’ Impacts Involving Vehicles of Largely Differing Masses”. International Congress on Traffic Accident Investigation, Shanghai.

7. Henderson, B. and Hoyes, P. (2009). “A Study of Extreme Partial Collisions”. Impact – The Journal of the Institute of Traffic Accident Investigators. 17/3:4-7

8. Henderson, B. and Hoyes, P. (2010). “Is the Threshold for Injury a 3mph speed change in a Rear End Collision?” Forensic Science Society Spring Conference April 2010.

Chapter 7

Appendices

Appendix 1

Research

RESEARCH

1) GBB (UK) Limited are undertaking continuing research into the effects of low speed collisions.

2) Primarily, this is the consideration of the effect of sudden velocity change experienced by the human body during such collisions.

3) By agreeing to take part in such research you must be aware that there will be a risk of injury, however small that may be.

4) The intention of the research is not to cause injury, but to consider the effect downwards from what is currently considered to be the general threshold at which soft tissue injury begins to occur – that is changes in velocity of 5 mph and below.

5) As with any research of this kind the decision to take part is personal and absolutely no liability will rest with GBB (UK) Limited or its employees or agents for any injury caused.

6) DO NOT AGREE TO TAKE PART IF YOU DO NOT ACCEPT THE POINTS ABOVE IN FULL.

Appendix 2

Experiment Proforma

REF NO

GBB (UK) Limited

Name	

Date of Experiment	

Now that you have undertaken the experiment, would you please complete the sections below listing any symptoms and specific area(s) of pain.

Symptoms within 6 hours

If you have experienced adverse symptons eg pain, please indicate on the scale below (with a circle) your level of symptoms (10 the highest)

0	1	2	3	4	5	6	7	8	9	10

Symptoms within 12 hours

level of symptoms

0	1	2	3	4	5	6	7	8	9	10

Symptoms within 24 hours

level of symptoms

0	1	2	3	4	5	6	7	8	9	10

Symptoms within the course of the next 7 days

level of symptoms

0	1	2	3	4	5	6	7	8	9	10

Would you please confirm whether you have been required to attend your local accident and emergency department or needed to seek advice from your general practitioner, physiotherapist, pharmacist etc.

Please confirm whether or not you have required any painkillers. If yes, please specify.

Please confirm whether you have been required to modify any activities of daily living in the week following the tests. IE: paid employment, housework, shopping lifting, sports etc.

ONCE COMPLETE PLEASE RETURN TO GBB (UK) LIMITED IN THE ENVELOPE PROVIDED

THANK YOU FOR YOUR ASSISTANCE

Appendix 3

Crash Testing – 1 June 2005

Crash Testing 1st June 2005

Car Information

VH No.	Make	Model			Engine Size	Registration	Damage	Curb weight
1	Toyota	Celica	ST L/B	2dr	1972cc	A747KKC	None	1135kg
2	Vauxhall	Carlton	GI	4dr	1796cc	K596EDT	None	1166kg
3	Vauxhall	Cavalier	GS	5dr	1998cc	L926OMF	None	1204kg
4	Volkswagen	Polo		3dr	1043cc	E979RND	None	700kg
5	Peugeot	405	GLD	4dr	1905cc	H798VBV	Front	1080kg
6	Peugeot	405	GL	4dr	1580cc	G914CWM	None	1020kg
7	Ford	Fiesta	I	3dr	1119cc	K187NWM	Front	810kg
8	Rover	Metro	Nightfire	3dr	1120cc	L47FRJ	None	810kg
9	Vauxhall	Nova		3dr	993cc	F174FWE	None	775kg
10	Ford	Escort	LX I	5dr	1391cc	L851TDU	None	1040kg
11	Citroen	AX	Spree	3dr	1527cc	M316PFR	Front	735kg

Appendix 4

Crash Testing – 1st June 2005

Test Details

Crash Testing 1st June 2005

Test Details

Test No.	Info	Bullet Car					Target Car			
		Registration / Car Number	Driver	Passenger	Speed (mph)	Angle	Registration / Car Number	Driver	Passenger	Speed
1	Rear end (no data for target vehicle)	1	Eric Taylor	Dave Aitchinson	9.1	0	2	Phil Hoyes	Laurie Pennington	0
2	Rear end	2	Paul Brooks	Ian Law	11.1	0	1	Eric Taylor	Dan Bradshaw	0
3	Rear end	3	Steve Garnham	N/A	11.4	0	8	N/A	N/A	0
4	Rear end	8	Ronnie Trivett	N/A	11.8	0	3	Simon Farrell	N/A	0
5	Reverse into front	7	Mike Doyle	Sheena Haytrack	-5.5	0	4	John Sutcliffe	N/A	0
6	Rear end	6	Gordon Pearce	N/A	9.9	0	5	N/A	N/A	0
7	Rear end 50% offset	6	Gordon Pearce	N/A	10.0	0 (50% offset)	5	N/A	N/A	0
8	Rear end 70% offset	6	Gordon Pearce	N/A	10.7	0 (70% offset)	5	N/A	N/A	0

Crash Testing 1st June 2005

Test Details

Test No.	Info	Bullet Car					Target Car			
		Registration / Car Number	Driver	Passenger	Speed (mph)	Angle	Registration / Car Number	Driver	Passenger	Speed
9	Test failed	9	Bryan Evans	N/A	N/A	90°	4	N/A	N/A	0
10	Static side impact	9	Bryan Evans	N/A	16.3	90°	4	N/A	N/A	0
11	Dynamic side impact	10	Bob Nicholls	N/A	12.8	90°	7	Dave Aitchinson	Sheena Haytrack	7.4
12	Glancing impact front corner	11	Ian Law	N/A	24.9	?	10	Brian Henderson	N/A	0
13	Rear end	7	Simon Farrell	N/A	1.9	0	10	Raymond Newman	E Gatzouris	0
14	Rear end	7	Simon Farrell	N/A	3.3	0	10	Raymond Newman	E Gatzouris	0
15	Glancing impact rear corner	3	Mike Harrison	N/A	32	?	5	N/A	N/A	0

Appendix 5

Simulator Results Log

TEST RUN NUMBER	SIMULATOR MAX g	SIMULATOR Δv in mph		HEAD MAX g	BODY MAX g	SIMULATOR Δt in seconds	
		First Peak	Second Peak			First Peak	Second Peak
1	1.681	2.347	2.96	7.837	2.552	0.14	0.21
2	0.939	1.56	1.971	3.312	3.596	0.15	0.32
3	0.942	1.246	1.847	3.617	4.347	0.13	0.3
4	0.871	1.984	2.062	3.205	4.091	0.15	0.32
5	0.948	1.435	2.143	3.999	3.962	0.14	0.29
6	1.29	1.574	2.48	3.51	3.621	0.13	0.31
7	1.775	1.389	2.075	2.572	4.176	0.12	0.29
8	1.557	2.452	3.02	3.877	3.401	0.13	0.29
9	1.109	2.018	2.493	2.259	3.529	0.13	0.34
10	1.134	2.218	2.259	1.953	3.492	0.14	0.19
11	1.265	1.791	2.194	1.831	3.609	0.14	0.29
12	1.24	1.883	1.948	2.106	2.259	0.11	0.28
13	1.27	1.897	2.275	2.885	3.334	0.12	0.31
14	2.0645	2.398	3.114	3.357	3.809	0.12	0.29
15	1.44	2.572	2.62	1.755	3.279	0.12	0.33
16	1.287	1.826	2.792	1.465	3.565	0.13	0.29
17	1.287	1.864	2.042	2.32	3.571	0.12	0.29
18	1.339	2.038	2.846	3.457	4.365	0.12	0.3
19	1.331	2.088	2.685	0	0	0.11	0.28
20	1.295	1.985	2.53	0	0	0.13	0.3
21	1.168	1.919	2.429	3.078	3.217	0.12	0.28
22	1.336	2.065	2.56	2.257	3.004	0.12	0.29
23	1.367	2.802	NIL	1.343	2.937	0.17	NIL
24	0.972	1.791	2.117	3.759	3.15	0.14	0.32
25	1.209	1.8	2.288	0	0	0.14	0.33
26	1.597	2.706	2.04	2.051	3.59	0.11	0.33
27	1.485	1.949	2.927	2.479	2.6	0.11	0.32
28	4.91	1.493	1.571	2.048	3.83	0.06	0.24
29	5.074	1.949	2.927	1.047	0.528	0.06	0.24
30	2.51	3.51	NIL	3.77	3.33	0.17	NIL
31	2.72	3.54	NIL	4.01	2.99	0.18	NIL
32	4.4	2.89	3.27	4.05	3.78	0.09	0.32
33	2.24	2.12	3.31	3.07	2.71	0.08	0.28
34	2.22	2.33	3.31	2.69	2.9	0.09	0.28
35	2.32	2.2	2.8	3.31	3.45	0.08	0.2
36	1.5			2.2	2.9		
37	1.72	2.36		2.08	3.32		0.2
38							
39							
40							
41	1.62	2.99		2.5	3	0.06	0.15
42	1.61	3.2		3.4	2.75	0.06	0.15
43	1.4	3.32		2.24	3.25		
44	1.38	3.02		3.46	3.66		
45	1.37	2.74		2.4	4.23		
	1.718869	2.225829	2.497031	2.679976	3.087714	0.119459	0.278571

Appendix 6

Simulator Details Log

SIMULATOR PROGRAMME								
Run No.	Name	Occupation	Age (yrs)	Height (m)	Weight (kg)	Neck (cm)	Symptoms	Comments
1	Test							
2	Simon Farrell	Investigator	24	1.72	95		None	
3	Laurie Pennington	Investigator	24	1.72	70	-	None	
4	Gordon Pearce	Investigator	54	1.80	105	-	Mild discomfort at back of chest cleared within 10 min	
5	Steve Garnham	Investigator	50	1.73	69	-	Mildly uncomfortable	
6	Robert Nichols	Investigator	42	1.90	120	47	None	
7	Ronald Trivett	Investigator	41	1.83	76	41	None	Whiplash injury several years earlier
8	Keith Liddemore	Claims Officer	55	1.57	76	39	Initial surprise	
9	Allan Cox	Investigator	56	1.98	111	47	None	
10	Phil Hoyes	Investigator	27	1.88	82	43	Shaken but no discomfort	
11	Phil Hoyes	Investigator	27	1.88	82	43	Shaken but no discomfort	Looking up and to the left at time of impact
12	Daniel Bradshaw	Investigator	35	1.78	105	-	Slight ache in upper neck area cleared within 10 min.	
13	Raymond Southern	Solicitor	41	1.73	94	42	None	Whiplash in 2003 lasting 9 months
14	E.R. Jaco	Orthopaedic Surgeon	47	1.81	92	41	Forehead pain 3/10 resolved within 5 sec. Within 10 minutes, dull ache in region of both shoulders resolved within 6 hours.	RTA @ 50 mph ten year earlier. (Orthopaedic Surgeon)
15	Martyn Lovell	Orthopaedic Surgeon	40	2.00	127	46	None	Mild whiplash in 1985 & 1992 lasting approx 2 weeks.
16	Craig Nunn	Paralegal	25	1.78	98	42	None	
17	Steve Garnham	Investigator	51	1.73	69	39	None	

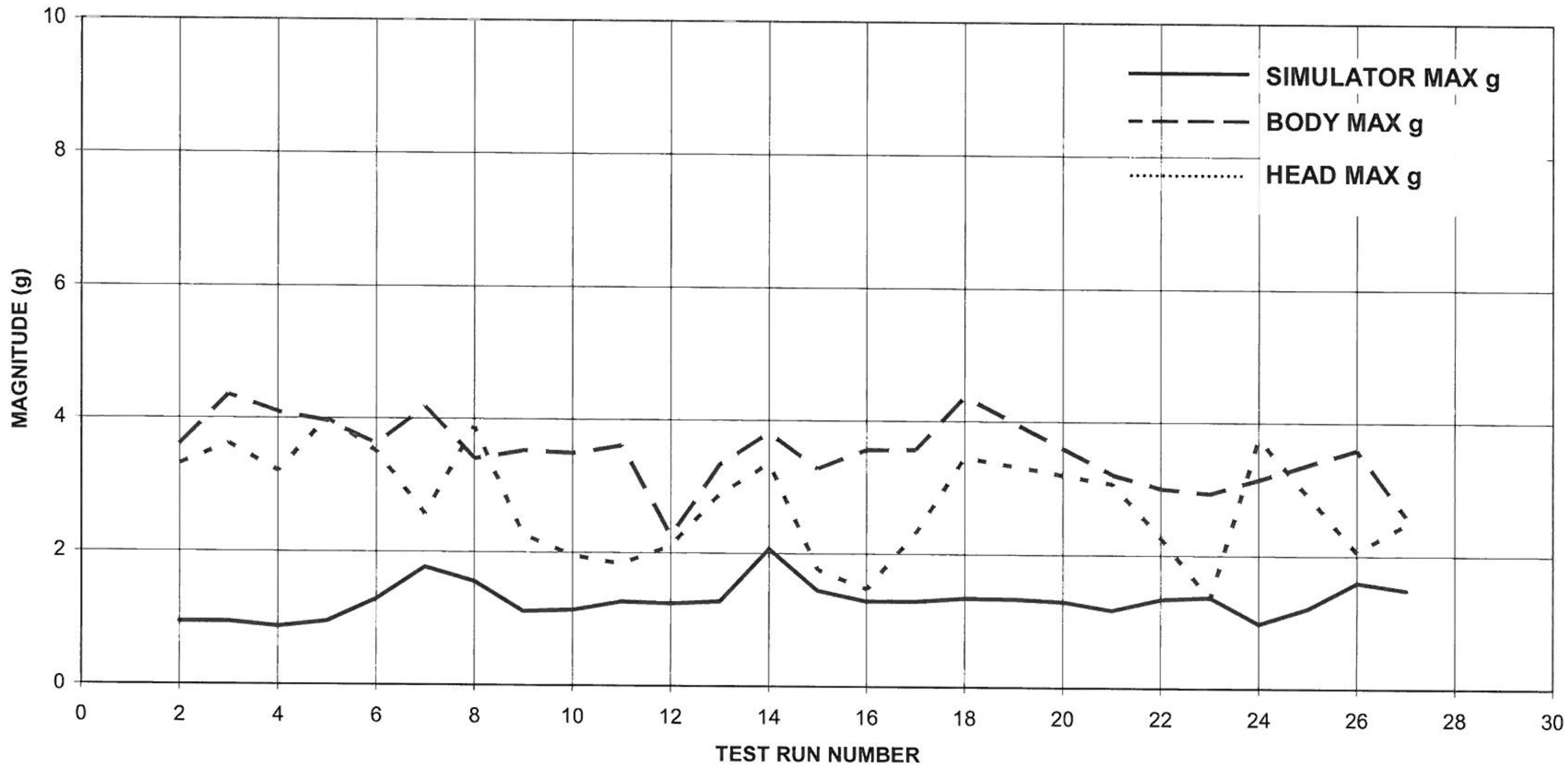
Run No.	Name	Occupation	Age (yrs)	Height (m)	Weight (kg)	Neck (cm)	Symptoms	Comments
18	Robert Nicholls	Investigator	42	1.90	121	47	Dull headache cleared within 10 min.	Stroke in 1999
19	Ian Law	Investigator	53	1.78	95	44	None	Tests 19 to 22 were carried out on the same day
20	Ian Law	Investigator	53	1.78	95	44	None	
21	Ian Law	Investigator	53	1.78	95	44	None	
22	Ian Law	Investigator	53	1.78	95	44	None	
23	Brian Henderson	Investigator	44	1.78	82	40	None	Slight stiffness in left shoulder/neck area immediately prior to testing
24	Brian Henderson	Investigator	44	1.78	82	40	Slight stiffness at base of skull. Slight headache. All symptoms resolved within 6 hours.	Tests 23 and 24 carried out on same day. Head positioned against the head restraint
25	Kerstin Pryke (Female)	Student	20	1.60	68	36	None	
26	Roger Wade	Orthopaedic Surgeon	36	1.78	85	-	None	Neck and shoulder symptoms within previous two years.
27	Ian Simpson	Barrister	49	1.83	81	38	None	Lower back strain for 2 weeks in 1989
28	Sandile Makeleni	Researcher	29	1.75	75	37	None	
29	Sandile Makeleni	Researcher	29	1.75	75	37	None	
30	Sandile Makeleni	Researcher	29	1.75	75	37	None	Accelerometer positioned at lower back
31	John Sutcliffe	Investigator	51	1.83	67	38	None	Tests 31 and 32 were carried out on the same day
32	John Sutcliffe	Investigator	51	1.83	67	38	None	
33	Ian Law	Investigator	53	1.78	105	44	None	Tests 33, 34 & 35 were carried out on the same day. The purpose was to test if the impact was sufficient to spill water from a plastic cup held in the hand. The tests were filmed.
34	Ian Law	Investigator	53	1.78	105	44	None	
35	Simon Farrell	Investigator	26	1.73	98	44	None	

36	Bryan Evans							
37	Angus Duncan							
38	Matthew Stansfield	Director	29	1.905	103		None	
39	Neil Empson	Investigator	54	1.88	110		None	
40	Daniel Mallon	Investigator	26	1.79	75		None	
41	Simon Farrell	Investigator	28	1.72	93		None	Seated Normally
42	Simon Farrell	Investigator	28	1.72	93		None	Twisted looking to left simulating looking for traffic approaching from rear left hand side. Performed 5 minutes after test 41.
43	Matthew Stansfield	Director	31	1.9	110		None	No seatbelt, driving position
44	Nick Hoare	Investigator	44	1.93	107		None	Seatbelt, driving position
45	Philip Hoyes	Director	33	1.83	81		None	Seatbelt, hands on lap

Appendix 7

Simulator Summary Graph

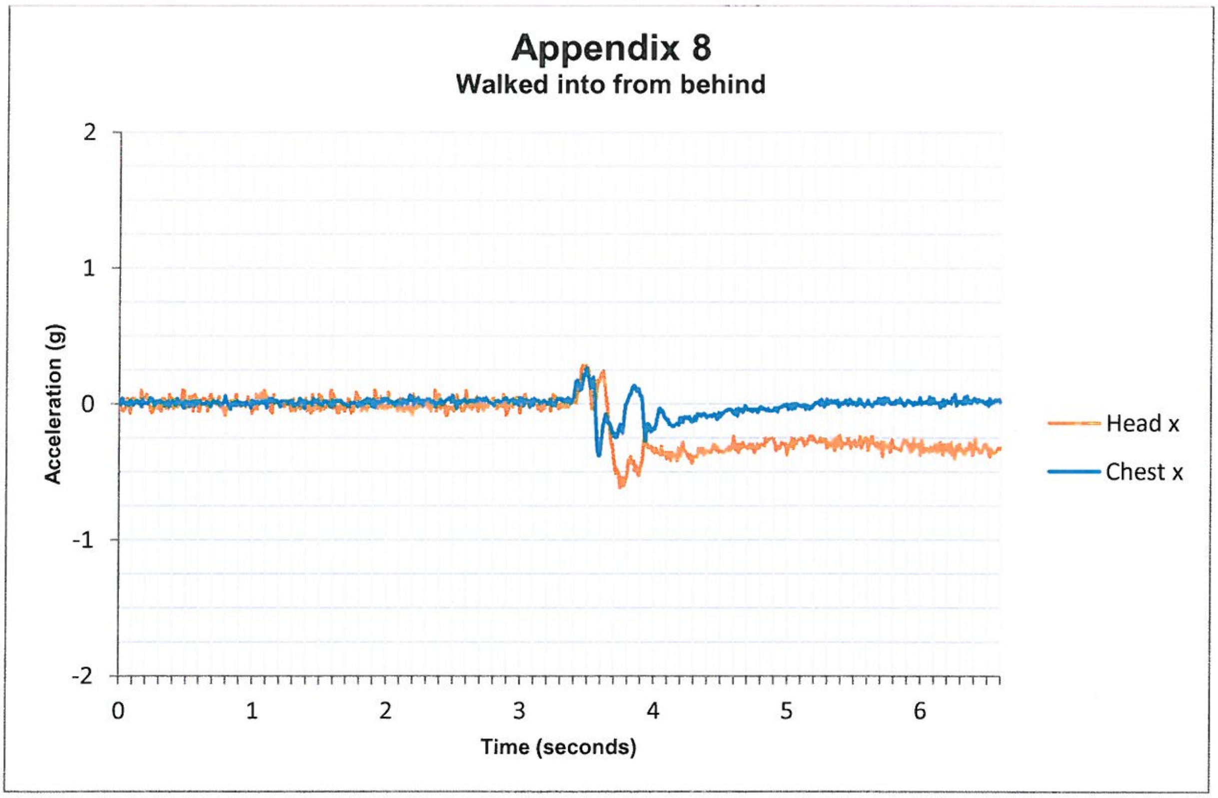
GRAPH OF ACCELERATION



Appendix 7: Summary of Simulator Accelerations – runs 2 - 27

Appendix 8

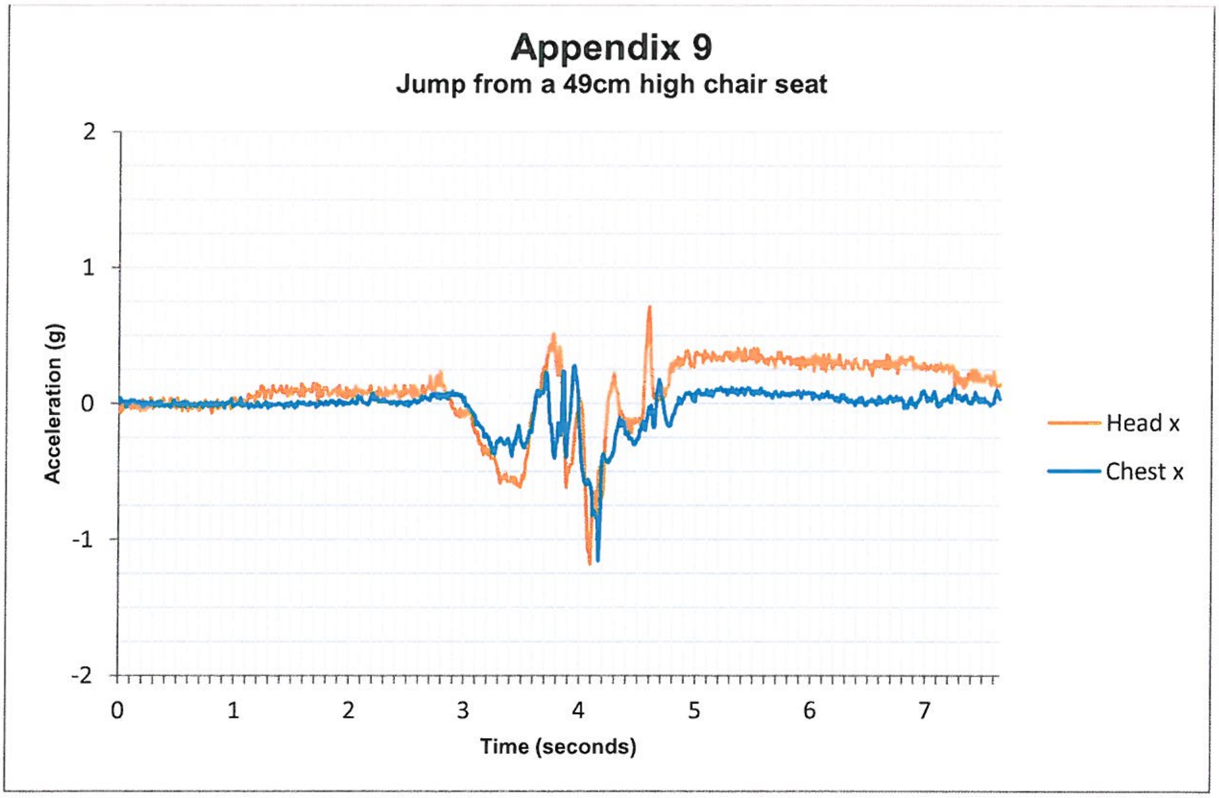
Walked into from behind Graph



Appendix 8: Acceleration Result for Pedestrian/Pedestrian Collision at Walking Speed

