European Enhanced Vehicle-safety Committee

Recommendations for a Low-speed Rear Impact Sled Test Pulse

EEVC WG20 report
September 2007

Report published on the EEVC web site: www.eevc.org

EEVC WG20 Report – Document Number 166

Recommendations for a Low-speed Rear Impact Sled Test Pulse

September 2007

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On behalf of the European Enhanced Vehicle-safety Committee (EEVC) Working Group 20

Number of Pages (including Appendices)
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Summary

This document summarises the most up-to-date information that is available regarding rear impact crash pulses and their relationship to whiplash associated injuries. A review of approximately 150 papers has been undertaken and the most relevant information collated. It is not currently possible to objectively verify the presence of whiplash associated injury, so most of the sources reviewed here have used insurance claims, either verified by non-medical interview or without verification. This review has made the assumption that the insurance claims used in the studies are, at least in the majority, related to real injuries.

It is apparent from the data reviewed that a large variety of crash pulses for a specific Δv will be produced even for a single struck car model. Some impacts give bimodal or multimodal pulses, some triangular pulses, and many other general pulse shapes are possible. This may be affected by many factors including: the mass ratio, stiffness and structure of the crash partners; the degree of overlap; the level of engagement of the two bumper systems; the type of bumper energy absorber fitted, and the presence of a tow-bar on the struck vehicle.

It is not understood whether specific features of these very varied pulses (such as transient spikes in the acceleration pulse) are responsible for increasing the risk of injury, or whether it only the general characteristics of the pulse (such as Δv, mean acceleration and peak acceleration) that are important. To correlate pulse characteristics such as the number of peaks and shape of the pulse with injury risk would require a much larger crash pulse recorder and injury database than is currently available. The available data is also limited by being based on a limited number of vehicle models from a single manufacturer; it is not known whether features of these vehicle models produce atypical pulses or not.

From the information reviewed it was not possible to recommend a single specific pulse shape as correlating with injury. However, two pulse shapes seemed most supportable: a bimodal shape, with a steep rise and large first peak, followed by a smaller second peak and more gradual drop-off in acceleration; and a triangular pulse with a steeper initial rise in acceleration and more gradual drop-off in acceleration. The trapezoidal pulse that is defined for a number of current or proposed test procedures does not seem to be representative of real vehicle pulses in low-speed rear impacts.

Given that the information reviewed does not allow a particular pulse shape, or the characteristics of particular pulse shapes, to be definitively correlated with injury (or claim of injury), most studies have evaluated the correlation between injury or claim rates and pulse characteristics such as Δv, mean acceleration and peak acceleration. These parameters may be calculated directly from crash pulse recorder data, which should provide the most accurate data available. Alternatively, the Δv and mean acceleration can be estimated from accident investigation data such as vehicle intrusion measurements or photographs of the damage to the vehicles (this latter will be the least accurate method), although the accuracy of such estimates for low-speed rear impact is not clear. In particular, the computer programmes used to calculate Δv from damage profiles (either measured or estimated from photographs) are not suitable for under-run (or, presumably, over-run) impacts and should not be used for these cases (Lenard *et al.*, 1998). Many of the laboratory crash tests reviewed feature either under-run or over-run and it is not clear that such cases have been excluded from accident investigation estimates of low-speed rear impact crash pulse characteristics.

The most recent studies using the Folksam crash pulse recorder data show a correlation between crash severity, in terms of Δv and mean acceleration, and duration of symptoms. In order to target longer-term whiplash injuries with a test procedure, it would seem from the information reviewed that a Δv of 20 $km.h^{-1}$ with a mean acceleration of 5-6 g would be the most reasonable pulse characteristic. This would be well outside the range of pulse characteristics for volunteer tests where no injury or only minor, short-term injury occurred, but would be more severe than most of the test procedures currently proposed. In addition to the pulse described above, a lower severity pulse may be useful to ensure that the low risk of injury at a lower pulse is not compromised by efforts to meet a more severe pulse test.

The recommendations from this report are:

- Real-world low-speed rear impact pulses are very variable and the available data is limited. It is currently not possible to correlate detailed pulse shape with injury risk, and the evidence for a link between pulse characteristics (such as Δv and mean or peak acceleration) and injury (or claims) is weak. However, within these limitations it is recommended that the following pulse is used to target longer-term whiplash injuries:
    - Δv of 20 $km.h^{-1}$, with mean acceleration of 5-6 g, either
        - Bimodal, with a steep rise and large first peak, followed by a smaller second peak and more gradual drop-off in acceleration, or
        - Triangular, with a steeper initial rise in acceleration and more gradual drop-off in acceleration.
    - 20 $km.hr^{-1}$ is approximately the mean Δv indicated in the literature for long-term injuries, with a typical range of 16 to 25 $km.hr^{-1}$.
    - Long-term injuries cost approximately £3 billion pounds annually in the UK alone, using the UK Department for Transport 'Willingness to Pay' costing method [WG20 document number WD167].

- As this pulse is more severe than those currently used in consumer testing, it is recommended that testing is undertaken to confirm that the dummy chosen for rear impact testing with this pulse is robust, repeatable and reproducible at this higher pulse severity.