Appendix 9

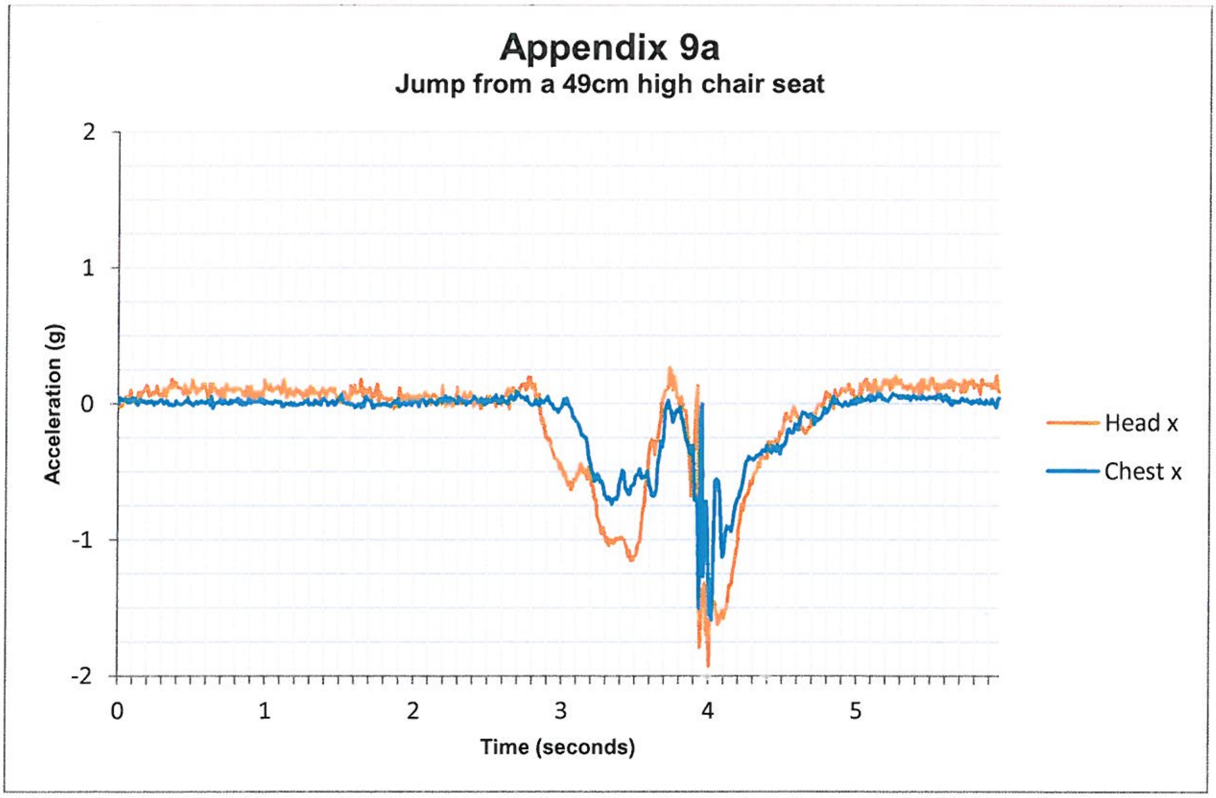
Jump from 49 cm high chair Graph



Appendix 9: Resultant Acceleration for a Jump to the Ground from 49 cm High Seat

Appendix 9a

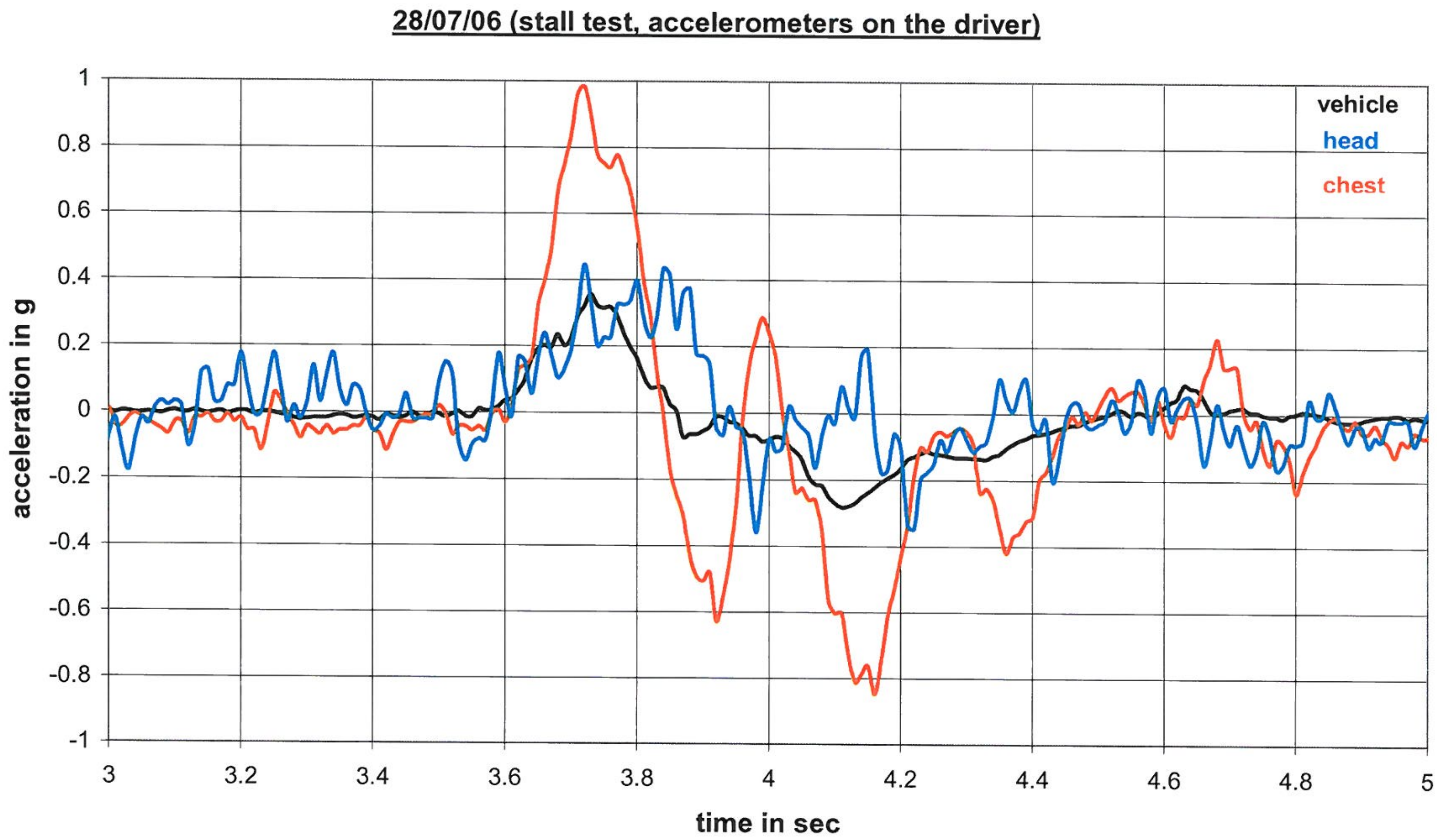
Jump from 49 cm high chair Graph



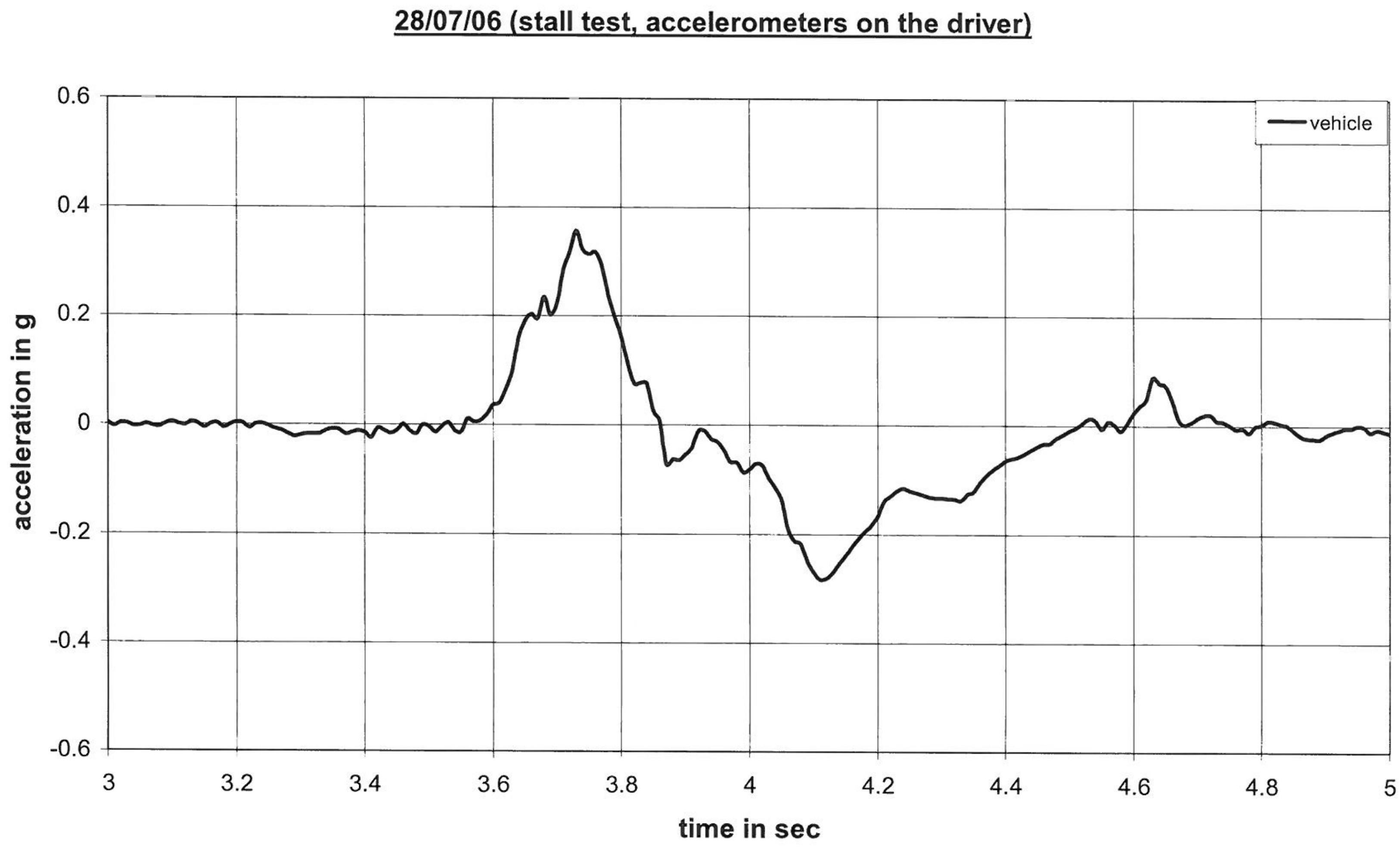
Appendix 9a: Resultant accelerations following jump from a 49 cm high seat

Appendix 10

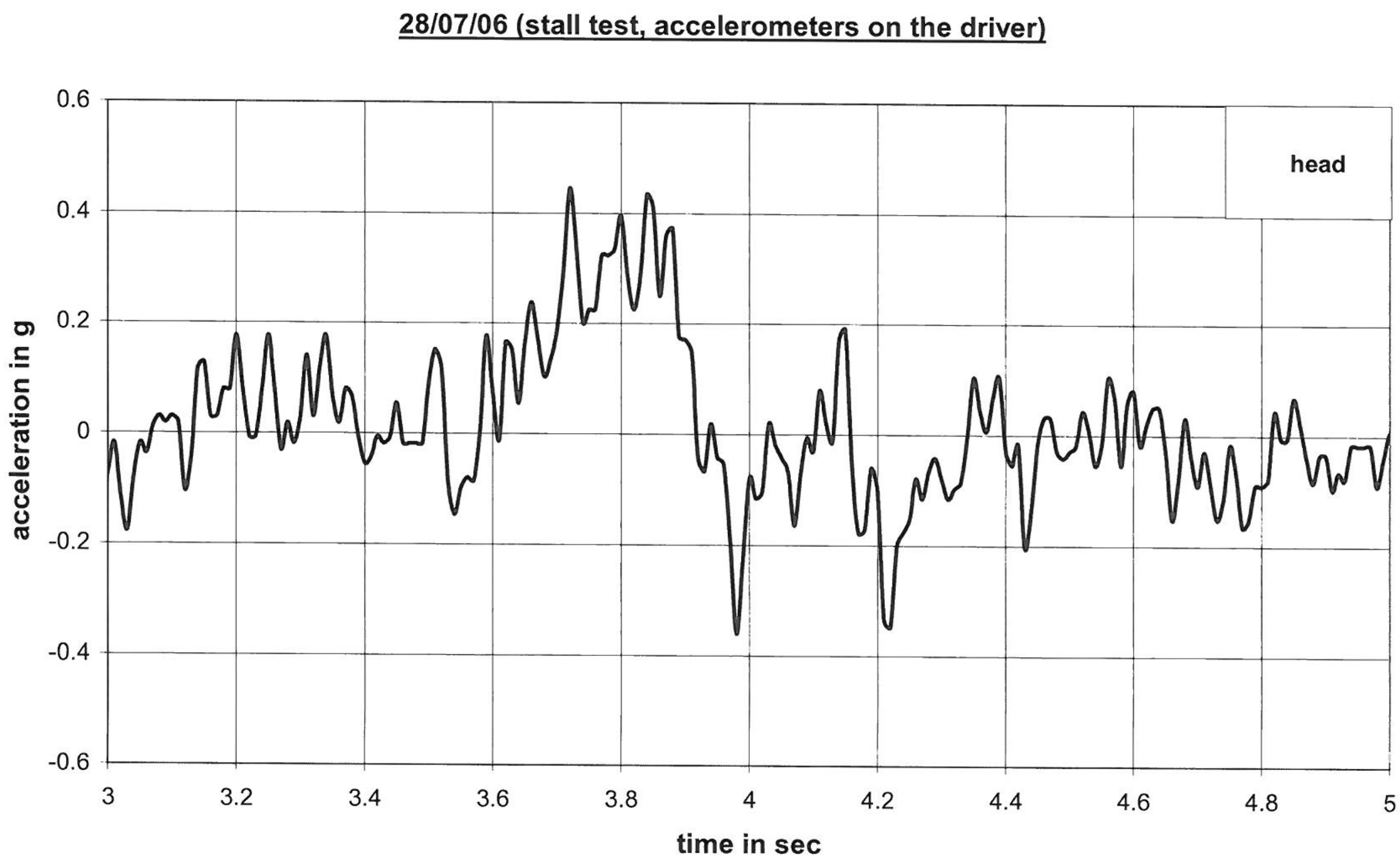
Vehicle Stall Test Graphs



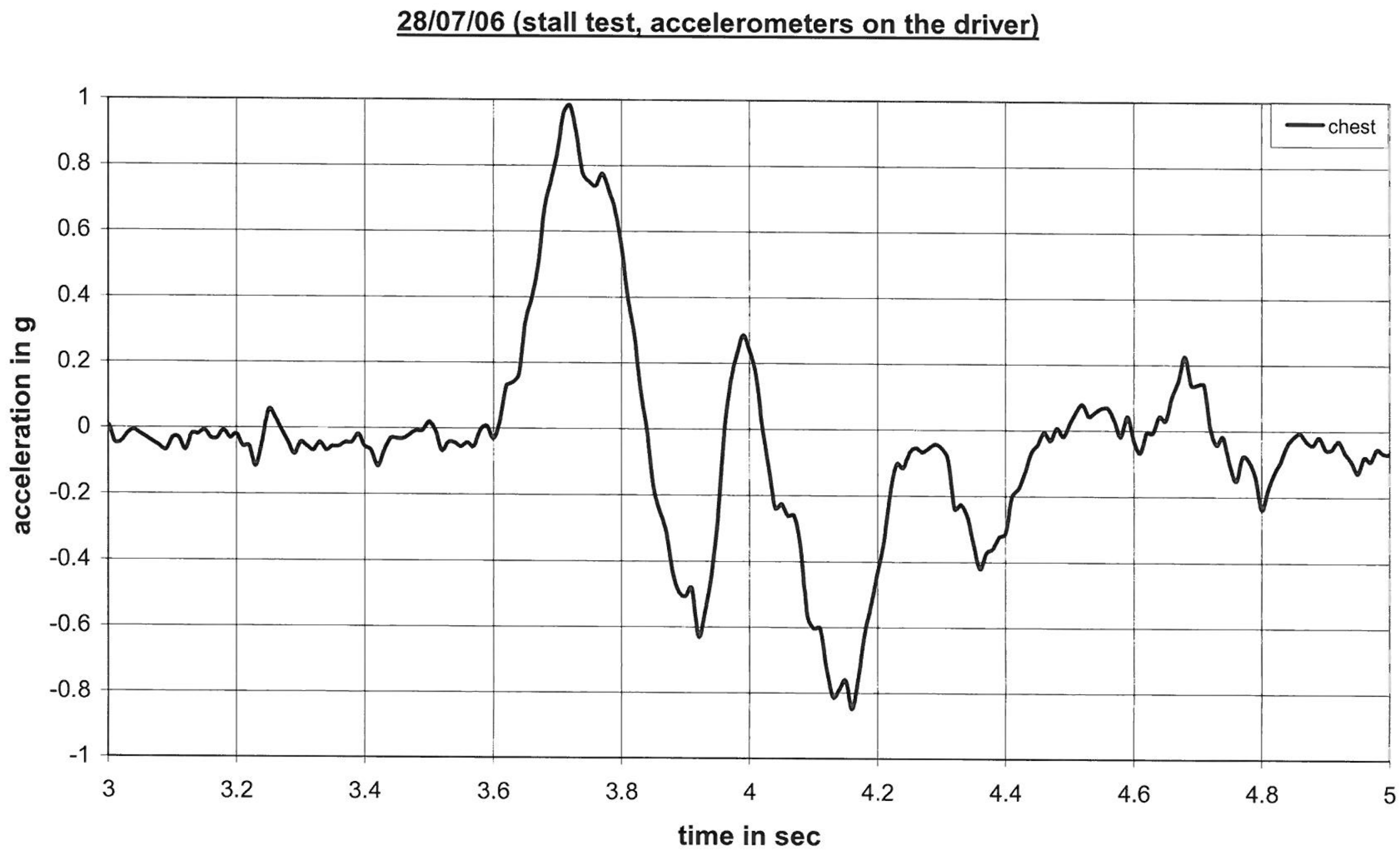
Appendix 10.1: Time course graph showing driver accelerations from a stalling vehicle



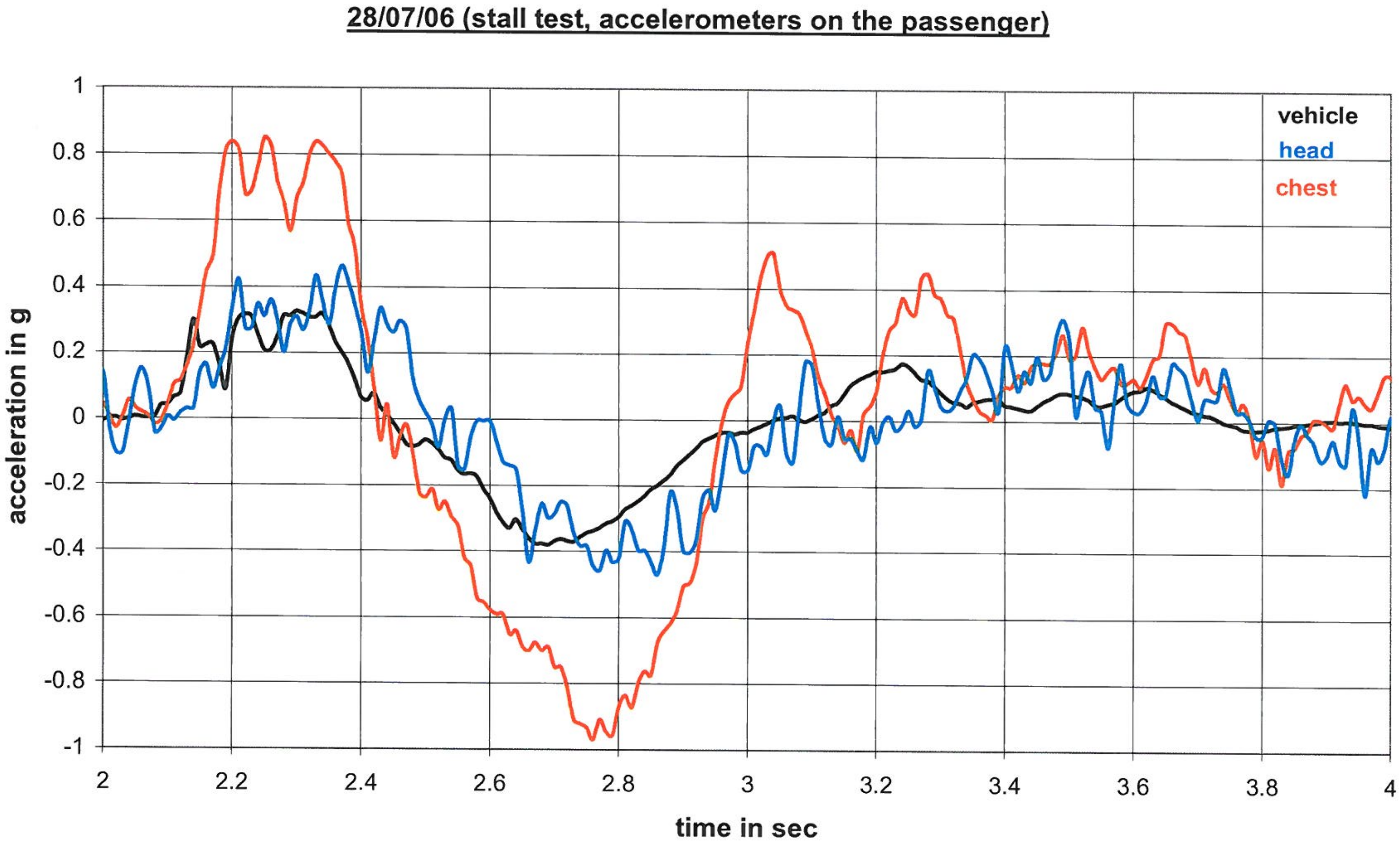
Appendix 10.2: Time course graph showing vehicle accelerations from stalling