- In addition to the pulse described above, a lower severity pulse is recommended to ensure that the current low risk of injury at a lower pulse is not compromised by efforts to meet a more severe pulse test.
    - This would ensure that seat back stiffness, reactive head restraint actuation and active head restraint triggering are not optimised for a high severity pulse alone.
    - WG20 has not investigated this in detail to date, but approximately 10 $km.hr^{-1}$ seems to be indicated.
    - If a single pulse is to be used, some members of the WG recommended that a mid-severity pulse be used, such as the a 16 $km.hr^{-1}$ pulse, so that the assessment of seats isn't biased too strongly to either end of the severity range. A single pulse would, however, carry the risks of not maintaining current good performance at the frequently occurring, low-severity impact range, nor providing adequate incentive to provide good protection across most of the long-term injury severity impact range.

- In order to choose between a bimodal and a triangular pulse shapes Δv and mean acceleration, it may be possible to evaluate both pulse with the recommended rear impact dummy and injury or seat performance criteria from EEVC WG12 on the following basis:
    - If one pulse shape consistently classifies seats as having a lower performance, this pulse should be used as the use of the less severe pulse may cause the benefit arising from the introduction of the test procedure to be underestimated;
    - If both pulses give similar classifications, or if the classification is inconsistent, consideration could be given to selecting the pulse shape that is easiest to implement on typical laboratory sled test equipment, which is likely to be a unimodal pulse shape.

- There is little information in the open literature regarding the achievability and reproducibility of pulses for low-speed rear impact testing, which is required for defining a corridor for the pulse. However, this is currently being evaluated for consumer seat testing. It is recommended that the results, when available, should be used to define the corridor for the pulse recommended in this report.

- It should be noted that the recommended pulse is at a higher severity than is being investigated for consumer testing. It is therefore recommended that the achievability and reproducibility of the pulse is confirmed through additional testing before being implemented in the WG20 test procedure.

1 Introduction

Whiplash injuries (AIS1 neck injuries) have been a problem in rear impact crashes for a number of years. These injuries are not serious or life threatening in themselves but often have long associated recovery times and can also incapacitate the sufferer; they therefore represent a high cost to society. In response to the growing problem of AIS1 neck injuries being sustained as a result of rear impacts, the EEVC formed Working Group 20 with the aim of devising a rear impact test procedure. In parallel with the activities of the WG20, consumer testing organisations such as EuroNCAP (European New Car Assessment Programme) and the IIWPG (International Insurance Whiplash Prevention Group) have been active in developing their own test procedures with a view to influencing seat manufacturers to design safer seats.

The purpose of this document is to summarise the most up-to-date information that is available on rear impact crash pulses, their relationship to injury and the ability of current rear impact dummies to detect differences between particular pulse shapes and severities. A literature search has been conducted to collect public research papers with information relating to all aspects of rear impact crash pulses. A search for any information on real world data and the relationship of crash pulse parameters to injury was conducted, covering the past seven years (2000 to present), with a view to updating the information presented in WD49. Further searches for information on rear impact volunteer and dummy testing and the development of neck injury criteria for use in rear impacts were also conducted to cover the last 17 years (1990 to present) with a view to defining the highest level of pulse which would be non-injurious and to assessing the sensitivity of current rear impact dummies to various pulse characteristics such as Δv, peak acceleration, pulse duration, etc. The searches used TRL's knowledge base, which contains abstracts from numerous publications, and was supplemented with an existing database of whiplash literature.

The searches resulted in approximately 150 research papers. However, in most cases the information these papers provided has been somewhat limited as most were written for reasons other than to define a suitable crash pulse for a rear impact test regulation. It is not currently possible to objectively verify the presence of whiplash associated injury, so most of the sources reviewed here have used insurance claims, either verified by non-medical interview or without verification. This review has made the assumption that the insurance claims used in the studies are, at least in the majority, related to real injuries.

Recommendations have been made for a regulation rear impact crash pulse(s), specifically targeted to reduce the incidence of AIS1 neck injuries by improving seat design.

2 Literature Review

2.1 Real-World Rear Impact Crash Pulse Data

2.1.1 Real-World Pulses from Crash Pulse Recorders

The only crash pulse data recorder information for low-speed rear impacts in the literature is from the on-going Folksam study in Sweden. The crash pulse recorders are fitted to a number of vehicle models from a single manufacturer. Example pulses from this study have been published, such as those from Linder *et al.* (2003) in Figure 1 and Figure 2. As can be seen in Figure 1, the pulse shape for a single vehicle model can be very variable, presumably depending on the degree of overlap between the two vehicles, the presence of under-ride or over-ride, the stiffness and structure of the front of the striking vehicle and so forth. The data for the second vehicle model are rather more consistent (Figure 2), consisting of a generally triangular shape with a steep leading edge and a gradual drop-off in acceleration. In general, Linder *et al.* (2003) reported that for the same make and model of car, pulses with the same Δ*v* had a variety of associated mean accelerations and pulse shapes.

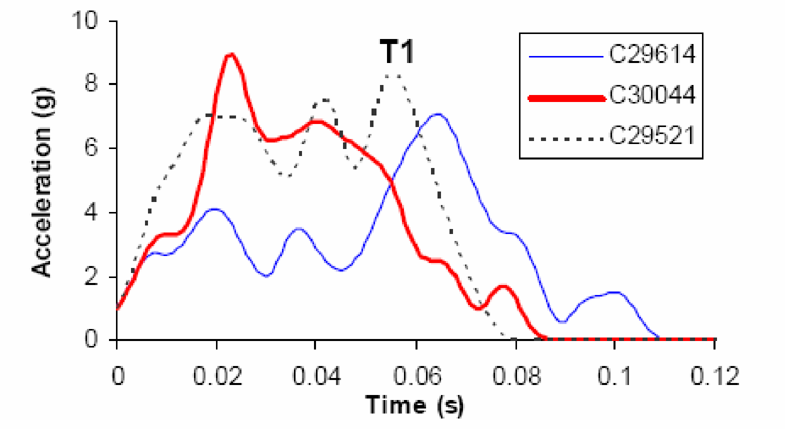

Figure 1: Pulses measured in vehicle model T1 in real world crashes with Δ*v* = 12.0 km.h^{-1} to 14.7 km.h^{-1} (Linder *et al.*, 2003)

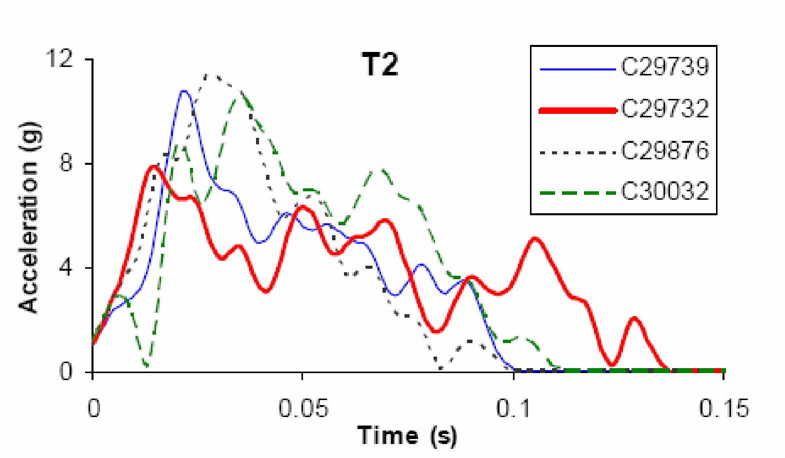

Figure 2: Pulses measured in vehicle model T2 in real world crashes with Δ*v* = 17.1 km.h^{-1} to 20.4 km.h^{-1}, Linder *et al.* (2003)

Another pair of crash pulses from this study were reported in Zuby *et al.* (2003), as shown in Figure 3.

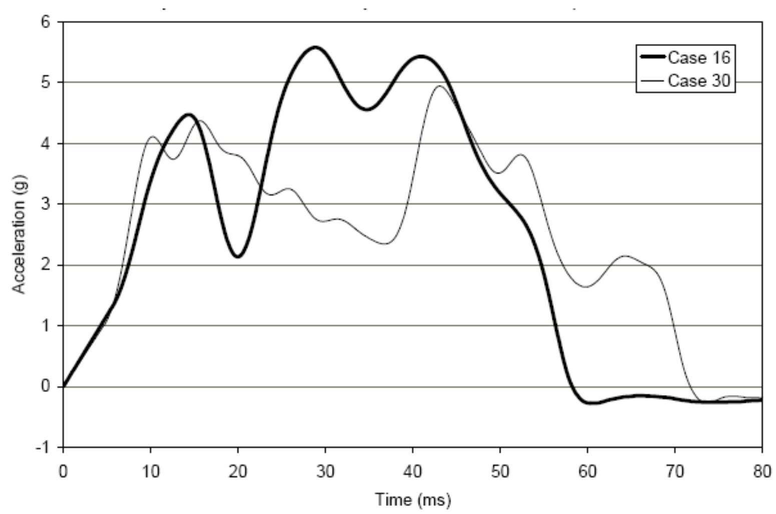

Figure 3: Two crash pulses from a 1998 Toyota Corolla as recorded by a Folksam Insurance crash pulse recorder, Δv = 7 km.h^{-1} , Zuby *et al.* (2003)

Another paper using the same data source (Krafft *et al*. 2002) examined the mean acceleration of the crash pulses over different time intervals. This study used 53 crashes (once multiple impacts and cases where the recorder did not record the complete pulse were excluded) involving a total of 94 occupants. The authors analysed the effect of different crash pulse characteristics on different durations of symptoms (as reported by the occupants in an interview). They also analysed the mean accelerations of the crash pulses recorded over particular time intervals for different groups of occupants (with different durations of symptoms). With this information they generated the curves in Figure 4. (No neck injuries were reported for peak accelerations below 4g and mean accelerations below 2g, this correlates with the volunteer testing data presented in Section 2.4.). This data is similar to that found from accident investigation shown in Section 2.1.2 in that the data is less detailed than individual pulse shapes, but has the advantage that it is based on measured, rather than estimated, crash pulses.