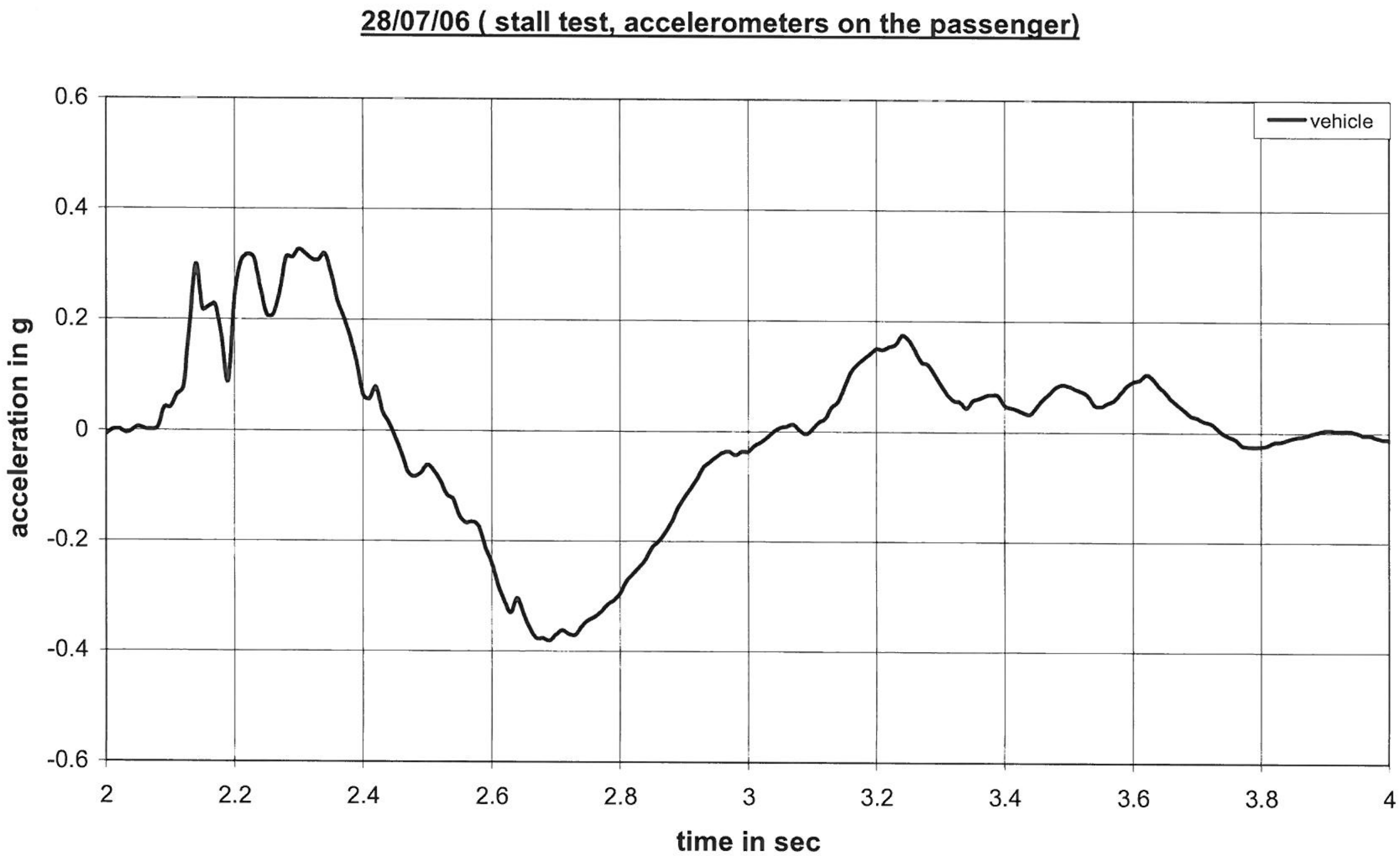
Appendix 10.3: Time course graph showing driver head accelerations from a stalling vehicle



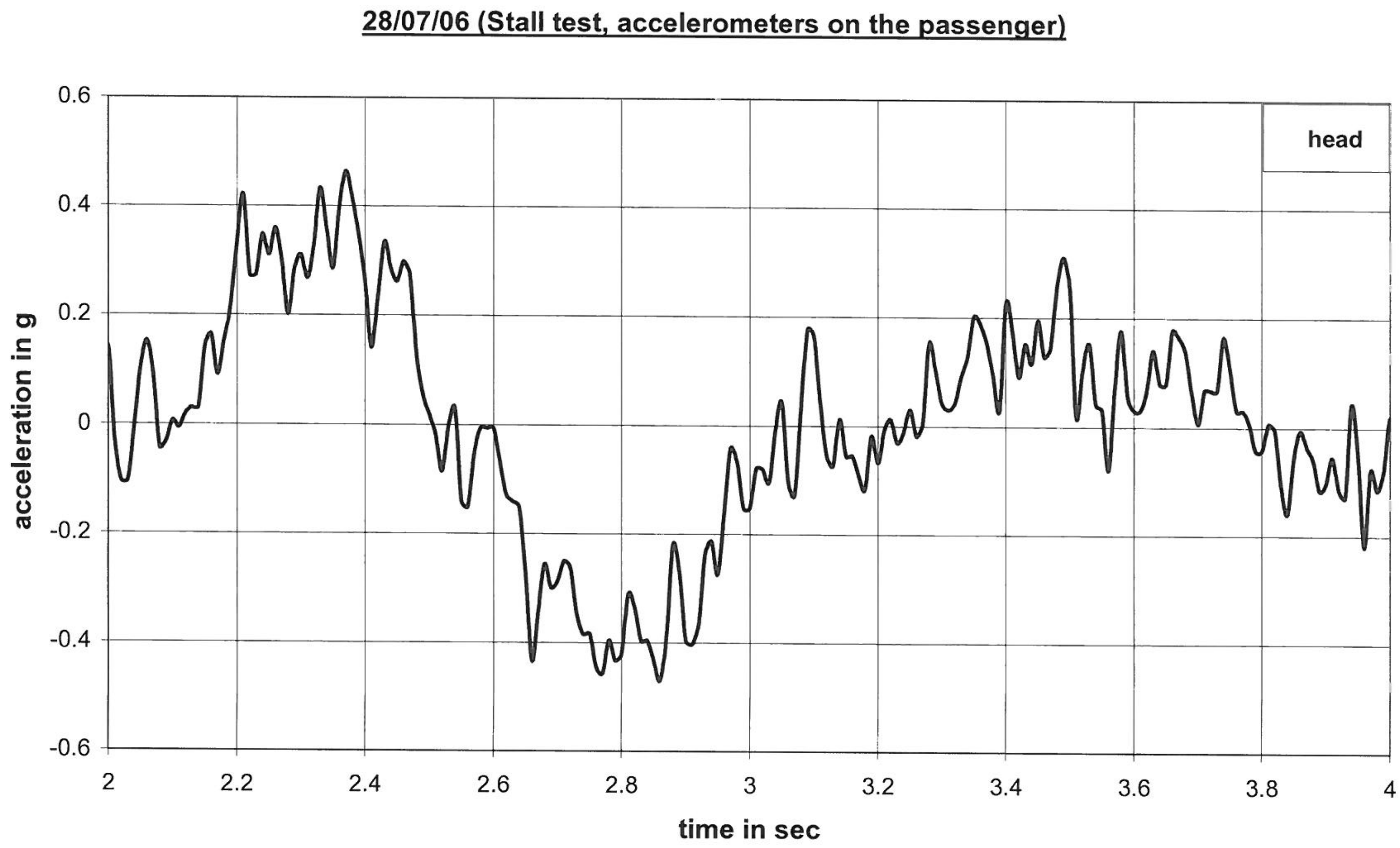
Appendix 10.4: Time course graph showing chest acceleration results for driver in a stalling vehicle



Appendix 10.5: Time course graph showing vehicle and occupant accelerations from a stalling test

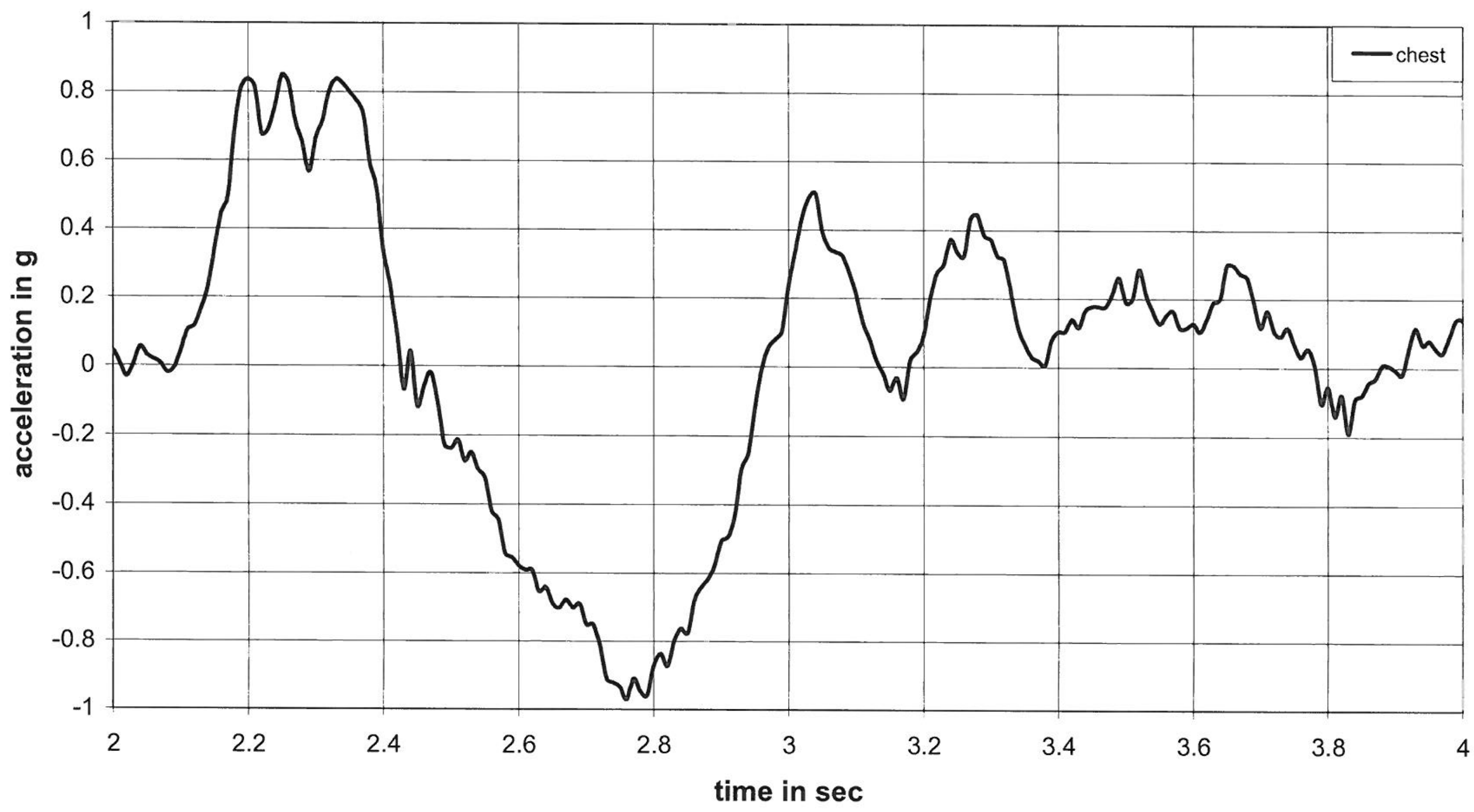


Appendix 10.6: Time course graph showing vehicle accelerations from a stalling test



Appendix 10.7: Time course graph showing head accelerations from a stalling test

28/07/08 (stall test, accelerometers on the passenger)

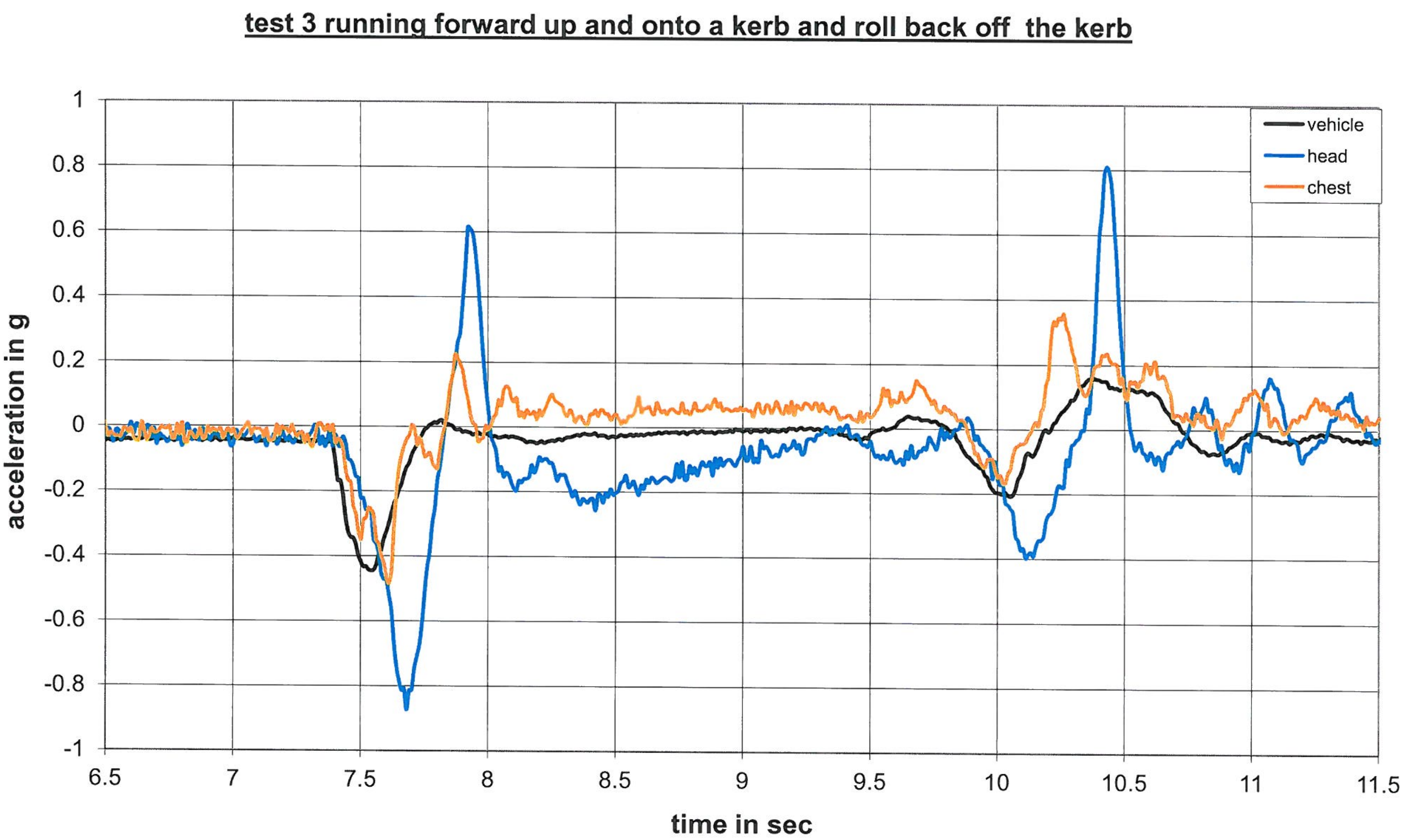


Appendix 10.8: Time course graph showing chest accelerations from a stalling test

Appendix 11

Test 3

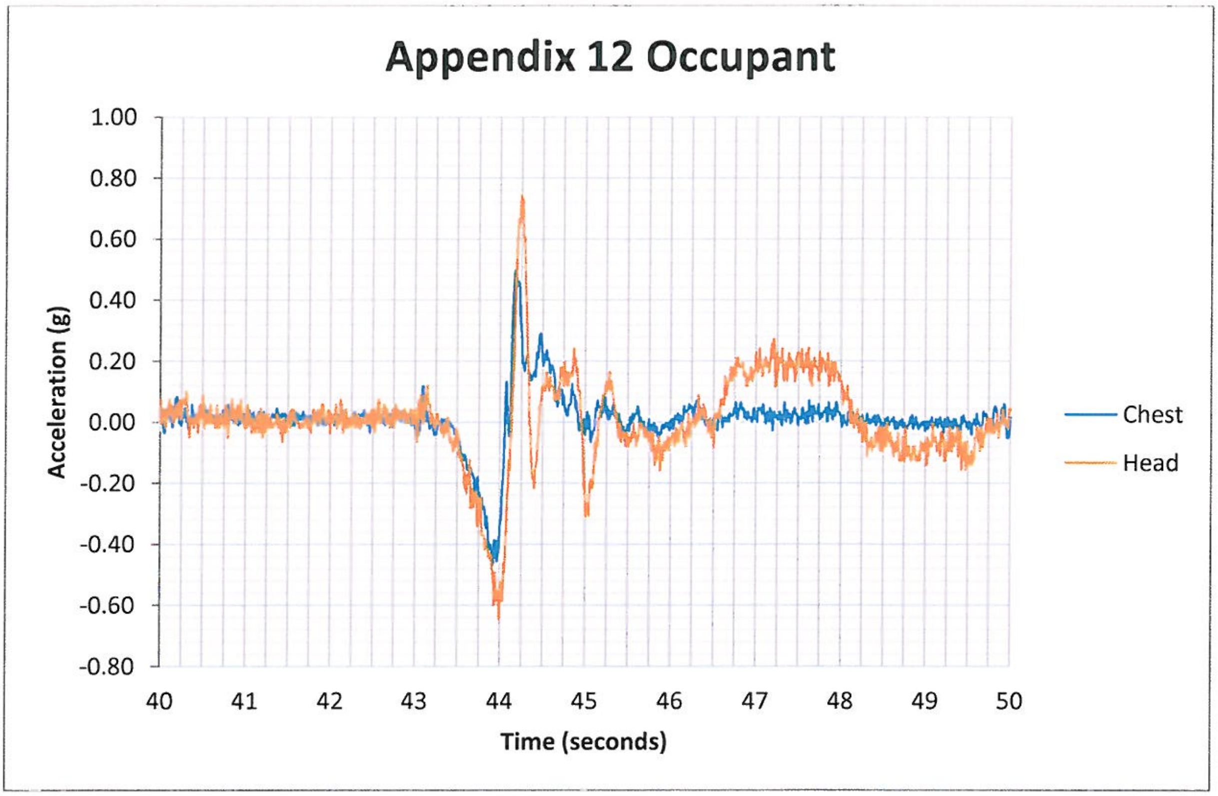
vehicle running forward up and onto a kerb and roll back off the kerb



Appendix 11: Time course graph showing vehicle and occupant accelerations for vehicle running forward up onto kerb and rolling back off

Appendix 12

Occupant

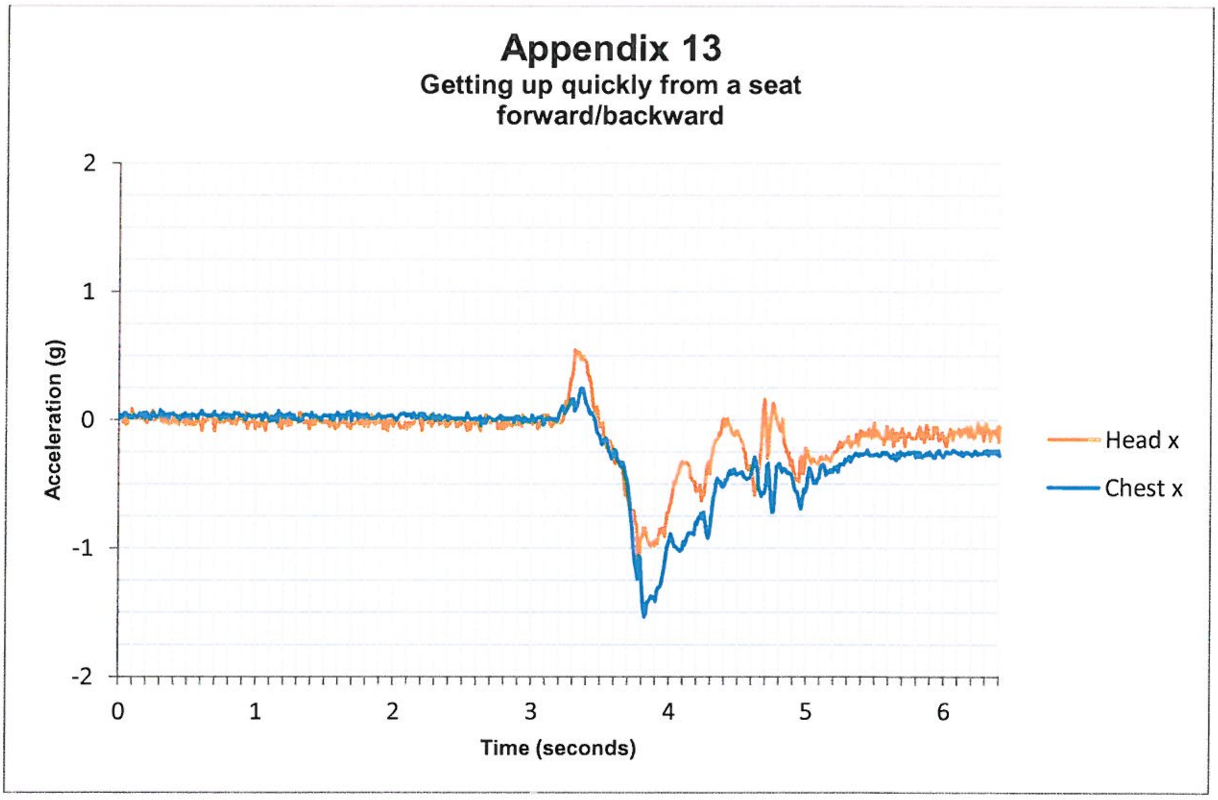


Appendix 12: Time course graph showing occupant accelerations resulting from kerb test

Appendix 13

Getting up from a seat

forward and backward

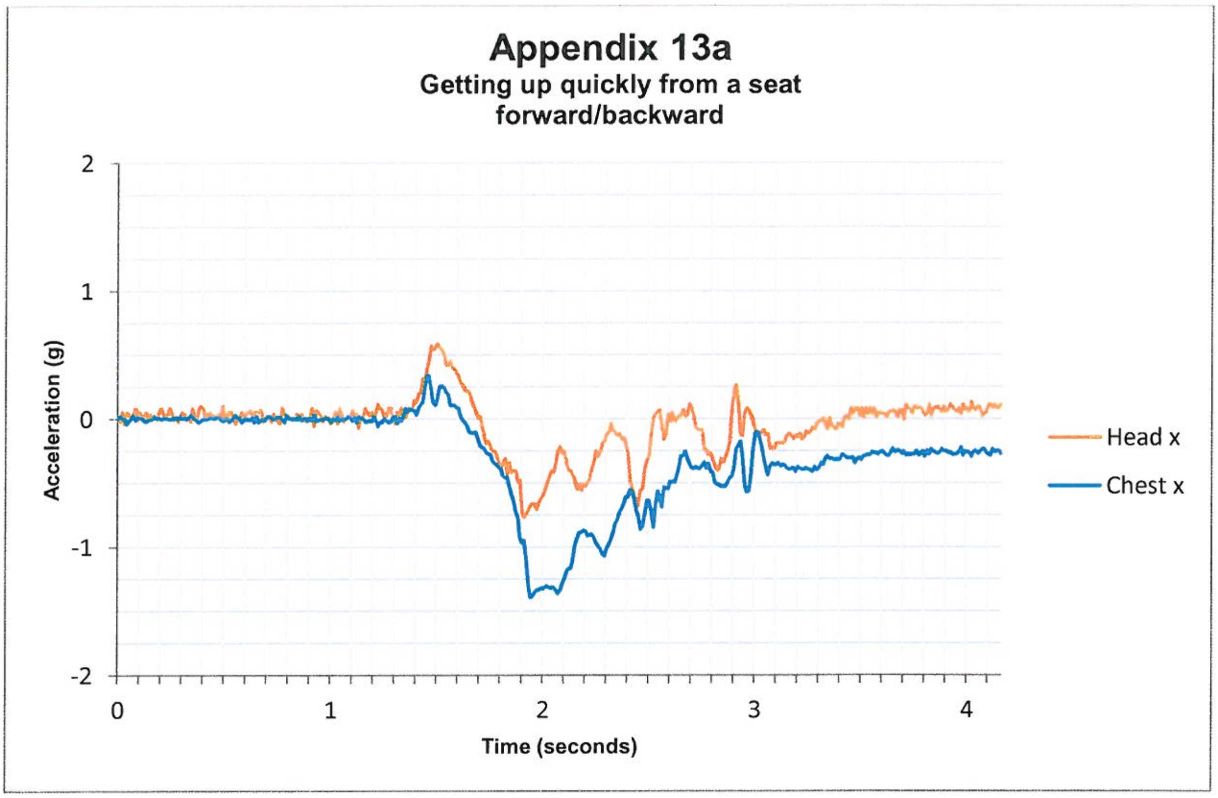


Appendix 13: Time course graph showing head and chest accelerations when getting up quickly from a chair

Appendix 13a

Getting up from a seat

forward and backward

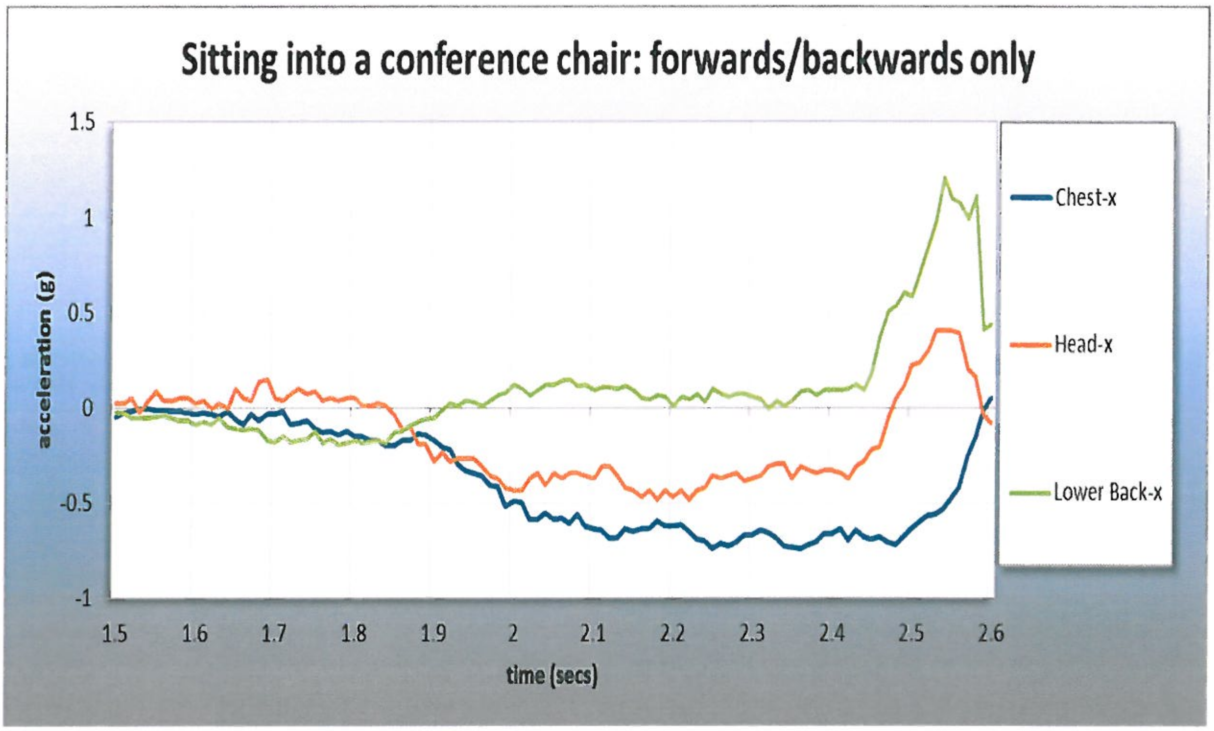


Appendix 13a: Time course graph showing head and chest accelerations when getting up out of a chair

Appendix 14

Sitting into a conference chair forwards/backwards only

Appendix 14



Appendix 14: Time course graph showing resultant accelerations from sitting in a conference chair

Appendix 15

An Original Publication

Putting the 5mph injury threshold to the test

Brian Henderson reveals the results of his extensive research into the impact of low-speed-change collisions

Brian Henderson is the managing director of GBB (UK) Ltd Forensic Collision Investigation and Research

'Beyond a speed change of 5mph, the risk of neck injury is high. The risk between 3mph and 5mph is a grey area that would need further exploration, and injury cannot be ruled out.'