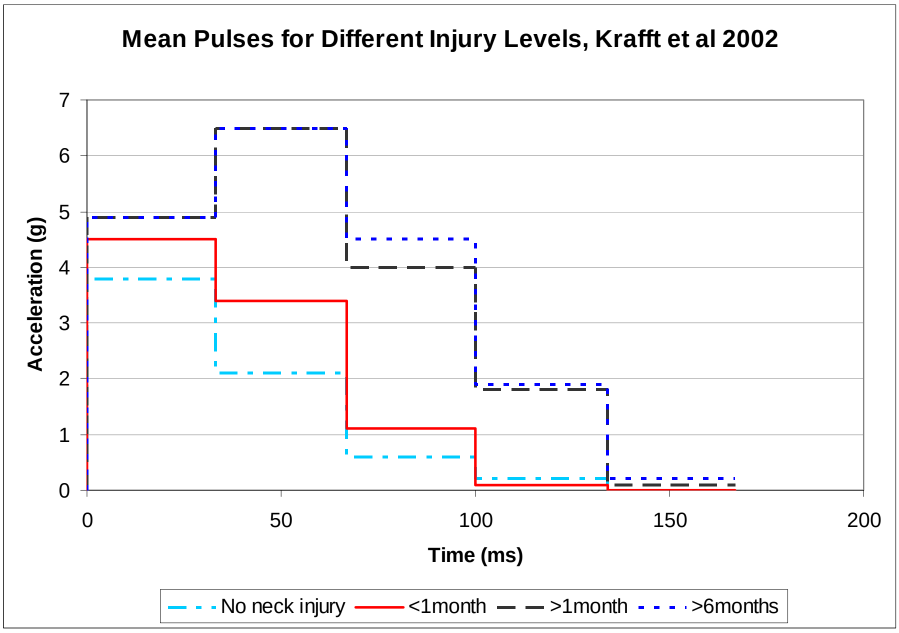

Figure 4: Mean acceleration pulses for different injury symptoms (Krafft *et al.*, 2002)

2.1.2 Real-World Pulse Characteristics from Accident Analyses

Where vehicle accelerations in an accident are not measured directly using a crash pulse recorder, they are estimated from information recorded by accident investigators. This may include measurements of the damage or intrusion on the vehicles involved, photographs of the damage to the vehicles, knowledge of the masses of the vehicles, and estimates of the velocity of both vehicles immediately prior to impact. The estimates made from measurements of vehicle intrusions have been validated in a number of papers (e.g. Lenard *et al.*, 2003) for relatively high speed frontal and side impacts. The accuracy of these measurements for low-speed rear impacts is less clear and likely to be affected by whether the two vehicles have good structural engagement, under-ride or over-ride. Estimates based on photographs of the damage (as in Langweider and Hell (2002) and Schick and Hell (2005) below) are likely to be less accurate than those based on measurements of intrusion made on the case vehicle.

Langwieder and Hell (2002) analysed data from the GDV accident database to put proposals forward for a harmonised rear impact dynamic test for seats and head restraints. 170 vehicles where an occupant had claimed a cervical spine disorder were analysed using the PC-Crash computer programme. Their findings showed that the majority of accidents in the database occurred with Δv below 15 $km.h^{-1}$ (4.2 $m.s^{-1}$) (see Figure 5). However, the database was dominated by vehicles produced before 1990 and hence this may not be representative of current vehicles or injury patterns. The authors conclude that ‘it appears to be beneficial at first to examine the most common impact configuration, which amounts to about Δv 16 $km.h^{-1}$ with a mean crash pulse of approximately 6-8 g’. This is not linked to severity of injury, other than some discussion that the authors consider injuries at a Δv of up to 15 $km.hr^{-1}$ to be suspicious of being fraudulent, if no special circumstances (such as previous injury) exist. Langwieder and Hell reported that fraudulent (or unlikely to be true) claims of cervical spine disorder were estimated at 50% for German insurance data (Figure 6) and 30-40% for US insurance data.

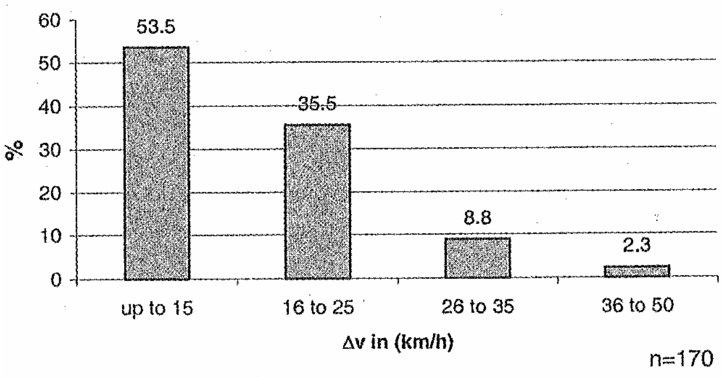

Figure 5: Distribution of Δ*v* (Langwieder and Hell, 2002)

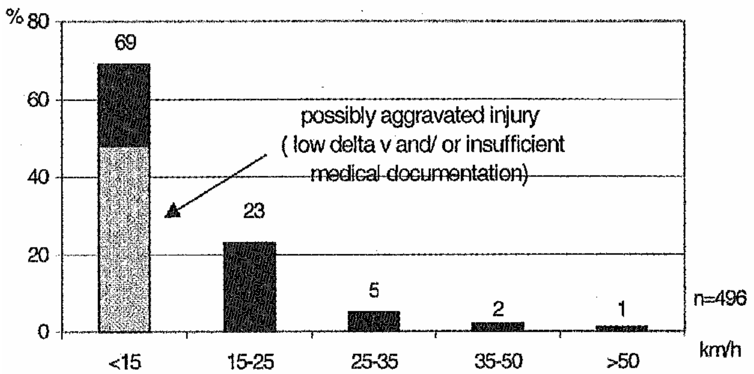

Figure 6: Δ*v* and claimed cervical spine injuries (Langwieder and Hell, 2002)

Schick and Hell (2005) analysed 187 cases from 2001 in which an occupant suffered from WAD for more than two weeks, following a rear impact (taken from a German insurance database representing 10% of the market share of German insurers). From the original sample, 102 cases were selected where an occupant suffered from WAD for more than 6 weeks. This group was then split according to whether the occupant's symptoms lasted for more than 6 months (chronic cases) or not (control group). Twenty-one of these cases were reconstructed using the PC Crash programme; the authors' noted that 'significant difference [between the chronic case and control (lesser injury) groups] would therefore not be detectable due to the low numbers'. However, when they compared the two groups, the mean accelerations and Δ*v* were the same (see Table 1).

	Mean Δ*v* (range) (km.h^{-1})	**Mean acceleration (range) (g)**
Chronic Case Group (> 6 months, 4 cases)	19.4 (12.3 to 28.8)	5.5 (3.48 to 8.15)
Control Group (6 weeks to 6 months, 17 cases)	19.4 (11.2 to 29.3)	5.5 (3.18 to 8.29)

Table 1: Mean Δ*v* and acceleration for chronic whiplash and control groups (results not statistically significant) (Schick and Hell, 2005)

Kullgren *et al*. (2003) used a statistical analysis of Folksam crash pulse recorder and police reported data to predict the level of risk of sustaining injury to a particular body region for a given Δv. A Δv of 8 km.h^{-1} (2.2 m.s^{-1}) corresponded to an injury risk of 0.45, and a Δv of 20 km.h^{-1} (5.6 m.s^{-1}) to a risk of 0.8 in rear impacts. There was no consideration of duration of symptoms in this analysis and AIS 1 neck injury may include more that solely whiplash-type injuries.

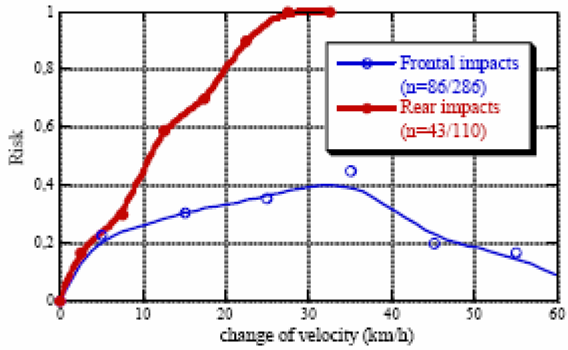

Figure 7: Risk of AIS 1 neck injury in frontal and rear impacts versus change of velocity, from crash recorder data (Kullgren *et al.*, 2003a)

Linder *et al*. (2004) reconstructed real world crashes with known injury outcomes using Folksam crash pulse recorder data, with the aim of correlating injury criteria values (as measured by a dummy) with actual injury outcome for an adult occupant. The injury data were obtained via interviews conducted by Folksam staff; it was made clear to the occupants involved in the study that injury data collected by the interviewers would not be used in any claim or have any effect on compensation provided in an effort to produce unbiased data. The cases were grouped according to mean acceleration and the mean risk of sustaining AIS1 neck injury with symptoms lasting longer than 1 month was calculated for each acceleration category; this yielded three categories with mean injury risks of 0%, 10% and 30%.

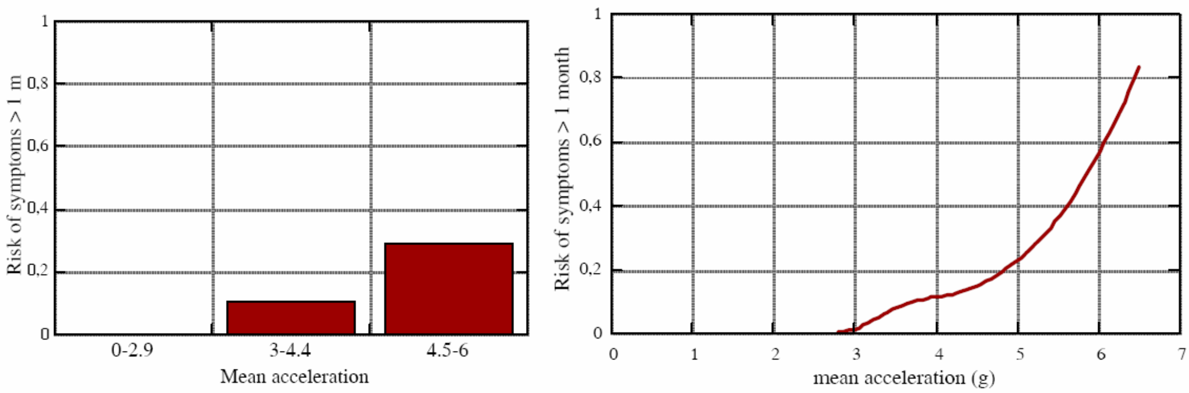

Figure 8: Risk of neck injury symptoms > 1 month (Linder *et al.*, 2004)

Twenty-five cases from these categories were selected for reconstruction (occupants with previous neck injuries and cases where the Δv was below 4 km.h^{-1} or above 30 km.h^{-1} were excluded). A BioRID IIc was used for all tests and since all data was from Toyota cars of one of three models, the set-up could be easily recreated. Repeatability tests were also conducted and a variation of between 4 and 12% was found for maximum values of the different parameters assessed. The results for a small selection of the tests were also compared to tests conducted using the same pulse and set-up but with a "body in white" to assess to what extent the pulse would be attenuated by the seat attachment to the floor. There were differences in the results, but this was due in part to the use of newer seats; the differences were not assessed for statistical significance. The results of the study are illustrated in Table 2.