Much has been promulgated about soft-tissue neck injury in recent years, and it is often cited that below a certain speed change injury will not occur. Many studies have been made, primarily in the US, following collision testing of one sort or another.

The common argument is that the threshold is 5mph, but before a sweeping statement such as that can be considered, one needs to be aware of what is actually being talked about.

Physics facts

Collisions between motor vehicles are subject to Newton's Laws of Motion, as are the contents of those motor vehicles – including the occupants.

In a collision, momentum (mass x velocity) is conserved. This means that the total momentum before the collision is equal to the momentum after the collision. In simple terms, where one vehicle is stationary, all the momentum before the collision is with the striking vehicle and after the collision it is shared between the striking vehicle and the struck vehicle.

The amount of momentum given to the struck vehicle will determine its velocity immediately after the collision, in other words, its change in velocity or D_v (delta v).

The greatest change in velocity for the struck vehicle occurs when the centres of mass of the vehicles are aligned. Again, in simple terms, a square-on, rear-end shunt.

Where there is a large misalignment or the collision is a glancing blow, very little momentum is transferred to the struck vehicle.

For the purposes of this article I will deal only with the effects on the occupants of the struck vehicle in a squarely aligned, rear-end collision.

Assessing the likelihood of injury

Historically, the argument about injury or likelihood of injury has been the domain of the medical expert, albeit without any true scientific evidence on which to base an opinion.

My colleagues and I have been involved in crash testing and other research for a number of years. As a consequence of our research we are now better placed to consider a likely threshold for injury.

That does not mean that we can say whether a person can be injured or not, but it does mean that we are able to say that a given collision will likely result in acceleration of given magnitude to the vehicle's occupants. Further, we are also able to suggest what physically happens to occupants of a vehicle as a consequence of applied accelerations.

What actually happens in a crash?

In a rear-end collision as described earlier, the occupant of a vehicle is at the greatest risk of whiplash-type injury. The following is a step-by-step account of the events of a crash:

- When the two vehicles come together, at first contact there will be no damage at all to the vehicles.
- The striking vehicle continues forwards and its movement is resisted by the struck vehicle.
- Damage (if any) is now caused up to the point of maximum engagement. Once this point is reached, no further damage will occur.

- The struck vehicle, including the fixed internal features, will now be moving.
- The seat therefore begins to move forward. The body, because of its inertia, initially resists that movement and sinks into the seat padding.
- It is effectively scooped up and it too moves forward. The head, however, does not.
- As with the body, the head initially resists movement but then it too is accelerated.
- In the same order, the vehicle and then the body begin to slow down.
- The head is still accelerating.
- The situation therefore is that the head was initially lagging behind but then it is accelerated forwards ahead of the chest.

It is this movement that is the trigger for whiplash, if the initial acceleration at the chest is large enough, together with even greater acceleration applied at the head. In other words, there needs to be a large difference in the acceleration applied at the head in comparison to the chest, but it too must be exposed to considerable acceleration.

Crash testing

For example, I have written a paper dealing with a crash test undertaken in June 2005. It can be found at www.gbbuk.com/technical.asp and its title is CT2/2005/1.

In the test, we attempted to crash two vehicles so that the resultant change in velocity was around 5mph. The crash resulted in an actual change in velocity for the struck vehicle of 5.97mph.

The maximum positive acceleration at the chest was 4.7g and at the head it was 8.3g. The difference was 3.6g. The time difference was 0.07 seconds. This is the delay between chest movement and head movement as described above.

It is interesting to note that the acceleration applied to the struck vehicle was 2.43g.

We attempted to crash two vehicles so that the resultant change in velocity was around 5mph. Injury did occur in this test – symptoms of strains and headache lasting up to five days.

Injury did occur in the test – symptoms of strains and headache lasting up to five days, all of which are recorded within the research paper.

This would tend to support a general threshold of 5mph, given that relatively mild symptoms lasted for a number of days when the speed change was around 1mph over the argued threshold.

However, this threshold could only be considered as a general threshold, as not all vehicle occupants react in the same manner. Perhaps it could be seen as a starting point for healthy, correctly seated occupants.

My ongoing research aims to refine a threshold, based on greater knowledge.

Lower speed changes

In crash tests at lower speeds (or indeed offset collisions at greater speeds) the same level of acceleration of the occupants did not occur.

With that in mind, having constructed a simulator, a series of tests were undertaken with velocity changes of between 1.8 and 3.1mph. Again, all occupants were fitted with accelerometers at the head and the chest.

The acceleration recorded on the test rig (vehicle) was between 0.87g and 2.06g. The average maximum acceleration applied at the chest and the head was 2.93g and 3.46g respectively.

This is a difference of 0.53g. (See the graph below.)

Results

What this research shows so far is that with a velocity change up to 3mph, the acceleration applied at the chest and the head were fairly close together in terms of magnitude. That is, 0.53g as opposed to 3.6g in a collision resulting in a near 6mph change in velocity (delta v). This has also been mirrored in actual collision testing.

The other interesting point is that the accelerations at the head and chest do not rise linearly with an increase in velocity beyond 3mph, but rather each rises more rapidly, with the head more than the chest.

It is my opinion that beyond a speed change of 5mph, the risk of neck injury is high. The risk between 3mph and 5mph is a grey area that would need further exploration, and injury cannot be ruled out. The risk below 3mph is minimal. It may be that as the research continues it can be further refined or redefined.

The research, which was self-funded and completely independent, can be utilised by either claimant or defendant in these types of cases.

Summary

Previous received wisdom has included the following:

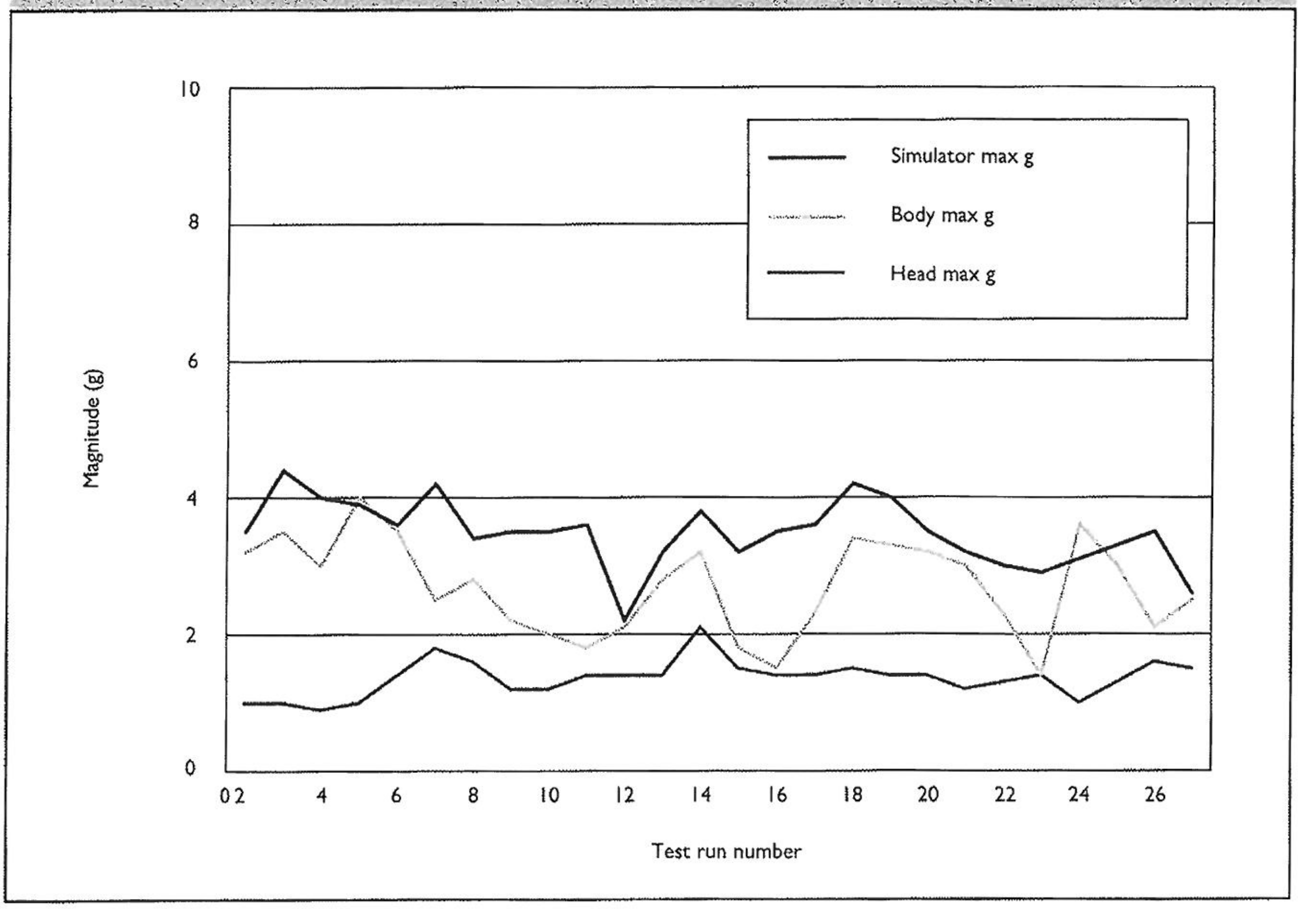
- Historical American research suggests a whiplash threshold of 5mph.
- Whiplash symptoms were evident in a UK study for collision testing with a speed change of 6mph.
- Whiplash symptoms were not evident in collision testing with speed changes below 6mph, or simulation testing with speed changes below 3mph.

Conclusions

Based on our research, we can now confidently suggest that:

- speed changes above 5mph indicate a high risk of injury;
- speed changes between 3-5mph are a grey area where injury cannot be ruled out; and
- speed changes below 3mph indicate minimal risk of injury. ■

Graph of acceleration



Appendix 16

An Original Publication

Deconstructing a collision

Roger Wade, Brian Henderson and Ian Simpson take an in-depth look at the science of RTA neck injuries and outline the many factors to be considered in claims

Roger Wade is a consultant orthopaedic surgeon, Brian Henderson is the managing director of GBB (UK) Ltd, Forensic Collision Investigation and Research, and Ian Simpson is a barrister at London Chambers

The Quebec Task Force defines whiplash as 'an acceleration-deceleration mechanism of energy transfer to the neck'. If an RTA occurs where this mechanism is present and the resulting forces applied to the neck are sufficiently large, a 'whiplash' has taken place. It is simpler to restrict the use of the term 'whiplash' to define this bio-mechanical phenomenon. Newton's laws of physics can be applied to whiplash and an objective measure of the energy transfer calculated. This is enveloped in a specific area of the science of accident reconstruction.

Whiplash injuries and associated symptoms are due to presumed underlying damage to the structures in the neck. Unfortunately, the symptoms that are described by the 'victim' are purely subjective, ie they are described by the claimant and there are no objective measures. A review of the medical literature can be applied to variables involved in the accident in an attempt to quantify the likely recovery.

When this type of injury is assessed in the medico-legal setting, these arguments are usually taken in isolation. It only takes a search of court cases in this field to show that the claimant's advocate will usually rely on the medical expert and the defendant's advocate will base their argument on the engineering evidence.

This method is clearly flawed. The medical expert cannot take the description of a 'written-off' car as meaning that the forces involved were large, just as a collision expert cannot ascertain whether a certain individual is likely to be at risk of injury based on the exchange of energy alone. This article will examine first the mechanics of a collision and then go on to consider the medical factors that may influence a whiplash claim.

'It only takes a search of court cases in this field to show that the claimant's advocate will usually rely on the medical expert and the defendant's advocate will base their argument on the engineering evidence.'

Time delay

Unfortunately, the information required is usually not all available at the same time – the early medical evidence is gained from GP notes and the expert is usually only instructed later, sometimes even when the symptoms have settled. Collision experts are typically only involved if the case is felt to be in the group of low-velocity impacts – again, usually later on in the case. It is fundamental that these two aspects of this type of injury are considered together by experts who are privy to all the information. Only then can more objective conclusions be drawn.

The recent judgment of the Court of Appeal in *Casey v Cartwright* [2006] may promote a contraction in the timeframes in which the relevant expert evidence is obtained, but it is still probable that any injury symptoms will have settled before that process is complete.

Mechanical evidence

Accident analysis involves the assessment of vehicle damage, correlating this with full-size crash-test data and then carrying out momentum conservation calculations based on the laws of Newtonian physics. From these the change in velocity, the delta-v (D_v), that is experienced by the vehicle can be calculated. This is the objective measure of acceleration applied to the vehicle and subsequently correlates to the acceleration-deceleration mechanism to the victim's neck – the whiplash.

What happens during a collision?

Contact: the bullet vehicle makes initial contact and as it penetrates the target vehicle it applies force to it.

Momentum conservation: the applied force multiplied by the time increment for which it is acting is the impulse. The momentum of the target vehicle is increased by an amount equal to the impulse. The bullet vehicle experiences an impulse of equal magnitude in the opposite direction in accordance with Newton's third law (see box, below). Thus, the momentum of the bullet vehicle decreases by this amount. By this process momentum is conserved. Momentum is not conserved, however, if an external force, such as braking, is applied during the collision.

Work of deformation: during impact the structures deform. The energy required for this deformation comes from the stored kinetic energy within the vehicles. Some energy is also converted to sound and heat.

Maximum engagement: at this point the vehicles will have a common velocity and deformation is at its maximum. What happens next depends on the proportion of elastic and inelastic deformation. Elastic structures will recover their shape and thus will reapply forces to the vehicles pushing them apart. Non-elastic structures will show permanent damage.

Momentum is conserved but kinetic energy is not conserved, as some is converted in creating sound, heat and permanent damage to the vehicles.

There are an infinite number of variations on the theme of the general collision described above.

The progress of a collision depends on the speeds and relative masses of vehicles and on their construction. The construction of a vehicle is crucial, as progressive collapse of non-elastic structures minimises accelerations to the occupants.

Restitution
A collision can be described in terms of its coefficient of restitution (COR). At its minimum (COR = zero) there is no elastic deformation. Theoretically, this type of collision will only occur at a very high-impact speed. In reality, almost any collision that takes place at an impact speed greater than 20mph is essentially inelastic, with a COR of zero.

For a collision to have the maximum COR (one) the impact speed would have to be zero or, if it were not zero, the materials from which the vehicles were constructed would have to be very stiff, such that they did not flex during the collision. The reason for this is that even elastic materials will generate heat, due to internal friction, when they deform and then reform during the course of a collision. This heat will represent an energy change to the system of colliding vehicles and so by definition the collision could not be perfectly elastic.

It is almost universally accepted by researchers that the COR increases as collision speed decreases.

For increasing values of impact speed, the COR decreases as elastic deformation becomes a smaller part of the total deformation. Vehicles do not have their own characteristic COR that they bring to a collision. Each collision is unique and the COR is a function of impact speed and the construction of each vehicle.

The COR of a collision is important, particularly in low-speed impacts, as it has an influence on the value of the D_v experienced by the target vehicle and, therefore, on the probability of whiplash injury to its occupants.

Impact on the occupant
The impact force of the collision takes about one millisecond to pass through the vehicle. The momentum transfer causes the target vehicle to accelerate and every part that is attached receives just the amount of force to cause the same acceleration to all parts. The occupant is not rigidly attached to the seat and so does not receive force to accelerate at the same rate. This is seen as the occupant sinks into the seat and their maximum acceleration is delayed. The body of the occupant then catches up and accelerates past the normal seating position until restrained by the seatbelt.

The construction of a vehicle is crucial, as progressive collapse of non-elastic structures minimises accelerations to the occupants.

The head is loosely attached to the body by the neck and its motion is further delayed. The maximum relative movement between the head and body occurs when the head accelerates past the body as the body is returning to the seat. Disparity between the motion of the head and body must be accommodated by the neck, and if the structural capabilities of the neck are exceeded then the result may be whiplash. It follows that the more momentum that is transferred to the struck vehicle during a collision, the more the motion of the occupant. It is the process of transfer of this momentum and energy and the resultant motions that may cause injury; this is studied in simulated crash tests by measuring head and chest accelerations (see 'Putting the 5mph injury threshold to the test' *PILJ*48).

Logically, it follows that accurate accident reconstruction provides a scientific answer to the likely momentum that has been transferred through the neck, and this provides a quantitative measure of the whiplash. This will be considered later, following the medical evidence with the application of D_v.

Newton's laws of motion

1) An object will remain stationary or continue in uniform motion in a straight line unless acted upon by an external force.

2) When an object of constant mass has a resultant force applied to it, the object will accelerate in the direction of this force. The magnitude of acceleration (a) will be proportional to the force (F) and inversely proportional to the mass (m). F=ma.

3) When two objects, A and B, are in contact, the force that A applies to B is equal in magnitude but opposite in direction to the force that B applies to A.

In an accident, the target vehicle will accelerate due to collision forces according to the second law. The bullet vehicle will experience forces equal in magnitude in the opposite direction according to the third law and so will decelerate according to the second law.

Medical evidence

We must always remember that medical evidence is not based on hard and fast rules such as the laws of Newtonian physics. The body has an infinite number of variables and, as such, the study of the response to a specific injury is difficult. This is not to say that the studies that have already been undertaken on whiplash injuries are not valid, but it is important to quote them in context. To provide a better understanding of whiplash injuries we feel it is essential to avoid the 'all or none' argument of the injury: we are not here to argue the case for either 'chronic whiplash' or whiplash injuries not existing.

The medical factors involved in whiplash injuries are presented here with a view to allowing a more balanced judgement, so they can be used to help determine prognosis. However, this is just an overview – never lose sight of other articles and the pros and cons of each. A good expert should know whether papers cited in cross-examination are relevant: it is not acceptable just to provide a one-sided argument; a range of opinions should be included. It is important to remember that all articles have their limitations and they should not be used to discount evidence.

The medical evidence can be broken down into a number of study types:

- classification of injury;
- clinical studies of whiplash victims and follow-up of symptoms;
- controlled studies of volunteers in crash tests;
- population studies of whiplash injuries in different countries;
- the study of neck pain in the general population; and
- the quest for the objective marker for whiplash-injury victims.

Classification of injury

There are a number of studies that classify whiplash injuries. One that is validated and widely used is the Gargan and Bannister scale (see below). This places victims in various groups based on how restrictive their symptoms are; unfortunately, these are purely subjective. The Quebec Task Force added physical signs to their classification (also shown in the box below), but only the distinction between grade 2 and grade 3 has objective signs.

It must be remembered that grade-3 symptoms rarely occur in whiplash-type injuries and probably do represent a structural problem that would show on further investigation.

Other, more complicated, questionnaires exist that allow percentage figures to be applied to the symptoms suffered. On face value, this may allow the disability to be more accurately assessed, but does not get past the fact that it is still based on subjective reporting of symptoms.

Many of these scales are used in clinical papers to assess the progression or resolution of symptoms. Although this is better than not using any classification system, it certainly has its flaws. The scales are subjective but do allow severity of the whiplash injury to be quantified. A medical report should include reference to these established scales in its assessment of this type of injury.

Clinical studies

There are a number of studies looking at recovery following whiplash-type injuries. The studies base recovery on the scales described above. In their series Gargan and Bannister quote a complete recovery in 38% of patients; 30% with ongoing non-intrusive symptoms; 30% with ongoing intrusive symptoms; and 2% with disabling symptoms. Residual disability with regard to sporting activity at two years was shown to occur in 28% (*Murray et al* 1993). The rate of recovery showed an interesting trend: victims with symptoms at three months usually continue with some symptoms. Palmer and Raymaker showed that at six months over 50% of victims had pain, at 12 months this had fallen to 40% and at two years it was 22% (see box, 'Relative risk of long-term problems', on p9 for further examples of factors to be considered).

A number of studies have also looked at the success of treatment following whiplash. It is well documented that collars make no difference, non-steroidal anti-inflammatory medication affords benefit only in the short term, physical therapy is no better than self-help, and surgery is only indicated in specific groups of severe whiplash with structural damage.

There is certainly a psychological element to chronic whiplash injuries and this is also well documented. Quantifying the true contribution from this element of a chronic injury is probably impossible. It is likely that certain personality types are more prone to chronic injuries, but in the eyes of the law these individuals have to be taken as they are at the time of the accident. If there is felt to be a large contribution from psychological overlay then an expert in this field should be instructed. This is not necessarily the case in the early stages of the injury, except to say that a significant psychological response to the accident should be dealt with by an expert in this field.

Overall, the clinical factors of each case should be considered on an individual basis. Expert opinions based on

Scales of classification of injury

Gargan and Bannister scale

Group	Symptoms
A	None
B	Symptoms not interfering with occupation or leisure
C	Symptoms restricting occupation or leisure with or without use of analgesia, orthotics or physical therapy
D	Loss of occupation, continuous use of analgesia, orthotics, repeated medical consultations

Quebec Task Force classification

Group	Symptoms
0	No complaint about neck and no signs
I	Complaint of neck symptoms and no signs
2	Neck symptoms, tenderness and decreased range of movement
3	Neck symptoms and neurological abnormality

Relative risk of long-term problems

There are a number of clinical factors that have been shown to affect the outcome of whiplash injuries. These are summarised below:

Clinical factor	Author	Relative risk (if quoted)
Female	Hohl et al 1974	Worse
Seatbelt	Christian 1976	1.5
Headrest	Kahane 1982 Minton 2000	0.9 Non-predictor
Awareness	Ryan et al 1994	15
Pain distribution	Squires et al 1996	8
Previous whiplash	Khan et al 2000	5
Abnormal examination	Norris et al 1983 Farbman 1973	Worse Non-predictor
Osteoarthritis	Maimaris et al 1998 Hohl 1974 Friedberg et al 1963	4 Worse 1.5
Abnormal neurology	Maimaris et al 1998	3
Rear impact	Spizter et al 1995 Deans et al 1987	2 Worse
Front-seat passenger	Allen et al 1985 Deans et al 1987	3 Worse
Age (over 31)	Hohl et al 1974	Worse
Age (over 50)	Nygren et al 1984 Deans et al 1987	1.5 Worse
Age (over 60)	Gotten et al 1956	Worse
Attendance hospital	Hohl et al 1974	2
Early onset symptoms	Deans et al 1987 Hohl et al 1974 Farbman 1973	2.4 Worse Non-predictor

The list is not exhaustive and you can see that some factors will have much higher risk in one study, while in other studies they do not. Some are just not quantifiable. These factors give guidance to which victims are at more risk and should be included in the history of a whiplash injury and in determining the prognosis.

reports that do not document these factors add little value in assessing a whiplash claim. All these studies should be taken in context, as the study groups are not controlled and the injury mechanisms may vary considerably.

Controlled crash studies

The role of crash testing and the study of injury are focused mainly in the field of low-velocity impacts. It is logical that in a low-velocity impact the occupant is less likely to sustain an injury and any injury should be less chronic.

Unfortunately, this is where the logical quantitative application of Newtonian physics clashes with the subjective evidence of the medical literature. This is not to say that either is right or wrong, or that each has equal weighting in a specific case. Evidence from both fields should be considered by experts in those fields and from this a considered and balanced opinion can be obtained.

As already mentioned, the D_v of the impact is significant in whiplash cases. A number of studies have shown that a D_v of less than 5mph is unlikely to cause significant injury (see 'Studies of low-velocity collisions' overleaf). There may be symptoms for a few days, but not beyond this, and certainly not chronic symptoms. What is most illustrative of the forces involved in low-velocity impacts is the comparison made to activities of daily living (*Allen et al* 1994). Essentially, the forces that occur on the neck during a low-velocity impact are like sneezing, or slumping into a low chair.

Because studies involve volunteers in crash-test conditions, evidence based on such research may be discounted on the grounds that the victim is aware of the impending impact, they are young or the claimant fits a group of individuals at special risk of injury. However, this research should not be ignored simply because the volunteers do not exactly match the claimant.

Whiplash in other countries

There is definitely a cultural difference in the outcome of whiplash injuries. This has been studied in areas where compensation is not readily available, where there is an adversarial legal system or where claimants have to fund part of the claim themselves. In these instances, whiplash has been shown to be less common. This gives insight into the amount of suffering that victims describe following injury in a medico-legal setting, but it is difficult to apply in the argument for or against an individual claimant.

Neck pain in the normal population

There is certainly an underlying rate of neck pain in the general population. Overall, this is in the order of 40% on a yearly basis.

If a patient is at risk of neck pain on a cumulative basis, there is a point in time when they would have, on the balance of probability, developed neck pain naturally. Is it just that this episode of neck pain has coincided with the ongoing litigation? The link to the accident should be weighed on the balance of probability. This is certainly more relevant in individuals with pre-existing cervical spondylosis.

Casey v Cartwright
[2006] EWCA Civ 1280

Studies of low-velocity collisions

Author	Subjects	Type	D_V (mph)	Injuries
Szabo 1992	5 volunteers (3 male)	MRI before and after	4.8	Less than one day
McConnell 1993	4 volunteers (all male 25 to 43)	Experimental crash	1.8 - 4.9	No symptoms
Ono 1993	3 volunteers (all male 22 to 43)	Experimental crash	2.4 - 4.8	No symptoms
Siegmund 1993	Two males	Looked at forces in bumper cars	3.7 - 4.6	No symptoms
West 1993	Five men (25 to 43)	Experimental crash tests	1.0 - 9.9	Minor symptoms in high D_V
Geigl 1994	25 volunteers (2 females; 20 to 60)	Tried various rotations	3.6 - 7.2	No symptoms
Matsushita 1994	26 volunteers (22 men)	X-ray and MRI analysis	1.5 - 3.5	Maximum symptoms 2 to 4 days
Castro 2001	n/a	Placebo crash tests	0	20% sustained injury
Brault 1998	42 volunteers	Experimental subjects	2.4 - 4.8	Maximum 2 days
Castro 1997	19 volunteers	Experimental tests	5.2 - 8.5	Few minor symptoms
Neilson 1997	7 male volunteers	Found D_V frontal impact 12 to 20	1.0 - 6.6	Few for a few hours

Objective testing

There is no objective test for a whiplash injury. The only objective results are those found in the more severe group of injuries. These will have neurological abnormalities or other findings on further investigation. Fractures or dislocations would be visible and, although they have been caused by a whiplash injury, they are a notably different group.

Investigations do give some helpful information. The presence of long-standing osteoarthritis has a bearing on the outcome of whiplash injuries. The likelihood that symptoms last longer is well documented in the literature but it must be weighed against the fact that even asymptomatic individuals with osteoarthritis will get symptoms sooner than those with no osteoarthritis.

Summary

We have reviewed the arguments for and against the likelihood of a whiplash injury occurring. Is it possible to narrow the range of opinion following this type of injury from one which, at first glance, covers a wide scope from no damage to a permanent disability? To do this all the evidence should be considered (see 'Summary of factors in whiplash cases', right) and a range of opinion formulated for that individual.

Evidence from a medical point of view should include a thorough review of the case with all the associated factors and hopefully some indication of the accident mechanics.

A 'cut and paste' report, or one lacking in detail, by an expert with little or no interest in the field, who has not taken the time to consider all the medical factors is unlikely to be helpful to any concerned in the forensic process or, ultimately, the court.

Likewise, the engineering evidence of a low-velocity impact should not be accepted on face value and should be submitted by experts with a proven track record in this type of work.

It is not acceptable for a medical expert to give an opinion on a 'whiplash' injury without some explanation as to why and how the injury falls into that part of the injury spectrum and the range of expert opinion, nor is it acceptable for an expert to contend that no injury has occurred based solely on the low-velocity impact argument.

There is a middle ground, which allows that when all the evidence is considered for an individual case, the injury prognosis can be determined within a reasonable range of expert opinion to the standard of proof required for civil litigation. ■

Summary of factors in whiplash cases

Injury less likely	Injury more likely
Low-velocity impact	Significant damage to vehicles
Symptoms minor	Symptoms recorded in notes early on
No visit to GP	GP visits for analgesia
No recorded subjective signs early on	Objective and/or subjective signs recorded early on
No hospital visit	Hospital visit and X-rays
Fit and healthy individual	Other associated medical problems
Favourable clinical factors	Numerous clinical factors

Appendix 17

An Original Publication

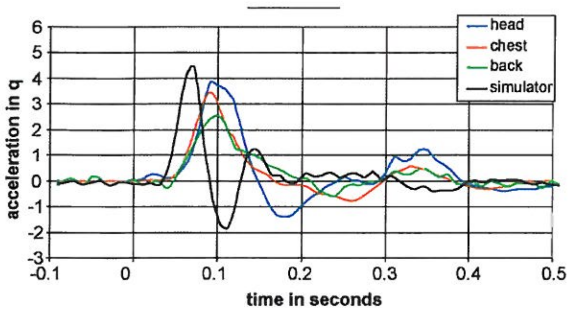


Figure 1 An example of one of the datasets. A similar pattern was seen in all of the volunteers.

[O40]
Does the low back displace significantly in low velocity rear impact shunts?

I. Starks*, B. Henderson, M. Hill, R. Wade

University Hospital North Staffordshire, UK

The neck is at more risk in a rear shunt accident due to the relative displacement of the body and head. The low back is more restrained and theoretically at less risk. We aimed to assess the displacement of the low back in a low speed collision. A series of controlled low speed crash simulations were undertaken during 2005. Accelerometers were applied to the head, chest and low back of six volunteers. Acceleration at each of these sites was recorded throughout the duration of the crash. This was compared with video footage of the crash simulation.

The lowest accelerations and displacements were noted in the low back (Fig. 1).

Whilst much has been published on "whiplash" in relation to low speed collisions, the scientific literature contains little in relation to low back injury. In this study the results clearly demonstrate that the lower back experiences the least acceleration of the back/chest/head components. It is generally accepted that in order for injury to occur then there must be sufficient displacement/acceleration for the injury mechanism to be triggered. These results clearly raise the question of whether the low back can be injured in such impacts and highlight the need for further research in this area.

Keywords: Low back; Rear impact; Low velocity

doi:10.1016/j.injury.2007.11.330

[O41]
Is the threshold for injury in whiplash really a delta-v of 3 mph?

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The Quebec Task Force defined whiplash as "an acceleration–deceleration mechanism of energy transfer to the neck". The incidence of whiplash-associated disorders in the UK is approximately 250,000 and rising. It is logical that the lower the velocity change following impact, the lower the risk of injury. The accepted velocity change (delta-v) for whiplash injuries following rear impact has been quoted as 5 mph. There is some debate as whether this is valid in the clinical setting. We aimed to investigate this further.

Between 2003 and 2005 a series of low speed controlled crash simulations were undertaken. There were a total of 27 runs on 23 individuals. In each case, accelerometers were placed on the head and chest of the volunteers. In addition, video recordings were analysed to assess displacement of the head and chest. The presence of symptoms was documented over a period of 7 days. The volunteers consisted of 23 males and 1 female with an average age of 38 (range 20–56). The average delta-v achieved was 2.3 mph (range 1.8–3.1 mph). The average maximum accelerations recorded were 3.46*g* at the chest and 2.93*g* at the head. The average difference was 0.53*g*. There was no significant displacement between the head and body. No symptoms were reported beyond 1 h.

Whiplash is triggered if the disparity between movements of the head and neck is of sufficient magnitude. It seems logical that there is a threshold below which whiplash will not occur. Our results have shown that below a delta-v of 3 mph there is little difference in the magnitude and timing of the movements of the head and chest.

Therefore the whiplash mechanism of injury does not occur at these changes of velocity.

Keywords: Whiplash; Delta-v; Threshold

doi:10.1016/j.injury.2007.11.331

[O42]
Temporal geometric changes in the post-traumatic thoracic and lumbar spine

J.S. Mehta[1,*], J. Hipp[2], I.B. Paul[1], V. Shanbhag[1], A. Jones[1], J. Howes[1], P.R. Davies[1], S. Ahuja[1]

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Background: Thoraco-lumbar fractures without a neurological deficit are usually suitable for non-operative treatment. The main area of clinical interest is the progression of the deformity at the injured levels.

Objective: Accurate assessment of the temporal behaviour in the geometry (progression of deformity) of the injured segments in non-operatively treated thoraco-lumbar fractures with normal neurology.

Materials and methods: One hundred and three patients with thoraco-lumbar fractures without a neurological deficit were treated non-operatively at our unit between June 2003 and May 2006. The mean age of our patient cohort was 47 years (16–90 years) and 54% of the cohort was male. Strict criteria were followed to determine suitability for non-operative treatment. Supine radiographs were performed at the initial assessment. Erect radiographs were performed when trunk control was achieved and at follow-up assessments thereafter. Quality Motion Analysis software (Medical Metrics Inc., Houston, TX) was used to measure angular changes between the end plates and changes in anterior and posterior vertebral body heights using a validated protocol. The radiographs were standardised for magnification and contrast and were superimposed from different time points.

Appendix 18

An Original Publication

EFORT 10th Congress of the European Federation of National Associations of Orthopaedics and Traumatology

VIENNA, AUSTRIA
3 - 6 June 2009

Free Paper Content CLOSE SESSION

Spine - Injury/vertebroplasty

Thursday, June 4 2009 / Room K
Time: 17:00 - 18:30

Moderators: Enrique Caceres Palou, Antonio Faundez
Speaker: Starks Ian

Presentation	Pid	Title
not available	F311	Does whiplash occur in low velocity rear impact shunts?

Authors

Starks Ian, Henderson Brian, Hill Richard, Wade Roger

Abstract

Abstract: The Quebec Task Force defined whiplash as "an acceleration–deceleration mechanism of energy transfer to the neck". It is logical that the lower the velocity change following impact, the lower the risk of injury. The accepted velocity change (delta-v) for whiplash injuries following rear impact has been quoted as 5 mph. There is some debate as whether this is valid in the clinical setting. We aimed to investigate this further. A series of low speed controlled crash simulations were undertaken. There were a total of 27 runs on 23 individuals. Accelerometers were placed on the head and chest of the volunteers. Video recordings were analysed to assess relative displacement of the head and chest. The presence of symptoms was documented over a period of 7 days. The volunteers consisted of 23 males and 1 female with an average age of 38 (range 20–56). The average delta-v achieved was 2.3 mph (range 1.8–3.1 mph). The average maximum accelerations recorded were 3.46g at the chest and 2.93g at the head. The average difference was 0.53g. There was no significant displacement between the head and body. No symptoms were reported beyond 1 hour. Whiplash is triggered if the disparity between movements of the head and neck is of sufficient magnitude. It seems logical that there is a threshold below which whiplash will not occur. Our results have shown that below a delta-v of 3 mph there is little difference in the magnitude and timing of the movements of the head and chest. Therefore the whiplash mechanism of injury does not occur at these changes of velocity.

Appendix 19

An Original Publication

A STUDY OF HUMAN KINEMATIC RESPONSE TO LOW SPEED 'REAR END' IMPACTS INVOLVING VEHICLES OF LARGELY DIFFERING MASSES

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International Congress on Traffic Accident Investigation, Shanghai November 2009

ABSTRACT

Vehicle-to-vehicle front-to-rear end low speed collisions are a common type of accident configuration. Research has been conducted, especially in the United States of America, to investigate and to try to quantify the relationship between occupant movement and vehicle impact speed. The authors of this paper have been involved in research into "low speed change" collisions for a number of years in an attempt to demonstrate how impact speed and occupant movement relate to European vehicles.

In recent years, these types of low speed collisions have lead to an increase in litigation relating to occupant injuries allegedly caused by the whiplash mechanism. More recently, a large number of personal injury claims have resulted from occupants of large passenger carrying vehicles (PCV), like buses, being involved in low speed collisions that trigger the whiplash mechanism leading to soft tissue injury.

Because of the likelihood of there being a large number of occupants in such vehicles, it is common for a relatively minor event to escalate into a very high value claim.

There exists a lack of information in the UK relating to low speed impacts of larger passenger vehicles and specifically impacts between vehicles with largely differing masses. This paper therefore presents the results of physical tests conducted to establish the magnitude of occupant movement experienced during a low speed collision between a passenger car and a PCV (a single deck bus).

INTRODUCTION

The question to be addressed is 'what level of movement occurs in those involved in a rear end bus collision?'

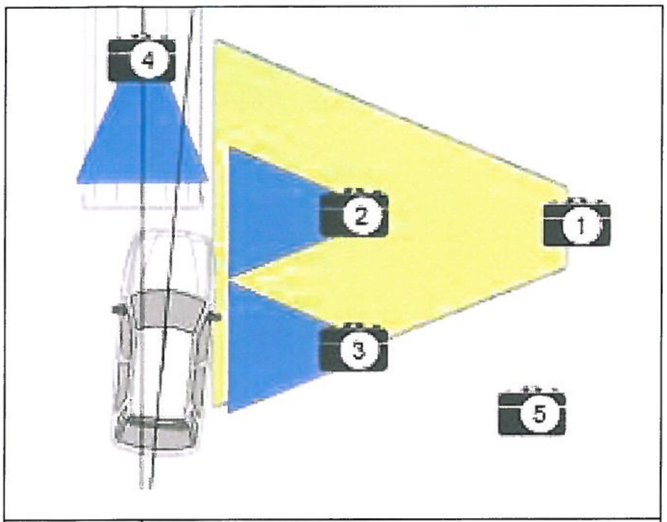
Dubois [1] performed 18 passenger car to bus collisions in their paper "Low Velocity Car-to-Bus Test Impact". With closing speeds between 1.47 and 9.34 mph, the changes in velocity for the bus were between 0.18 and 1.19 mph and the results, both in terms of vehicle and occupant behaviour, are comprehensive. However, the testing was conducted in the U.S.A and used North American vehicles built to specifications (and sizes) different from the vehicles typically encountered on UK roads.

Due to a lack of information available in the UK and faced with an increasing number of investigations involving large passenger carrying vehicles it was decided that a full scale physical test collision between a passenger car and a PCV would be conducted.

The impact speed was determined using a radar gun, from GPS and from integration of acceleration data recorded in the vehicle. The collision was also filmed using a high speed camera.

The recording equipment that was used consisted of two accelerometer units, one in each vehicle and external accelerometers placed on the head and chest of occupants of both vehicles.

Figure 1 indicates the collision configuration and shows the locations of the cameras used to record the impact;



Camera	Camera
1	Static. High tripod.
2	Static. Bumper level. High Speed. High Def.
3	Static. Medium tripod. Targeted at driver.
4	Internal. Wide Angle Lens.
5	Dynamic on tripod.

Figure 1 Diagram and details of test setup.

TEST DETAILS

Using the GBB test reference, this test is CT1-2009-1. The vehicles were set up to have a 50% overlap with the bullet vehicle being a 1996 Citroen ZX 1.9D Advantage with two adult male passengers (kerb weight: 1046kg, loaded weight: 1365kg) and the target vehicle being a 1994 Volvo B10B single deck bus with 18 male occupants and 2 females (kerb weight: 10161kg, loaded weight: 11807kg).

The PCV was a semi-automatic transmission vehicle which was stationary with the service brake applied and the gear lever in neutral mode. The vehicle was fitted with the Vericom VC 3000 data recorder, and a sample passenger was fitted with external 25g and 10g accelerometers at the head and chest respectively. The Vericom unit fitted to the target vehicle had a guaranteed accuracy of 0.003g within a dynamic range of ± 2g. Beyond that range the accuracy will decrease. The Vericom is limited in its ability to measure collision pulses given its operating range (±2g) and sampling frequency (100Hz), however it was sufficiently accurate to provide an indication of pre and post impact velocities. The sampling interval of the accelerometers was 0.01 seconds.

The Citroen was a manual transmission vehicle and was driven at a steady speed of around 9 mph as indicated upon the speedometer of the vehicle and GPS tracker (to allow an 8 mph impact). It was driven into the rear of the PCV and the brakes were not applied at any stage until the vehicle came to a complete stop after the collision.

The speed of the Citroen was checked by radar and GPS and was found to be 8 ± 1 mph. Accelerometer data from the Citroen indicated an impact speed of 8.0 ± 0.1mph. This was the value used in calculations.

OCCUPANT INSTRUMENTATION

Accelerometers were fitted on the forehead and chest of the rear seat passenger in the Citroen. Figure 2 below shows the positioning of the accelerometers and their orientation before and at a point during the impact.

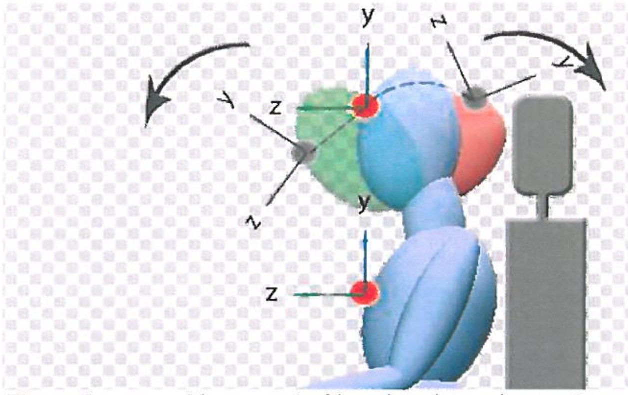


Figure 2 Movement of head and accelerometers during a collision. Head movement is dependent on impact direction.

The body of an occupant will experience an impact force through the seat. If this is sufficient, the body will accelerate under the action of this force but the motion of the head will lag behind that of the body during the early stages of a collision. This lag will cause the head to rotate and the orientation of the accelerometers to change as shown in figure 2.

In the striking vehicle, the major rotation of the head will be in the other direction as forces transferred to the head through the neck structure cause the head to accelerate past the body. It should be noted that the graphs of head accelerations shown in the results section of this paper have not been corrected for changes in orientation. The maximum acceleration experienced by the head will be the resultant acceleration calculated from the y and z components.

PRE-COLLISION CALCULATIONS

From knowledge gathered from previous collision testing (and in accordance with Newton's Second Law of

Motion) the lower mass vehicle will always experience the greatest speed change in a collision with a higher mass vehicle.

Whilst the acceleration of the PCV and subsequently the occupants therein was the main focus of the test, it was important to understand the likely effects upon the bullet vehicle and its occupants.

From observations of previous 'car-to-car' collisions, an estimated figure for restitution was obtained at the desired impact; however no data exists for a car-to-PCV collision.

Consideration of the car-to-car restitution figures was based upon an amalgamation of GBB data drawn from previous testing and research by Malmesbury and Eubanks [2]. Restitution values were plotted and a line of best fit was calculated. The resulting graph is show in Figure 3.

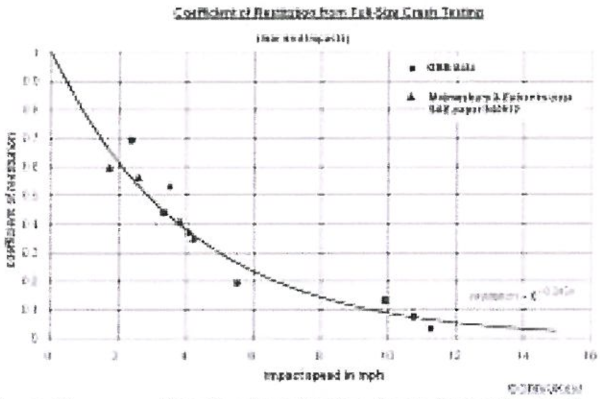


Figure 3 *Graph of restitution from Eubanks and GBB research.*

Figure 3 indicated a typical value of restitution for an 8 mph impact was 0.14. That value was incorporated into a momentum exchange calculation to provide values for the anticipated speed change of the PCV and of the car.

$$M = \frac{m_1}{m_2} = \frac{1046}{10161} = 0.1$$

$$v_1 = \frac{u_1(M - r)}{(M + 1)} + \frac{u_2(1 + r)}{(M + 1)} = \frac{8 \times (0.1 - 0.14)}{(0.1 + 1)}$$

$$= -0.3\, mph$$

$$\Delta v_1 = -0.3 - 8 = -8.3\, mph$$

$$v_2 = \frac{u_1(M + r)}{(M + 1)} + \frac{u_2(1 - Mr)}{(M + 1)} = \frac{8 \times 0.1(1 + 0.14)}{(0.1 + 1)}$$

$$= 0.8\, mph$$

$$\Delta v_2 = 0.8 - 0 = 0.8\, mph$$

A speed change of 8.3 mph was anticipated for the car and a speed change of 0.8 mph was anticipated for the bus based upon the unladen mass for each vehicle.

It would be unsafe for live human occupants to be placed in a target vehicle with anticipated speed changes in the 9mph region. The risk of injury would be too great.

By translating knowledge gathered from previous research it was estimated that for the bullet car in a 5 to 6mph speed change collision the positive disparity between peak head and chest accelerations should be in the region of 0.3g (z axis), whilst in the target vehicle it should be around 3.6g (z-axis).

It was therefore on this basis that the experienced volunteer investigator in this test was satisfied that the consequent accelerations (less than 3.5g) would be comfortably tolerated with minimal risk of injury.