Group	N	Average value for the group								
		Δ*v* km.h^{-1} (m.s^{-1})	Mean Acceleration (g)	AIS1 Neck Injury Risk	NIC (m^{-2}.s^{-2})	T1 x Acceleration (g)	Nkm	Fx (N)	Fz (N)	Head to HR Contact (ms)
C	9	18.7 (5.2)	5.3	30%	23.3	14.9	0.52	454	1202	87
B	6	12.4 (3.4)	3.6	10%	16.7	9.6	0.37	178	659	87
A	10	5.6 (1.6)	2.5	0%	9.9	4.8	0.18	113	204	95

Table 2: Average dummy readings and injury criteria for the three groups with different risk of injury for the driver (Linder *et al.*, 2004)

Krafft *et al.* (2005) assessed the effect of different crash pulse parameters on duration of symptoms, separated for male and female occupants. This study also used the Folksam database of accident data involving Toyota car models fitted with a crash pulse recorder.. The number of suitable cases was limited to 150 with a total of 207 occupants (132 of whom were uninjured; 51 had symptoms < 1 month; seven had symptoms > 1month and < 6 months; and 17 had symptoms for > 6 months, including three with lumbar or thoracic spine injuries). It was found that the average impact severity (in terms of both mean acceleration and Δ*v*) was significantly higher for occupants with symptoms lasting longer than one month than for occupants who were uninjured (see Figure 9 and Figure 10). Figure 11 and Figure 12 show the occupants grouped according to the Quebec Task Force WAD scale (Spitzer *et al*., 1995). The authors noted the difference in the results of analyses conducted for short or long-term symptoms and suggested that to avoid sub-optimisation, more than one pulse severity should be selected.

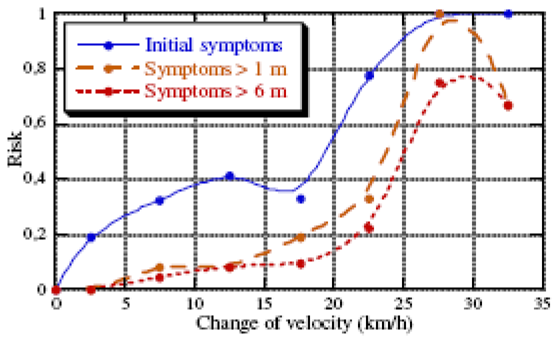

Figure 9: Injury risk in intervals of change of velocity for occupants with initial and long-term symptoms (Krafft *et al.*, 2005)

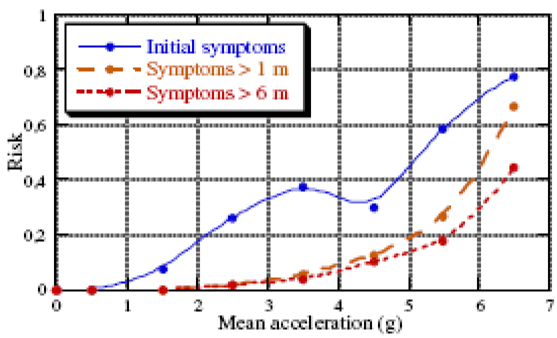

Figure 10: Injury risk in intervals of mean acceleration for occupants with initial and long-term symptoms (Krafft *et al.*, 2005)

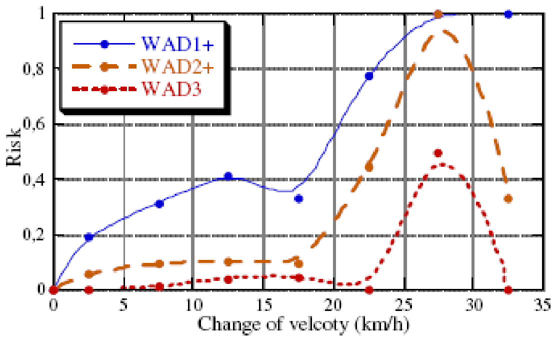

Figure 11: Injury risk in intervals of Δ*v* for occupants classified as different grades of WAD (Kraft *et al.* 2005)

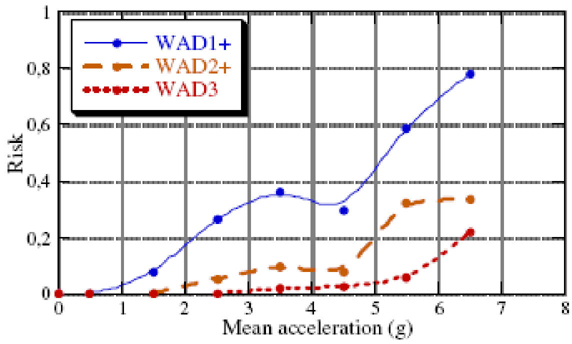

Figure 12: Injury risk in intervals of mean acceleration for occupants classified as different grades of WAD (Kraft *et al.* 2005)

Although several authors document injuries being reported at much lower pulse severities than suggested here, it is worth taking into account the findings of Castro *et al.* (2001); where volunteers were subjected to a placebo rear impact in a real car. Of the 51 subjects tested, nine experienced initial symptoms from the 0.03g simulated impact and three experienced symptoms lasting longer than 1 month. (Of the three occupants with longer term symptoms, two had existing back problems.) The authors used a psychological analysis of the subjects to analyse their results. These findings indicate that in some cases, genuine symptoms may be due to the stress caused by the crash or some pre-disposition to stress, rather than any physical damage caused by the crash pulse itself.

2.2 Pulses from Low-speed Rear Impact Laboratory Tests

Pulses from laboratory tests will not be related to the risk of injury in any way, but they are useful in illustrating the general form or shape of low-speed rear impact pulses.

2.2.1 Pulses from Car-to-Car Laboratory Tests

Heitplatz *et al.* (2002) reported car-to-car low-speed rear impact crash tests with Ford-group cars. All tests were 100% overlap with a target Δ*v* of 16 km.h^{-1}, and used a Ford Focus as the bullet car. The actual Δ*v* achieved ranged from 13.7 to 16.9 km.h^{-1}. Figure 13 shows the acceleration pulse for the struck vehicle (filtered at CFC 60) and Table 3 shows whether the impact was full bumper-to-bumper engagement, under-ride, or over-ride.

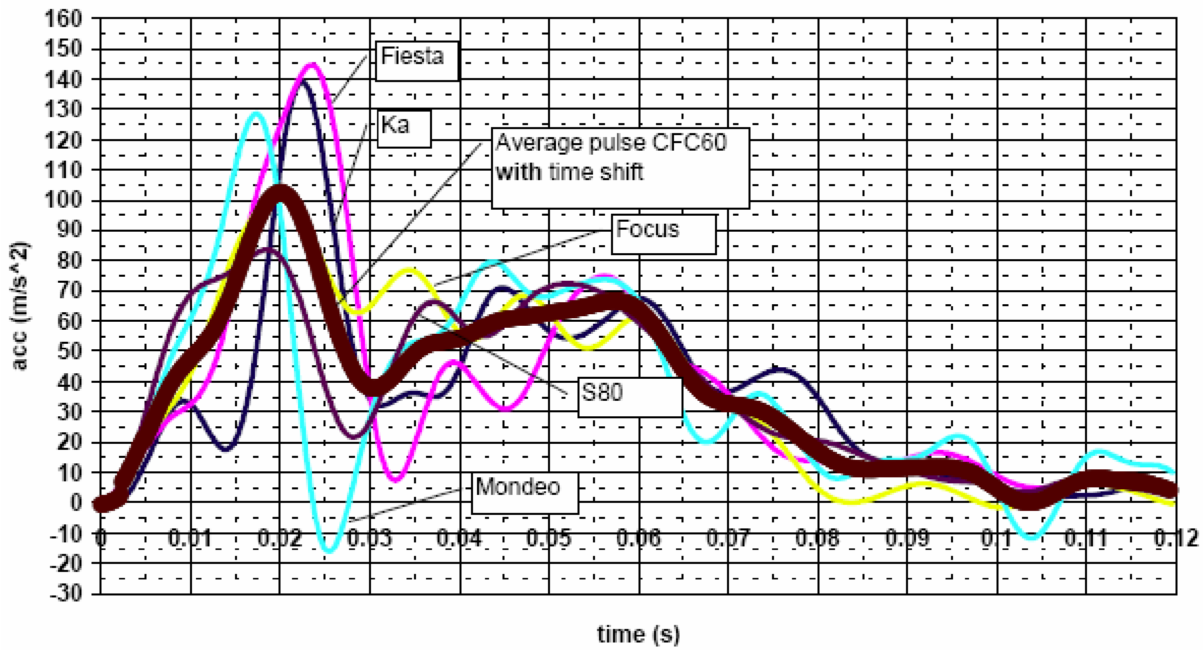

Figure 13: Average of all pulses compensated for shift in onset of acceleration (Heitplatz *et al.*, 2002)

Test	Impact class
Focus to Ka	Under-ride
Focus to Fiesta	Over-ride
Focus to Focus	Under-ride
Focus to Mondeo	Bumper to bumper
Focus to S80	Bumper to bumper

Table 3: Test matrix for car-to-car impacts (Heitplatz *et al.*, 2002)

The pulse shape in these Ford-group tests was typically bimodal, with a large first peak and a smaller, longer second peak. This was despite the range of under-ride, over-ride and good bumper engagement. The authors reported that a CAE study showed that the characteristic bimodal shape of the acceleration traces is caused by the back-swing of the free engine mass (causing a trough in the acceleration trace) followed by a new onset of acceleration as structural deformation resumes. They noted that all current mass-produced passenger vehicles share the same basic design features (e.g. reinforced rear structures and front mounted free-swinging engines). They therefore considered it reasonable to assume that for this test set-up the general features of the bi-modal pulse would also be exhibited by vehicles not included in this study. It should be noted that the pulse is therefore considerably affected by the striking vehicle in a way that is not reproduced by the insurance barrier-to-bumper test (the barrier has no free-swinging mass). However, Linder *et al.* (2003) show insurance barrier-to-bumper test results with, in some instances, similar bimodality.

Avery (2001) reported tests undertaken by Ford Motor Company using the same vehicles as Heitplatz *et al.* (2002), except that a Volvo S60 was used instead of a Volvo S80. The reported vehicle masses were also much lower (see Table 4). The Δv in these tests ranged from 13.7 to 16.5 km.h^{-1} and the vehicle pulses (filtered at CFC 20, compared with CFC 60 in Heitplatz *et al.*) are shown in Figure 14.