RESULTS

Bullet Vehicle – Citroen ZX

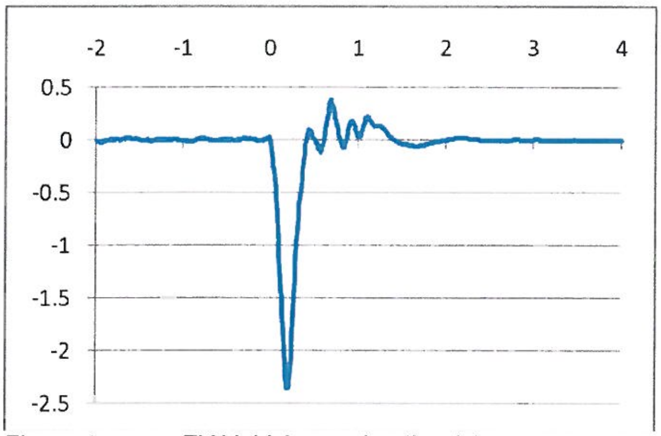


Figure 4 *ZX Vehicle acceleration (g)*

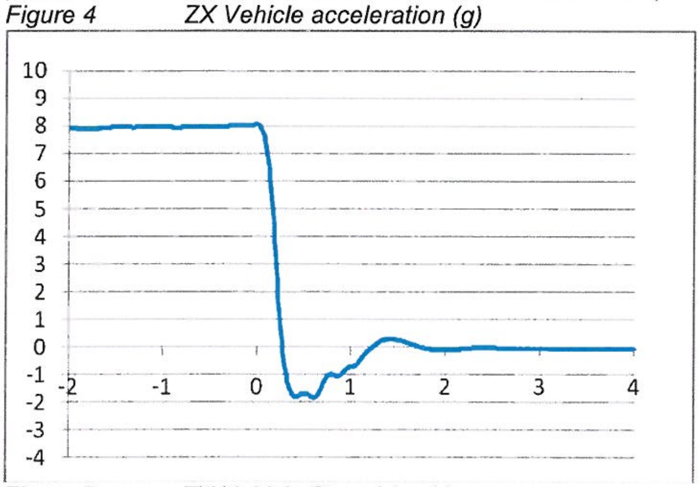


Figure 5 *ZX Vehicle Speed (mph)*

The timescale of the accelerometer was adjusted so that the collision started at 0 seconds. The start of the collision was defined to be when the acceleration became negative and stayed negative. Peak deceleration of 2.4g occurred at 0.19 seconds. The initial deceleration phase took 0.4 seconds, rebound then occurred.

From integration of the acceleration pulse, it was calculated that the impact speed was 8.0 ± 0.1 mph, and that the delta v (Δv) was 9.7 ± 0.1 mph.

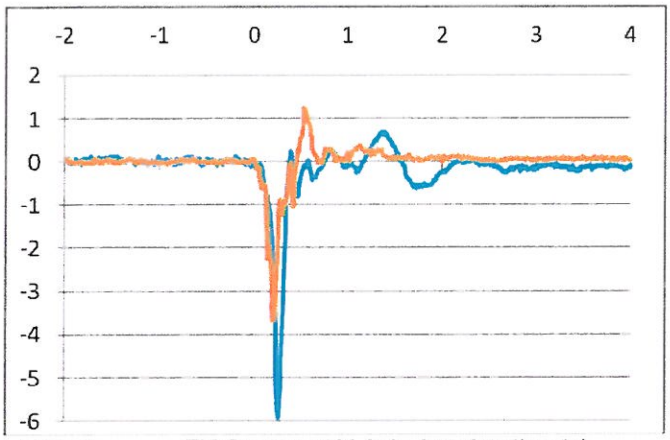


Figure 6 *ZX Occupant Y Axis Acceleration (g). Blue = Chest, Orange = Head.*

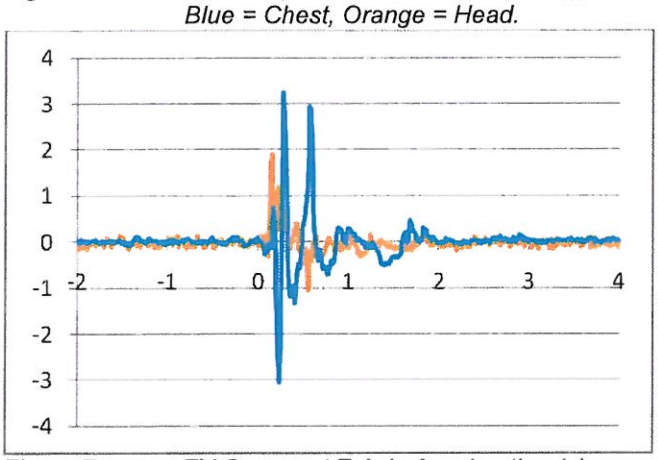


Figure 7 *ZX Occupant Z Axis Acceleration (g). Blue = Chest, Orange = Head.*

The occupant acceleration is expressed in two components; "Y" which denotes the vertical axis, and "Z" which denotes the longitudinal.

Y Axis - Peak vertical (Y) chest and head acceleration of 3.68g and 5.91g occurred at 0.2 and 0.26 second respectively.

At 0.26 second, the chest acceleration was 1.21g allowing for a maximum disparity of 4.7g.

Z Axis - A peak g of 1.9g occurred at the chest at 0.15 second. At this point, a head acceleration of 0.7g was experienced. (Peak 0.8g occurring at 0.17 second.). This first maximum disparity of 1.2g occurred.

A peak head acceleration of –3.06g occurred at 0.24 second. At this point the chest acceleration was 0.3g. The disparity was 3.36g.

A peak forward chest acceleration of 3.2g occurred at 0.27 second. The chest acceleration was 0.6g.

At 0.41 second, the head acceleration was –1.4g the chest being 0.2g. The disparity was 1.6g.

A second forward peak acceleration of 2.9g occurred at 0.57 second. The chest acceleration was –0.4g. The disparity was 3.3g.

Target Vehicle – PCV (Volvo B10B)

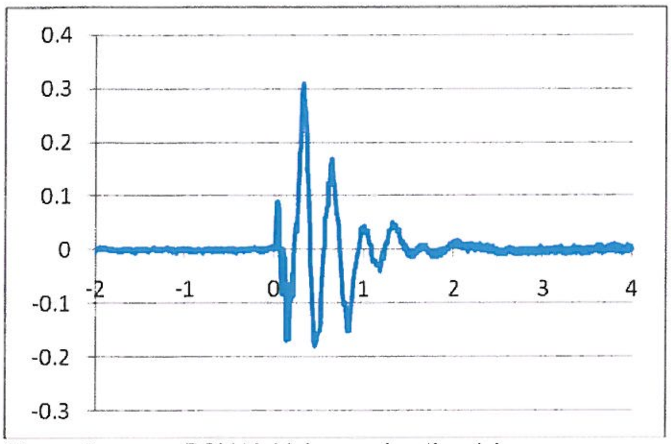


Figure 8 PCV Vehicle acceleration (g)

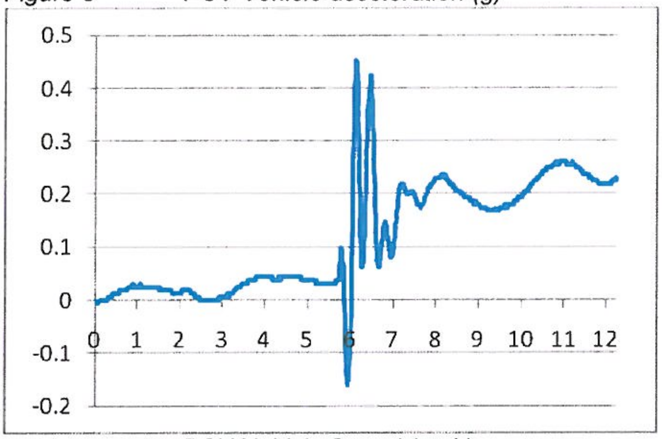


Figure 9 PCV Vehicle Speed (mph)

The timescale of the accelerometer was adjusted so that the impact started at 0 seconds. The acceleration reached a peak of 0.3g at 0.32 seconds. The speed change displayed oscillations as the vehicle's separated.

The wheels of the PCV were stationary and remained so throughout the collision phase. The sprung mass was accelerated to 0.43mph.

The un-sprung mass did not move as the acceleration applied was insufficient to overcome the frictional force between the tyres and road surface.

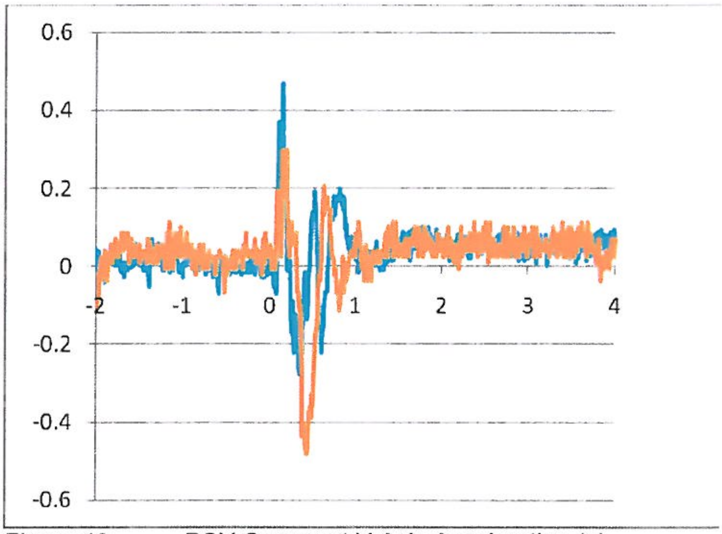


Figure 10 PCV Occupant Y Axis Acceleration (g). Blue = Chest, Orange = Head.

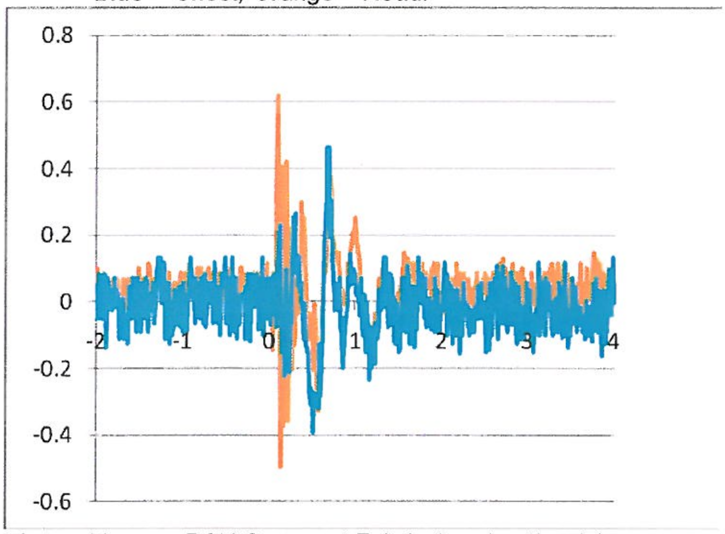


Figure 11 PCV Occupant Z Axis Acceleration (g). Blue = Chest, Orange = Head.

Y Axis – Peak vertical accelerations of 0.29g and 0.47g were observed simultaneously at 0.15 second. This suggests an instantaneous compression disparity of 0.18g.

A trough of –0.28g of the head occurred at 0.36 second, where the chest acceleration is –0.09g; a disparity of 0.19g.

A trough of –0.48g of the chest occurred at 0.44 second. The head acceleration was –0.14g demonstrating a disparity of 0.34g.

The time delay of 0.08 second may suggest an elongation of the neck structure.

Z Axis - The first head acceleration peak was found at 0.62g; the chest acceleration at that point being 0.1g. This occurred at 0.1 second and demonstrates a disparity of 0.52g.

At 0.14 second the peak head acceleration was –0.5g with the chest at –0.03g. The disparity is 0.47g.

By 0.52 second, the peak chest acceleration was –0.39g with the head at –0.21g. This is a disparity in favour of the chest of 0.18g.

CONCLUSION

Vehicle movement - The acceleration of the PCV peaked at 0.31g. The speed change was 0.43mph.

The acceleration of the car peaked at 2.4g. The speed change for the car was 9.7mph.

The time of the peak acceleration occurred at 0.19 seconds, considerably later than a typical rear end collision (0.1 seconds). This was due to the crumpling effect of the frontal components of the car.

The peak car acceleration was 7.7 times greater than the peak PCV acceleration.

The PCV was 9.8 times heavier than the car.

The calculated speed change figure for the bus was an over estimate of 0.42mph.

The speed change figure for the car was an under estimate of 1.39mph.

It was anticipated that the calculated speeds would have been over and under estimated respectively for the PCV and car due to the lack of true restitution results, the large mass vehicle being braked and a difference in figures between kerb mass and actual mass.

The estimated speed change to cause the damage to the vehicle in the photographs which prompted this experiment, was 9mph.

The speed change for the car in this experiment was 9.7mph. The damage is marginally greater in this experiment.

Injuries – The occupants on the PCV were asked to record any symptoms experienced after the tests for a period between 10 minutes and 7 days. No symptoms were recorded by any of the occupants.

Figure 12 Vehicle pre-impact

Figure 13 Impact Sequence

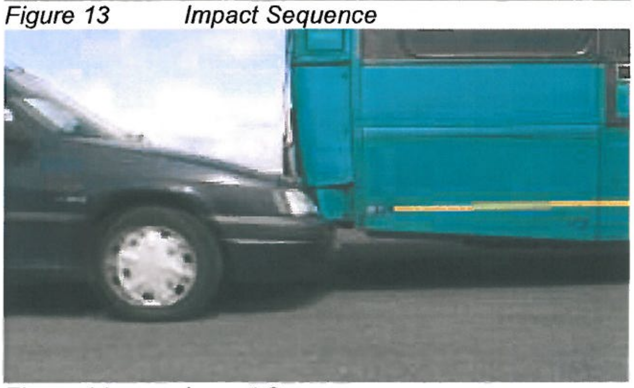


Figure 14 Impact Sequence

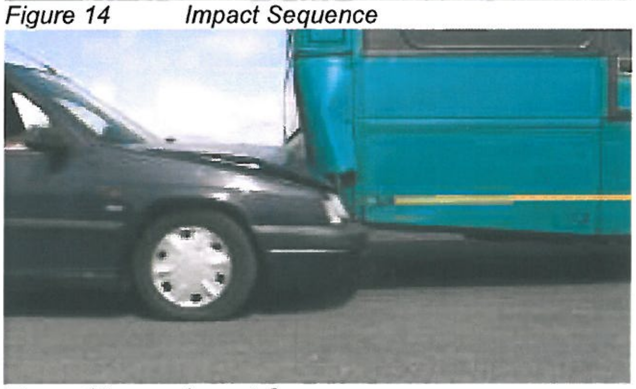


Figure 15 Impact Sequence

Figure 16 Impact Sequence (Max. Engagement)

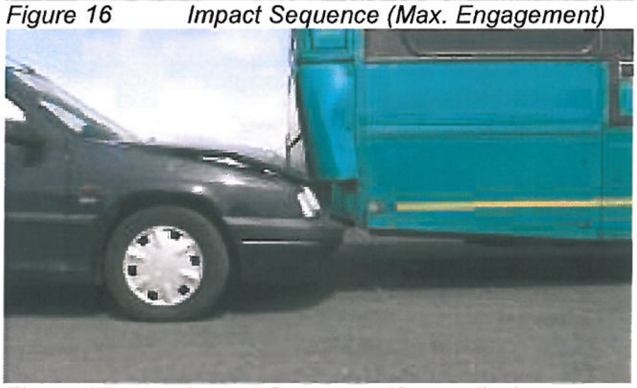


Figure 17 Impact Sequence (Separation)

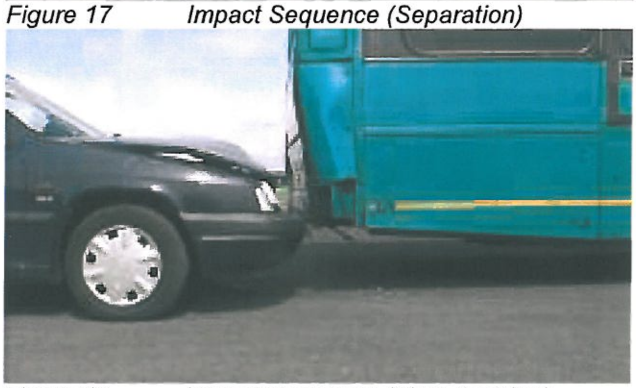


Figure 18 Impact Sequence (Final Position)

REFERENCES

1. *R Dubois, B McNally, J DiGregorio, G Phillips, "Low Velocity Car-to-Bus Test Impacts", Accident Reconstruction Journal, Volume 8, Number 5, September/October 1996.*
2. *R Malmsbury, J Eubanks, "Damage And/Or Impact Absorber (Isolator) Movements Observed in Low Speed Crash Tests Involving Ford Escorts", SAE Paper 940912, March 1994.*

CONTACT

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Appendix 20

An Original Publication

Impact

THE JOURNAL OF THE INSTITUTE OF TRAFFIC ACCIDENT INVESTIGATORS

Winter 2009 — Vol 17 No 3

- *A Study of Extreme Partial Collisions*
- *Quantifying the Effects of Surface Debris on Vehicle Deceleration Rate and Anti-lock Brake Systems*
- *Drivers and Sleep Related Accidents*
- *The Art of Being an Expert Witness*

A Study of 'Extreme Partial Collisions'

by Brian Henderson and Phil Hoyes GBB(UK) Ltd.

INTRODUCTION

In August 2009 a series of crash tests was undertaken using a variety of vehicles as part of the ongoing research programme at GBB(UK) Ltd.

Previous research at GBB had found that partial collisions severely restricted the amount of momentum that could be transferred when one vehicle collides with another. Those tests involved structural damage but led to the question; how partial can a partial collision be?

Two of the tests, referenced CT08/09 and CT09/09, were dedicated to understanding what happens in extreme partial collisions.

Kenneth S. Baker[1] describes two types of impact: full and partial. In a full collision "some parts of the colliding surfaces attain the same speed during impact...Motion between parts in contact will cease momentarily."

Baker explains that in a partial impact "no substantial parts of colliding surfaces attain the same speed during collision...The parts of the vehicle engaged are not strong enough to stop any substantial part of the vehicle. It continues to move onward until disengagement."

To investigate extreme partial collisions the tests CT08/09 and CT09/09 were designed to analyse a collision between exterior mirrors.

These incidents are commonplace.

Increasingly, such contacts are being suggested as causing acceleration or deceleration of a vehicle and thus unusual occupant movement.

In theory the hinged mechanism attaching the mirrors should not be capable of transferring sufficient force to alter the acceleration of either vehicle, but has this been tested in practice? A search of the SAE International database suggested not.

The collision test day was overseen by members of Sheffield Hallam University Engineering Department and Biosciences Department and the University of Central Lancashire School of Forensic & Investigative Science. Copart supplied one of the test vehicles.

TESTING

The vehicles used for the test were as follows;

1 Ford Focus, medium-sized 5-door hatchback 1.6l (bullet).
  Approximate mass: 1180 kg.

2 Volvo 960 3.0 medium to large-sized 5-door estate 3.0l (target).
  Approximate mass: 1490 kg.

Each vehicle was fitted with a 2g dual-axis accelerometer and an occupant in each vehicle had tri-axial accelerometers attached at the head (25g "Crossbow") and chest (10g "Crossbow").

In each test the Volvo was stationary and the Ford was accelerated from rest into a collision of wing mirrors before being decelerated back to rest.

Test CT08/09 involved the vehicles orientated head-on. The collision was then repeated for CT09/09 but the orientation was changed so that the Ford approached from the rear of the Volvo. Altering the orientation in this way allowed for any differences in resistance between the Volvo mirror deflecting rearwards or forwards.

The test set up is shown in figure 1.

There was no electronic method of starting recording of the sensors. An audible alarm was sounded and the occupants of the vehicles operated the data recorders. The occupants with accelerometers were asked to maintain a normal, straight ahead seat position.

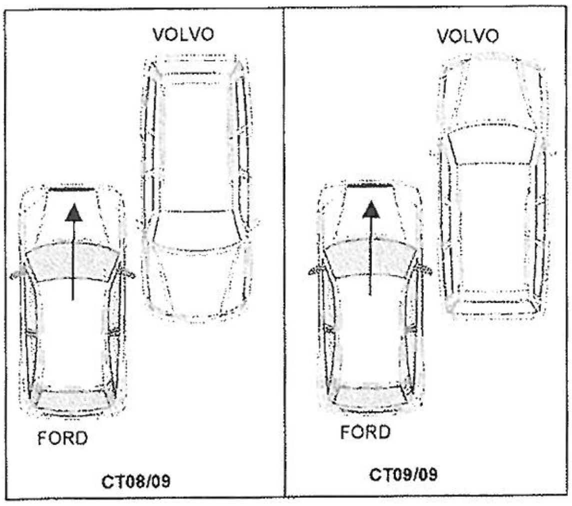

Figure 1.

RESULTS

The Ford Focus began its acceleration shortly after 5 seconds after the accelerometer was switched on. It accelerated hard to 24km/h and from the video footage it can be established that during the acceleration phase the door mirror of the Ford struck the door mirror of the Volvo.

Peak speed occurred at 7.5 seconds. The vehicle was braked steadily to a stop.

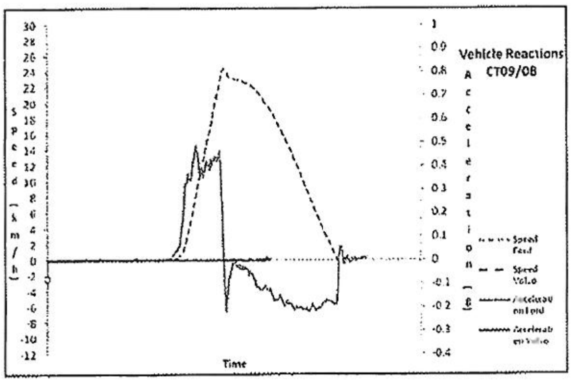

Figure 2.

The collision occurred during that 2.5 second period.

From the speed/acceleration graph (figure 2), it is impossible to determine when the collision took place as there was no untoward acceleration or deceleration of the either vehicle. The acceleration of the Volvo fluctuated consistently within the range +/-0.003 g. (Note that the recording equipment for each vehicle was not started at the same time. Although the results share a common axis to allow a comparison of magnitudes the graph should not be used to compare speed or acceleration between vehicles at a specific time.)

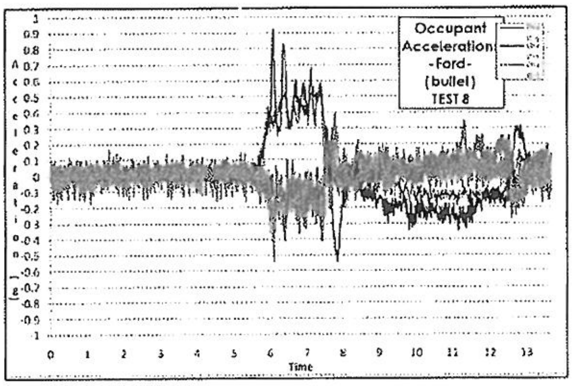

Figure 3.

A study of the occupant acceleration graph for the Ford (figure 3) shows movement of the occupants as the vehicle is accelerated and decelerated. From that graph too, it is not possible to determine when the collision took place. In other words there was no unusual movement.

A study of the occupant acceleration graph of the Volvo (figure 4) shows the normal movement of the occupant (simplified occupant acceleration graphs can be found at appendix 1).

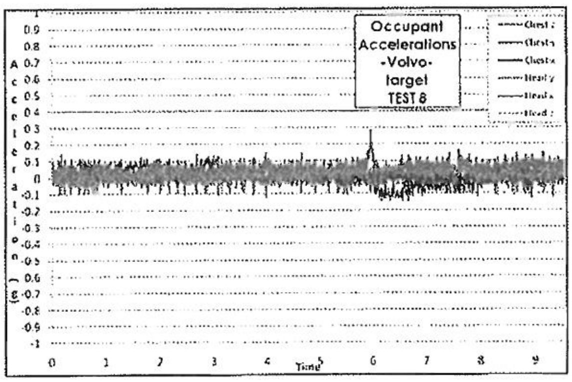

Figure 4.

There is slight negative movement of the head in the y-axis (upwards) at around 6 seconds together with positive movement in the x-axis (left). There are no corresponding spikes on the vehicle graphs and this suggests that the occupant movement was self-propagated: perhaps an incontrollable flinch or more likely an undisciplined glance towards the collision or other vehicle.

In terms of magnitude, it is the same as normal movement prior to the test taking place and provided a disparity between peak head and chest acceleration in the y-axis of around 0.1g.

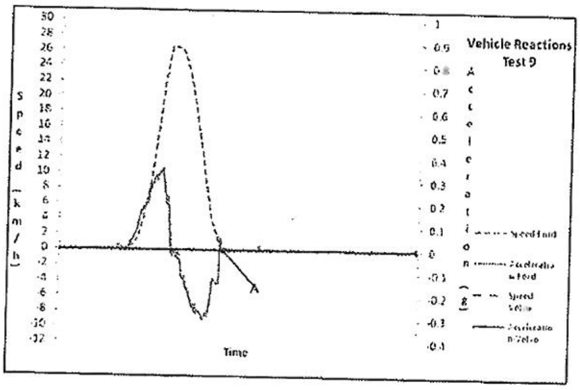

Figure 5.

In the second test the Ford was accelerated hard to approximately 27km/h.

Once again video footage confirmed that contact took place during the acceleration phase.

The Ford was braked reasonably hard (0.3g) to a stop.

The speed/acceleration graphs for both vehicles can be seen in figure 5.

The effects of this collision were similar to CT08/09 insofar as there was no untoward acceleration of the Ford. Acceleration readings from the Volvo were generally between +/-0.003 g, as with the first test with the exception of one area (highlighted as A in figure 5) where the acceleration of the Volvo rose to 0.006 g then fell to -0.008 g and back to 0. Since the exact point of contact on the graph cannot be identified, the small blip at A could indicate an effect of the collision, though the limited period of just 0.015 seconds could indicate an anomalous result.

When the Volvo occupant movement accelerations (figure 7) are considered alongside the video footage, the most likely reason for the blip at A becomes clear. As the Ford approaches, the test subject can be seen to be tilting his head to the left and watching in the nearside mirror. As contact

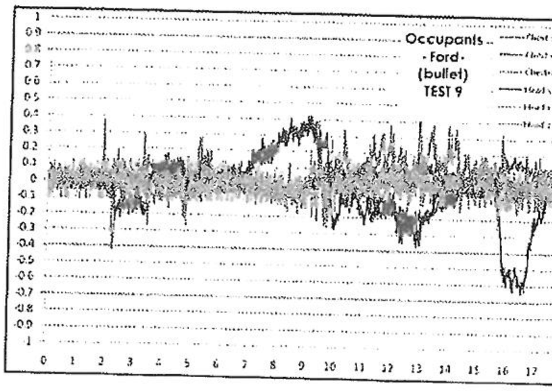

Figure 6.

occurs the test subject (a male of height approximately 1.9 m) swings his head away abruptly to look in the opposite direction. Spikes reaching -0.4 and +0.5 g occur in the left and right axis and correspond with the deliberate movements seen in the video footage. It is these deliberate motions that appear to have induced the minor fluctuations on the Volvo acceleration graph.

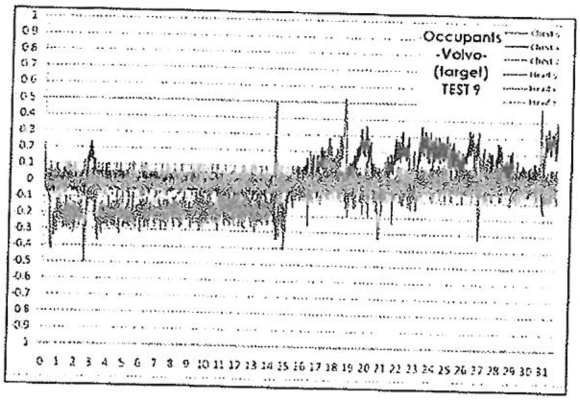

Figure 7.

It was impossible from either the speed or acceleration graphs from the vehicles or the occupant acceleration graphs to positively establish where any contact took place.

Movement of the occupants of the Ford could be seen during the normal vehicle acceleration and deceleration phase (figure 6).

CONCLUSION

Two tests were undertaken whereby the mirrors of two vehicles were in contact at speeds of 24km/h and 27km/h to investigate the effect of extreme partial collisions upon vehicle and occupant movement.

No movement of either vehicle could be determined from the accelerometer data obtained and attributed to the collision.

Normal accelerations were measured before, during and after the collisions. No unusual movement of occupants could be determined from acceleration data or video footage.

There was no movement of the Volvo visible in the video footage.

The conclusion drawn from these tests is that a 'collision' between mirrors attached to the body of the two motor vehicles did not accelerate either vehicle and did not cause any unusual occupant movement. The parts of the vehicle engaged were not strong enough to move any substantial part of either vehicle.

The video footage of these tests will shortly be available for viewing together with other technical papers at www.gbbuk.com.

REFERENCES

Kenneth S. Baker, 2001.Traffic Collision Investigation. Northwestern University Center For Public Safety.

CONTACT

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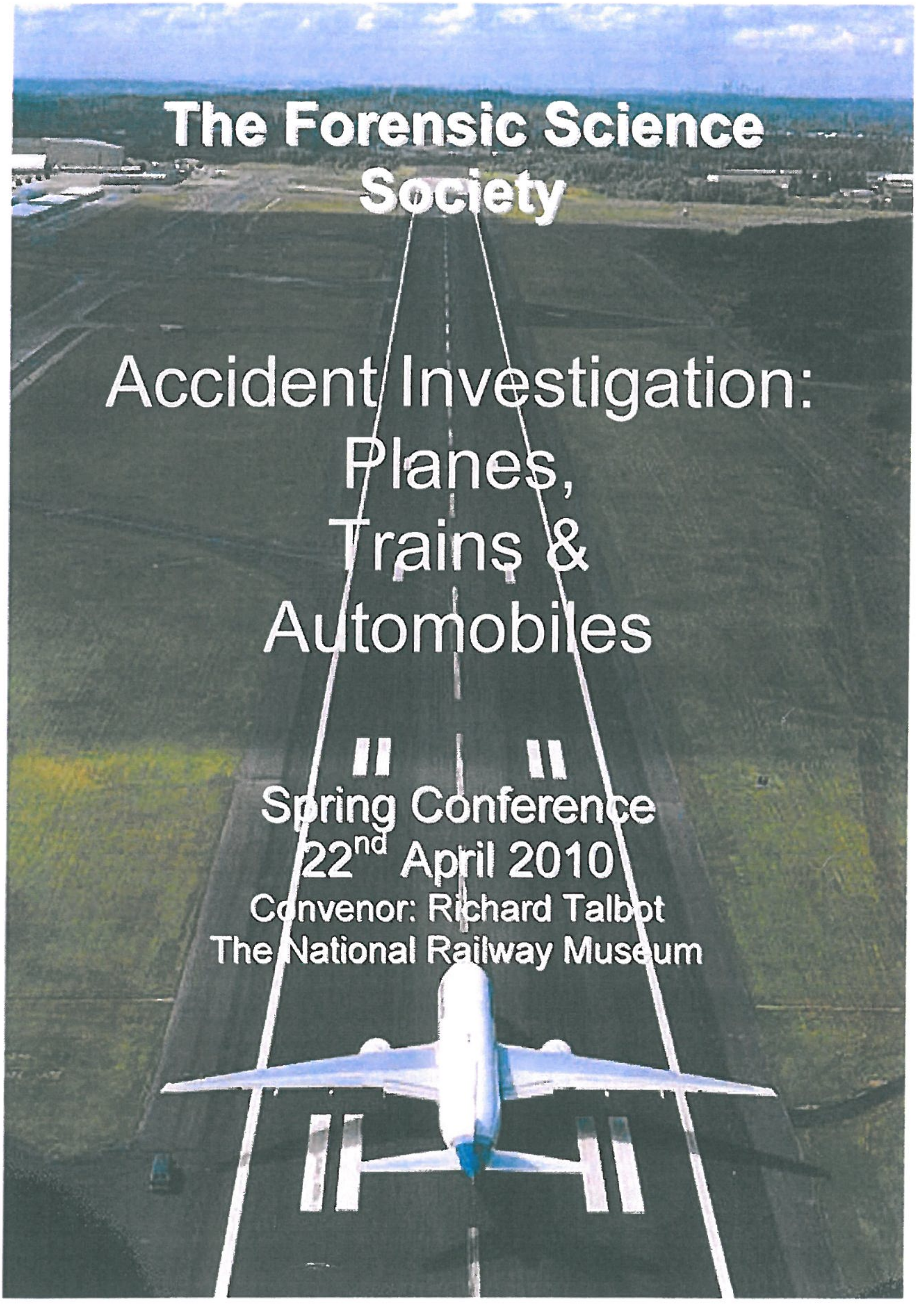
(Ref CT8/9-2009-1)

Appendix 21

An Original Publication


The Forensic Science Society
Accident Investigation:
Planes,
Trains &
Automobiles
Spring Conference
22nd April 2010
Convenor: Richard Talbot
The National Railway Museum

Programme

This meeting has been registered for CPD points with the Royal College of Pathologists, and the Bar Standards Board. If you wish to register, please sign the CPD attendance register on the registration desk at the start of each day you attend.

NB. The Law Society does not accredit this Conference – however, the conference can still contribute to the 75% of CPD points required for attendance at non-accredited meetings.

Thursday 22nd April 2010

08:30 **Registration**

09:00 **Welcome & Introduction**
Richard Talbot, Convenor, Forensic Science Society

Chairperson: David Rudram

09.15 **Should Experts in a Train Crash Investigation be Forensic Scientists?**
Peter Whent, DABS Forensic Ltd

10.00 **A Different Perspective**
Stuart Blackwood, Lothian and Boarders Police

10.45 **Tea/Coffee Break**

11.15 **In-Vehicle Data for Collision Investigation**
Iwan Parry, Transport Research Laboratory

12.00 **'Is the Threshold for Injury a 3mph Speed Change in a Rear End Collision?'**
Brian Henderson, GBB (UK) Ltd

12.45 **Lunch**

Chairperson: David Rudram

13.45 **'Marks and Trace Evidence – a Useful Tool in Collision Investigation'**
Dr Sarah Jacob, Forensic Science Service

14.30 **Palynology – Vehicles and Vessels**
Dr Anna Sandiford, Manlove Forensics Ltd

15.15 **Tea/Coffee Break**

15.45 **Investigating Britain's Fastest Crash**
Tim Alderson, North Yorkshire Police & David Price, Forensic Accident Investigation Services

16.30 **Close**
Dr Ann Priston, OBE, JP, FFSSoc
President, Forensic Science Society

IS THE 'WHIPLASH' THRESHOLD REALLY 3MPH?

(or "Putting The 3mph Threshold To The Test")

Philip Hoyes and Brian Henderson
GBB (UK) Ltd

Presented at The Forensic Science Society Spring Conference, York, April 2010.

ABSTRACT

There is a well-established relationship between vehicle damage, vehicle speed change, occupant movement and the potential for injury. Greater damage, with respect to structure, means a greater potential for injury. Speed change thresholds for injury have been suggested in previous literature. This research uses human test subjects, three full-scale vehicle collisions and 42 simulated collisions to investigate the correlation between speed change and occupant movement and uses it to test the suggestion of a second threshold where the accelerations are similar to an everyday activity.

INTRODUCTION

The link between damage and speed change is well-established (1,2,5,7,9,13). A positive relationship between vehicle speed change and the likelihood of occupant injury is also well documented (2,3,4,5,6,11). Previous international research and work by GBB (UK) Ltd suggest speed change thresholds for injury (3,4,6,12). The previous findings by GBB (UK) Ltd (12) suggested a new threshold focussed on the relative motion of the head and the chest. The aim of this research is to increase the existing dataset and investigate the occupant movement created by a low speed change collision in comparison with an everyday event. With increased real world data that newly proposed threshold is put to the test.

LITERATURE REVIEW

Vehicle crush deformation and energy equivalence relationships are widely accepted as technical accident reconstruction tools for estimating the change in velocity (delta-V) during an impact (5).

Delta-V has been accepted as a basis for evaluating damage severity and potential for injury severity (5).

In 1993 McConnell et al (3) recognised a lack of human experimental data for low speed impacts, which they defined as being those which resulted in a speed change (delta-V) for the target vehicle of 12.9 km/h (8 mph) or less. From nine successful test collisions between various types of vehicle they subjected male human volunteers aged 45 to 56 to speed changes from 3.04 km/h (2 mph) to 8.06 km/h (5 mph). In accordance with kinetic energy being proportional to the square of the velocity, they recorded a visible four fold decrease in collision related energy when the speed change was halved. They suggested a speed change of 6 to 8 km/h (4 to 5 mph) as being probably at or near to the typical human threshold for very mild, single event musculo skeletal cervical strain injury. A participating physician considered a speed change of 4 km/h (2.5 mph) to have been so very mild that a single exposure would be unlikely to result in any symptomology.

The following year, Szabo et al (4) also recognised a shortage in data regarding human occupant response to low speed impact, which they too defined as a delta-V of 13 km/h (8 mph) or less. They opined that "Actual crash testing with human volunteers remains the only valid method to determine response and tolerance to low speed, rear end impacts." Six crash tests were conducted using US Ford Escort motorcars, vehicles which were dissimilar to their UK namesakes and specifically chosen for their resistance to damage. The five volunteer subjects, of which two were female, were aged between 27 and 58 and had varying degrees of cervical and lumbar spinal degeneration. From their results the authors suggested an injury threshold of 8 km/h speed change (5 mph) and concluded that their work "enhanced the existing database of volunteer studies that, for restrained occupants with a head restraint available, single exposure to a rear-end collision with a Delta-V of 8 km/h or less is within human tolerance levels, and extends the database to include females with some degree of pre-existing spinal pathology."

From their research in 1995, Bailey et al (6) suggested a threshold for symptoms of 6.5 to 8 km/h (4 to 5 mph) in a rear impact.

In 1996 Murray Kornhauser (7) built upon the 8 km/h threshold suggested by McConnell and Szabo and proposed a threshold of 16 km/h (10 mph) as an order of magnitude of the Delta-V threshold for the 50th percentile male.

In 2004 research was presented at the International Insurance Whiplash Prevention Group Workshop (11) which analysed 131 crashes using European Toyota model vehicles with a total of 177 occupants and expressed an injury threshold in terms of probability. It was found that the risk of symptoms lasting more than one month was zero at a speed change of 2.5 km/h (1.5 mph) and 10% or less with a speed change of 12.5 km/h or less (7.8 mph). The risk of symptoms lasting more than six months was also zero at 2.5 km/h and 10% where the speed change reached 20 km/h (12.4 mph).

A conclusion that seat designs which reduce the acceleration of the chest and reduce the time until the head is supported by the head restraint should be encouraged suggested the notion of a link between injury and the relative motion of the head and the chest.

That same notion was investigated by GBB in the period 2003 to 2005.

A collinear test collision, referenced CT2/2005, was performed where the front of a Vauxhall Omega containing two adult male volunteers collided with the rear of a Toyota Celica, also containing two adult male volunteers.

Accelerometers in the Toyota recorded a speed change of 5.97 mph.

For the driver of the target vehicle the peak head acceleration (backwards/forwards) was 8.3g. and the peak chest acceleration (backwards/forwards) was 4.7g.

This provided a positive disparity of 3.6g.

The authors considered this disparity in acceleration to be the *whiplash mechanism*. The disparity has to be accommodated by the components of the neck.

The results are shown graphically in Figures 1 and 2 on the right.

The research, published in 2006 by Henderson et al (12), supported an injury threshold of 5 mph.

Importantly that work went further using the results of simulated rear impacts to propose a second threshold of 3 mph. Simulated rear impacts with speed changes in the order of 2.5 to 3 mph indicated that at that range there was no positive disparity on average. That led to the theory of three brackets when considering the possibility of whiplash-related injury in the target vehicle, those being as follows:

- *>5mph where the risk of injury was high as a consequence of a large disparity between peak head and chest acceleration.*
- *3 – 5mph where there was a risk of injury, but this was considered a grey area as the accelerational disparities were small.*
- *Speed changes below 3mph where little or no disparity was found and the risk of injury is minimal.*

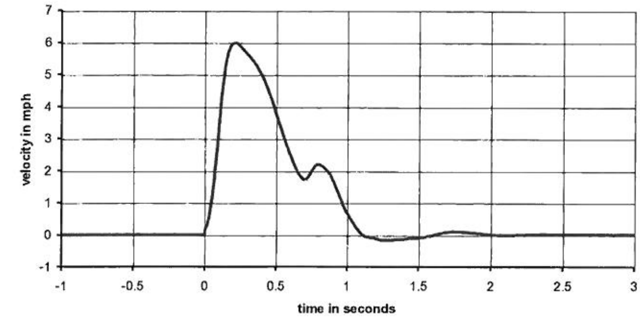


Figure 1. CT2/2005 target vehicle velocity.

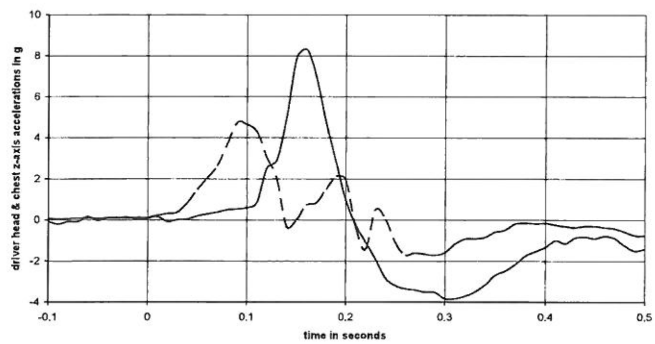


Figure 2. Head (solid line) and chest (dashed line) accelerations in the x(forward) axis.

METHODOLOGY

This technical paper deals with the following crash tests: CT2, CT5, CT6 of 2009. For simplicity in this paper they shall be simply referred to as test 1, 2 and 3.

CO-ORDINATE SYSTEM - The acceleration axis system was in accordance with SAE J1733-Sign Convention for vehicle Crash Testing. In relation to the vehicle the positive X, Y and Z axes were forwards, rightward and downward respectively.

VEHICLES – Two vehicles were used over the three tests. The first, a 2000(X) registered Alfa Romeo 156 T-Spark four-door saloon, 1747 cc petrol, manual (VIN: ZAR932000011*****) had an unladen mass of 1230 kg. The second, a Ford Focus 1.6L circa 1998-2002 five-door hatchback, petrol, manual (VIN: WFOAXXWPDAYL*****) had an unladen kerbside mass of approximately 1180 kg.

For Test 1 the Alfa Romeo was used as the bullet vehicle and the Ford as the target. For Tests 2 and 3 the configuration was reversed with the Ford becoming the bullet and the Alfa Romeo the target vehicle.

The reason for exchanging vehicle roles is that as part of other research the Ford Focus had been subjected to a 10 mph collision in between Tests 1 and 2. To avoid issues with alterations in elasticity it was decided that the roles of the vehicles be swapped.

Both vehicles were fully inspected before testing to determine any previous damage or repairs. The bumper systems were dismantled before testing and then again after each test. The bumper systems were unmodified, standard fitments to these vehicle models. Replacement bumper reinforcers were available if any damage was found that might alter the crash characteristics. The replacements were not required.

The unmodified seats and seatbelt systems were used in each vehicle.

Impact speeds were selected that would produce a change in velocity for the struck vehicle that would test the findings of our original research and investigate the region of 0 to 3 mph and slightly beyond.

The impact speeds were 1 mph, 3 mph and 6 mph which were calculated to produce speed changes of 0.9 mph, 2.2 mph and 3.6 mph.

The bullet vehicle was driven by a volunteer along a flat concrete surface into an aligned impact with the target vehicle. This method was employed because of its similarity with real-world collisions. Allowing the bullet to be driven into the target, rather than free-wheeled, gave better control over alignment, and it also allowed the driver of the bullet vehicle to be analysed, by accelerometers and video footage, for further research.

The target vehicle was in neutral with the handbrake disengaged. The positional lamps were illuminated as part of a separate university test running in conjunction with our own investigations.

Impact speeds were judged by the driver of the bullet vehicle using GPS.

A dual axis accelerometer and data logger (Vericom VC3000DAQ) was affixed to the approximate lower centre of the windscreen of both vehicles.

OCCUPANT – A different volunteer participant was selected for the target vehicle in each test. Each participant was male and an employee of GBB (UK) Ltd. Appendix A provides more detail regarding the participants. Prior to testing the design and performance of the study was described to each participant in a research protocol. They were informed of the aims, methods, sources of funding, benefits and associated risks in accordance with the Declaration of Helsinki. Signed declarations of consent were provided by all involved.

The participant was positioned in the driver's seat (front offside) with the seatbelt worn and asked to reposition the seat to replicate their normal, comfortable driving position. The participants were asked to hold the steering wheel and to make every effort to relax and not anticipate the collision.

The movement of the participant in the target vehicle was recorded by a video camera mounted on the opposite side window and fitted with a lens of short focal length.

Occupant accelerations were measured by tri-axis accelerometers. A 10 g unit (Crossbow model CXL10Lp3) strapped across the centre of the chest and a 25 g unit held against the centre of the forehead by elastic webbing (Crossbow model CXL25Lp3). Data acquisition was made by the Vericom 3000DAQ mounted within the vehicle using a sample rate of 100 Hertz.

RESULTS

Figure 3 shows the vehicle acceleration profiles for each of the three tests. Accelerations in the x-axis only are considered as it is these that result in the occupant injury (14).

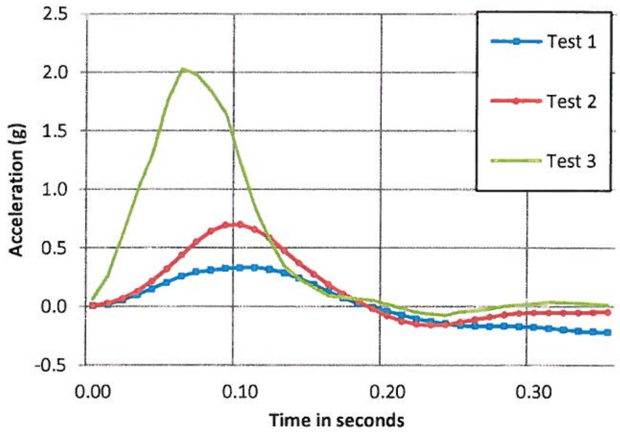


Figure 3. Target vehicle crash pulse from each test.

Figure 4 shows the speed change for the target vehicle in each test. The overall shapes of the traces are representative of those obtained from low speed impacts involving vehicles with typical bumper systems (15).

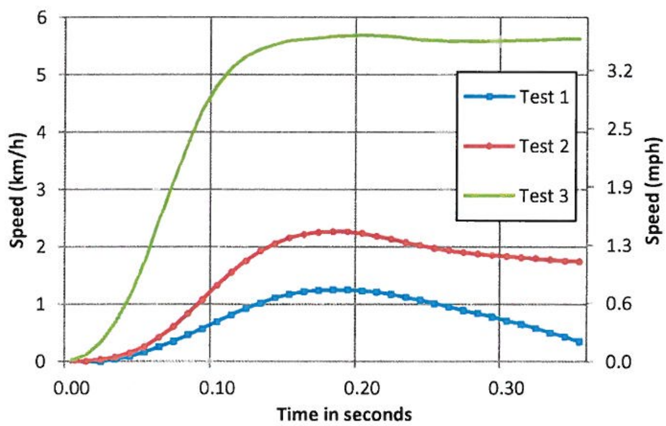


Figure 4. Target vehicle speed in each test.

Table 1 shows the peak values recorded from the target vehicle in each test.

Table 2 shows the peak values recorded from the occupant of the target vehicle in each test.

Test	Peak Acceleration (g)	Delta V (km/h)	Delta V (mph)
1	0.33	1.25	0.78
2	0.70	2.26	1.40
3	2.02	5.69	3.54

Table 1. Peak target vehicle values from each test.

Test	Peak Chest Acceleration (g)	Peak Head Acceleration (g)	Disparity G (A_{head}-A_{chest})
1	0.67	0.63	-0.04
2	1.07	1.36	0.29
3	2.70	4.88	2.18

Table 2. Peak target vehicle occupant values from each test.

Figures 5, 6 and 7, on the right, show the accelerometer results for the driver occupant of the target vehicle in each of the three tests.

Appendix B provides an abstract summary of one of the tests (test 1).

DISCUSSION

What is obvious from the above testing is that, not surprisingly, the higher the impact speed, the higher the resultant speed (delta-V) or speed change of the struck vehicle.

The higher the speed change, the greater the acceleration of the struck vehicle.

More important perhaps is the time at which peak acceleration occurs.

The greater the acceleration, the sooner peak g occurs.

This implies that for the vehicle occupants not only is there a higher acceleration to endure, but it occurs in a shorter time, thus increasing the peak force applied. (This is often referred to in the USA as the jerk.)

Conversely, at lower speeds, the mechanical action required to trigger the whiplash mechanism is not available. Lower acceleration results in a longer time frame.

Interestingly, in cases studied in recent years where the speed change is below 3mph, the occupants describe being 'jolted forwards then backwards'. The authors found this unusual as the occupant movement relative to the vehicle ought to be rearwards.

However, in video footage with such speed changes, the relative rearward movement between head and chest could not be detected. The disparity of movement between the head and the chest was so small that it required accelerometer data for it to be exposed.

What was seen in the video footage was that the synchronous movement of the head and chest in the rearward direction was slight and dwarfed by the movement in the forward direction.

The lower levels of acceleration within an extended time frame seem to preclude the rearward movement which is required to produce the disparity and consequently the trigger of the whiplash mechanism.

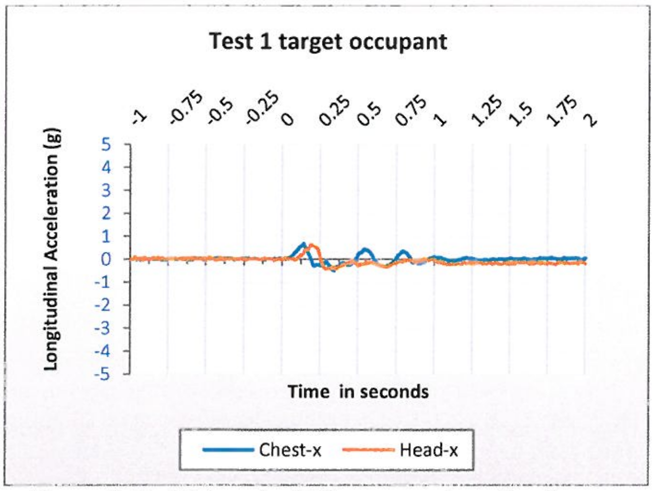


Figure 5. Test 1 target vehicle occupant accelerations.

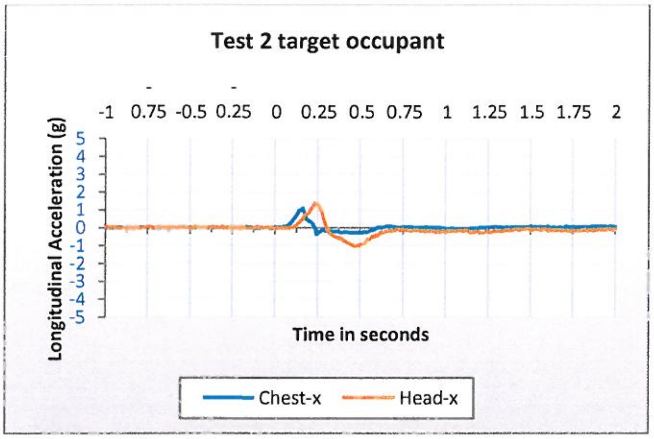


Figure 6. Test 2 target vehicle occupant accelerations.

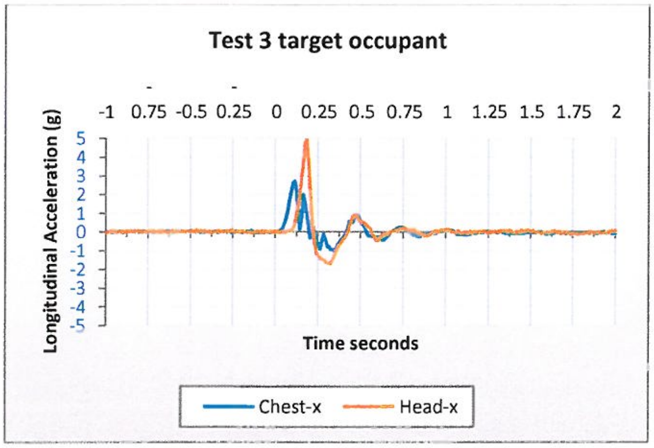


Figure 7. Test 3 target vehicle occupant accelerations.

SIMULATOR TESTING

The simulator testing referred to in *Putting the 5 mph injury threshold to the test* has been extended. The current position with 42 runs of 26 different volunteers (1 female) aged between 20 and 56 having been involved in the programme is that the speed changes ranged from 1.4 – 3.3 mph.

A summary graph of those 42 tests is shown at Figure 8. The average peak head acceleration was 2.68 g and the average peak body acceleration was 3.04 g.

On average therefore, there was no positive disparity between peak head and body accelerations. It also follows that due to the lack of disparity, it is highly unlikely that the whiplash mechanism would be triggered.

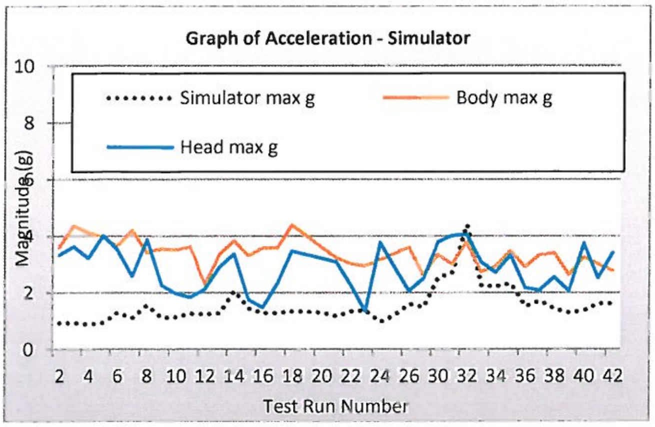


Figure 8. Rear impact simulator cumulative results.

Again, interestingly, in one case (test 8) where the speed change was above 3 mph (3.02 mph) a small positive disparity did occur. The disparity was 0.47 g.

A disparity of this value is only just discernible and, put in context, is comparable with those experienced when sitting into a chair. For this comparison the same volunteer was asked to sit from a standing position into three chairs each of a different design. Details are displayed in Appendix C and the results are summarised in Table 3, below (interest is only in the rearward movement in these tests).

Test	**Disparity g (A_{head}-A_{chest})**
Sitting into a comfy armchair	0.5
Sitting into a conference chair	1.0
Sitting into a cantilever chair	0.5

Table 3. Maximum positive disparity between the head and the chest sitting in three different types of chair.

It should be remembered that merely looking down to the ground produces a 1 g acceleration.

CONCLUSIONS

The purpose of this study was to build upon previous research into injury thresholds and focus particularly on the suggestion of a second threshold involving the relative motion of the head and chest.

A single full scale collision test supported an 8 km/h (5 mph) delta-V threshold for injury.

Three full scale collision tests and 42 simulated speed changes found that a delta-V of 4.8 km/h (3 mph) and below generally did not provide a positive disparity between peak head and chest accelerations. The isolated cases where a positive disparity was detected found them to be negligible and of a level comparable with those produced by sitting into a chair.

The rearward movement disparity associated with the triggering of the whiplash mechanism was absent in collisions with speed changes of below 4.8 km/h (3 mph).

This supported a second threshold of 4.8 km/h (3 mph) Delta-V where accelerations were comparable to everyday events such as sitting into a chair.

Between 3 and 5mph, on an upward sliding scale a disparity becomes evident and increases in magnitude.

Peak acceleration is experienced earlier the higher the closing speed of the collision.

No adverse symptoms were reported by the volunteer participants in any of the tests with speed changes below 5 mph.

REFERENCES

1. Nicholas S. Tumbas, Russell A. Smith, "Measuring Protocol for Quantifying Vehicle Damage from an Energy Basis Point of View". SAE Technical Paper 880072, 1988, doi:10.4271/880072.

2. Cheng, P. and Guenther, D., "Effects of Change in Angular Velocity of a Vehicle on the Change in Velocity Experienced by an Occupant during a Crash Environment and the Localized Delta V Concept," SAE Technical Paper 890636, 1989, doi:10.4271/890636.

3. McConnell, W., Howard, R., Guzman, H., Bomar, J. et al., "Analysis of Human Test Subject Kinematic Responses to Low Velocity Rear End Impacts," SAE Technical Paper 930889, 1993, doi:10.4271/930889.

4. Szabo, T., Welcher, J., Anderson, R., Rice, M. et al., "Human Occupant Kinematic Response to Low Speed Rear-End Impacts," SAE Technical Paper 940532, 1994, doi:10.4271/940532.

5. Robinette, R., Fay, R., and Paulsen, R., "Delta-V: Basic Concepts, Computational Methods, and Misunderstandings," SAE Technical Paper 940915, 1994, doi:10.4271/940915.

6. Bailey, M., Wong, B., and Lawrence, J., "Data and Methods for Estimating the Severity of Minor Impacts," SAE Technical Paper 950352, 1995, doi:10.4271/950352.

7. Kornhauser, M., "Delta-V Thresholds for Cervical Spine Injury," SAE Technical Paper 960093, 1996, doi:10.4271/960093.

8. Fay, R., Raney, A., and Robinette, R., "The Effect of Vehicle Rotation on the Occupants' Delta V," SAE Technical Paper 960649, 1996, doi:10.4271/960649.

9. Schmidt, B., Haight, W., Szabo, T., and Welcher, J., "System-Based Energy and Momentum Analysis of Collisions," SAE Technical Paper 980026, 1998, doi:10.4271/980026.

10. Brault, J., Smith, T., Wheeler, J., and Siegmund, G., "Cervical Muscle Response To Rear-end Automobile Collisions: Implications For Injury," presented at NACOB 1998, Canada, August 14-18, 1998

11. Zuby, D., "Whiplash Workshop," following IRCOBI Conference 2004, Austria, September 24, 2004

12. Henderson, B., "Putting the 5mph Injury Threshold to the Test," *Personal Injury Law Journal*. 48: 12-14, 2006

13. Anderson, B., Kress, T., Hungerford, J., Richards, S. et al., "Bumper Paint Damage in Low Speed Impacts," SAE Technical Paper 2007-01-0728, 2007, doi:10.4271/2007-01-0728.

14. Mansour, R. and Romilly, D., "Application of Energy-Absorbing Foam to the Seat Base to Mitigate Whiplash Injuries in Rear End Collisions," SAE Technical Paper 2011-01-0271, 2011, doi:10.4271/2011-01-0271.

15. Welcher, J., Szabo, T., and Voss, D., "Human Occupant Motion in Rear-End Impacts: Effects of Incremental Increases in Velocity Change," SAE Technical Paper 2001-01-0899, 2001, doi:10.4271/2001-01-0899.

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P. Fidler, GBB (UK) Ltd.

APPENDIX A.

Anthropometry:

Test 1 Male, 1.8m, 84 kg, 26 years old.
Test 2 Male, 1.87 m, 117.5 kg, 54 years old.
Test 3 Male, 1.8 m, 82 kg, 39 years old.

Post-tests Follow up.
No symptoms.

APPENDIX B. CT2/2009 Overview Low Speed, Rear-End Impact, 6th August 2009

TARGET VEHICLE

FORD Focus 1.6, 4-door hatchback (1998-2002)

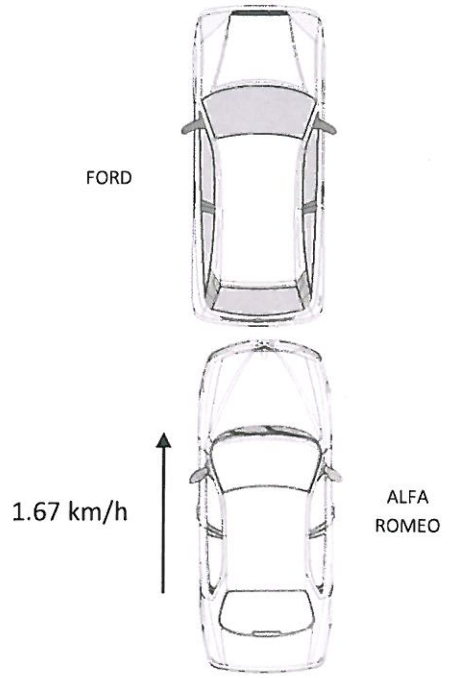
Vehicle Mass*	1180 kg
Occupant Mass	84 kg
Total Mass	1180 kg
Pre-Impact Speed	0
Speed Change (Δv)	1.25 km/h (0.78 mph)

BULLET VEHICLE

ALFA ROMEO 156, 4-door saloon (2000)

Vehicle Mass*	1230 kg
Occupant Mass	170 kg
Total Mass	1315 kg
Pre-Impact Speed	1.67 km/h (1 mph)
Speed Change (Δv)	0.78 km/h (0.48 mph)

*Includes 150 kg allowance for driver and luggage



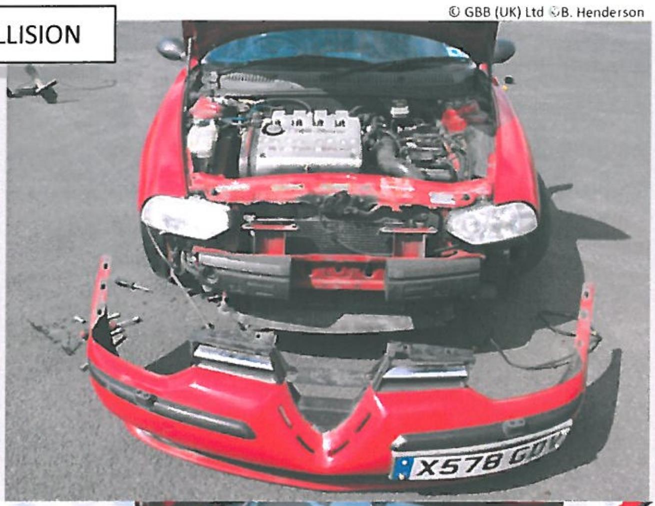
Pre-Existing Damage

Alfa Romeo, front	Ford, rear
Palpable dent to centre bonnet, front.	Light, shallow scratches to the rear bumper cover: photographed and positions noted.
Four shallow gouges to centre bonnet, front.	
Shallow, coarse, horizontal scrapes and screw-shaped indentation at offside of front bumper.	
Cracks emanate from offside number plate screw.	
Nearside number plate screw absent.	
Plastic gravel tray had been previously attached using cable ties. Component was removed and not fitted during the testing.	

Collision Damage

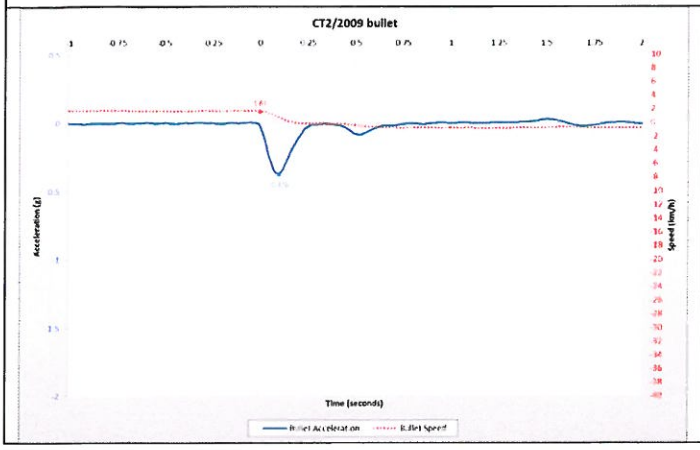
Alfa Romeo, front	Ford, rear
Small, vertical scratches to the black bumper insert offside.	Minor localised crazing in the paint.
Small, vertical scratches to the black bumper insert nearside.	Minor black transfer, vertical in direction.

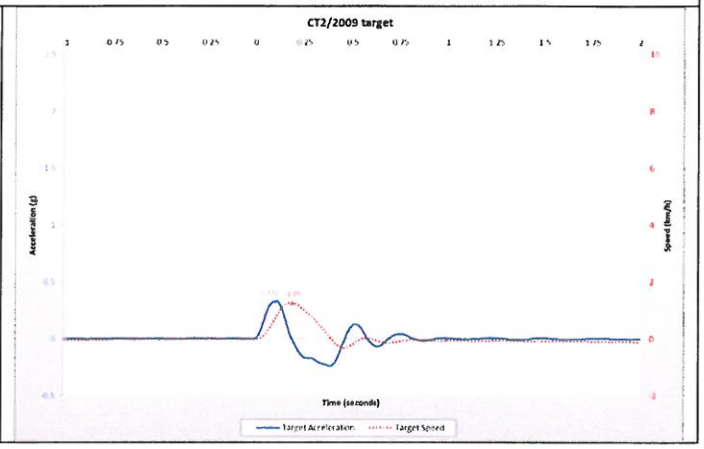
BEFORE COLLISION



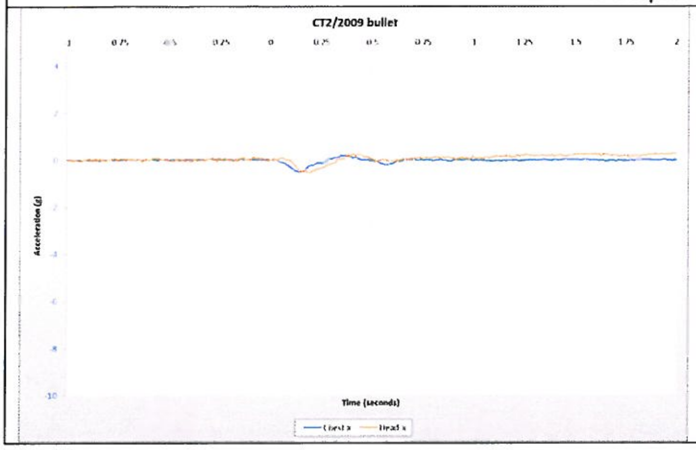
AFTER COLLISION

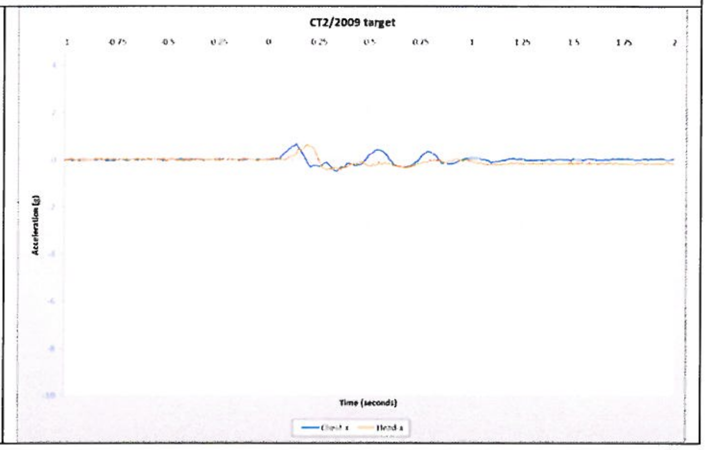
Vehicle Reactions





Occupant Reactions

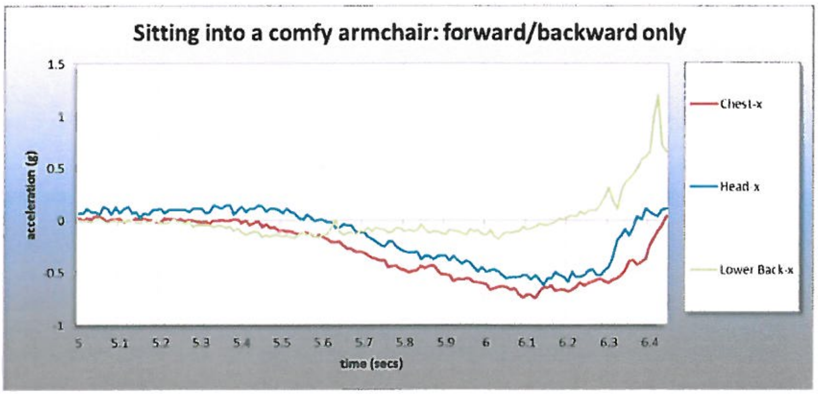




Where x= longitudinal (+forwards,-rearwards)

Occupant Symptoms	
Alfa Romeo	Ford
None	None

APPENDIX C.

<table>
<tr><td>Method</td><td>The subject was fitted with a tri-axis accelerometer on the forehead (25g) and another on the chest (10g) and asked to sit normally into each type of seat. A third tri-axis accelerometer was fitted on the lower back (10g) and secured by the trouser belt.
The axes are standard SAE orientation
i.e. the x, y and z axes were forward/backward, left/right and up/down
however care should be taken with direction
in these tests negative in the x axis represents rearwards
in processing the data the x axis values for the lower back were reversed to match the orientation of the forward facing accelerometers. No alterations were made to the y values because the left/right movement was negligible and not for consideration.</td></tr>
<tr><td>Sitting in a leather chair
</td><td>
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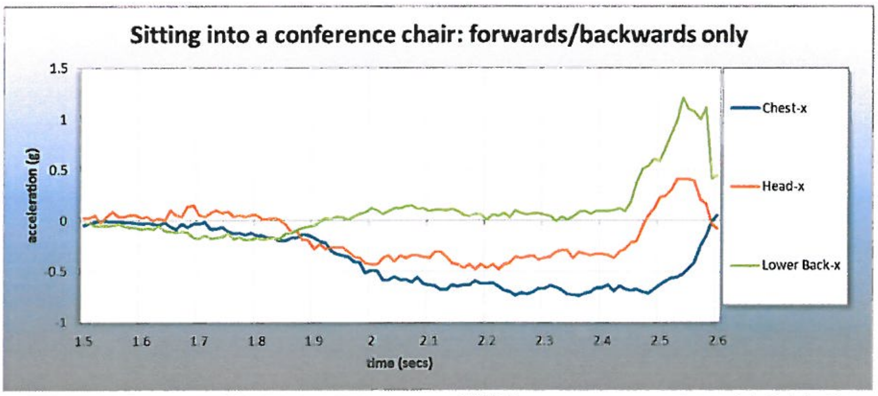
</td><td>
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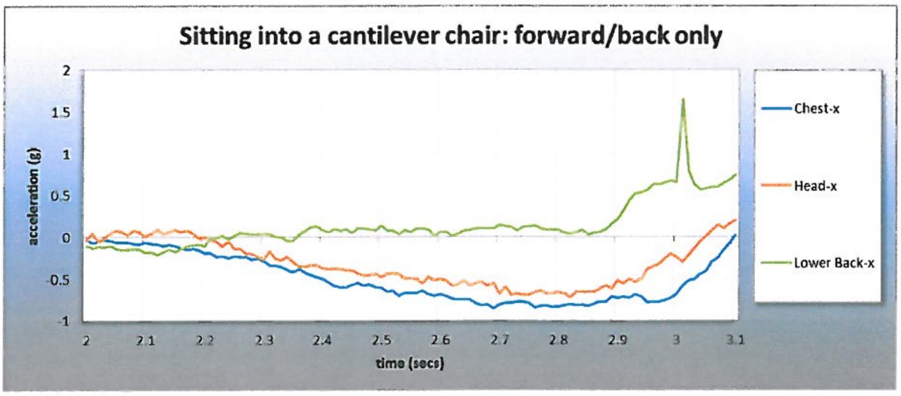
<tr><td>Sitting in a cantilever chair
</td><td>
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