Vehicle	Test weight (kg) (Heitplatz *et al.* 2002)	Test weight (kg) (Avery 2001)
Ford Focus (bullet)	1300	-
Ford Ka	1021	930
Ford Fiesta	1165	1000
Ford Focus	1384	1150
Ford Modeo	1675	1400
Volvo S80	1860	-
Volvo S6	-	1550

Table 4: Test vehicle masses for Heitplatz *et al.* (2002) and Avery (2001)

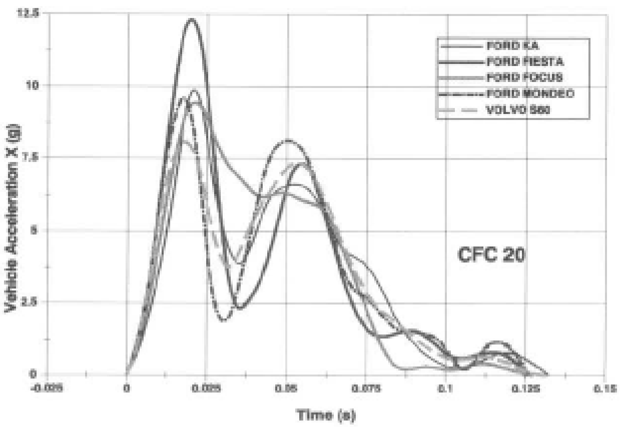

Figure 14: Acceleration pulses measured in five car-to-car crash tests (Avery 2001, from tests undertaken by Ford)

The bimodality of the crash pulse is more obvious here, possibly due to the more severe filtering that has been used. Crash pulses were also compared for VW Beetle-to-Beetle tests using the European-style Beetle bumper system with crush cans and the US Beetle bumper with hydraulic energy absorbers (see Figure 15) and for car-to-car and barrier-to-car tests using a Renault Laguna (see Figure 16. Both the nature of the bumper system and the nature of the impacting object made significant differences to the acceleration pulse of the struck vehicle. Interestingly, in the Laguna tests, the barrier test is bimodal and the car-to-car tests gives a unimodal response (in contrast to the expectation from Heitplatz *et al.*). Both of the VW Beetle and Renault Laguna data are reported in Linder *et al.* (2003), but with different filtering.

All of the car-to-car impacts were then used to generate a generic pulse, shown in Figure 19, which then simplified for ease of implementation on a HyGe sled; the signal, originally filtered at CFC 60 was filtered at CFC 18 and the trough forming the bimodal shape was removed.

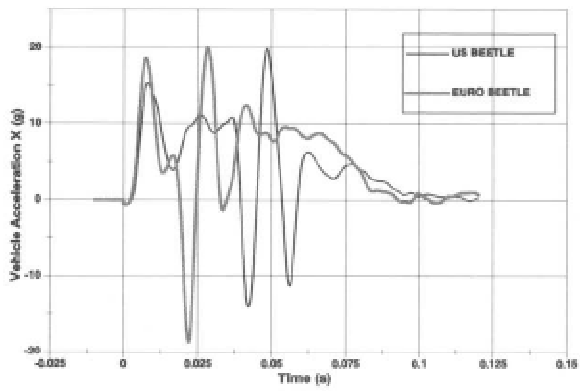

Figure 15: Acceleration pulses measured in two VW beetles fitted with European and US bumper systems (Avery, 2001)

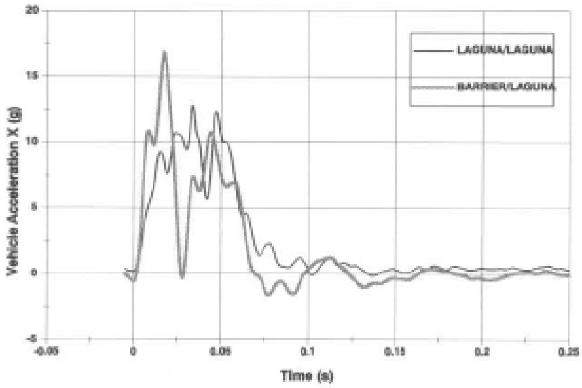

Figure 16: Acceleration pulses measured in two Renault Laguna impacts, on car-to-car, the other barrier-to-car (Avery, 2001)

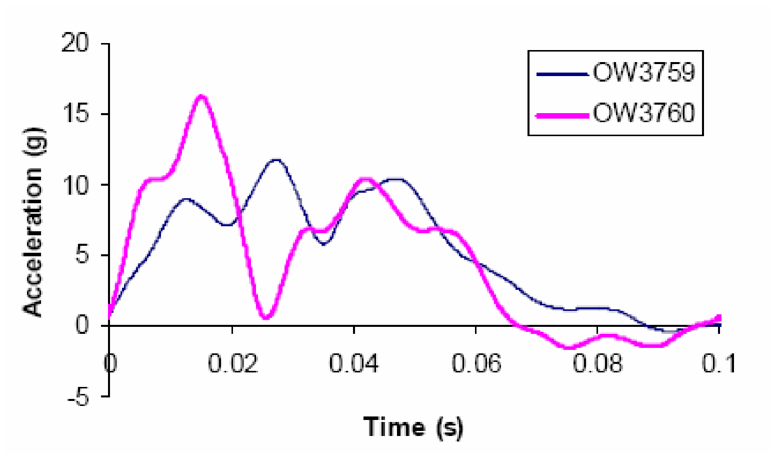

Figure 17: Pulses from the same make and model of vehicle impacted with a barrier and 100% overlap, Δ*v* = 17.2 km.h^{-1}, and the same make and model of vehicle at Δ*v* = 18.4 km.h^{-1} (Linder *et al.*, 2003)

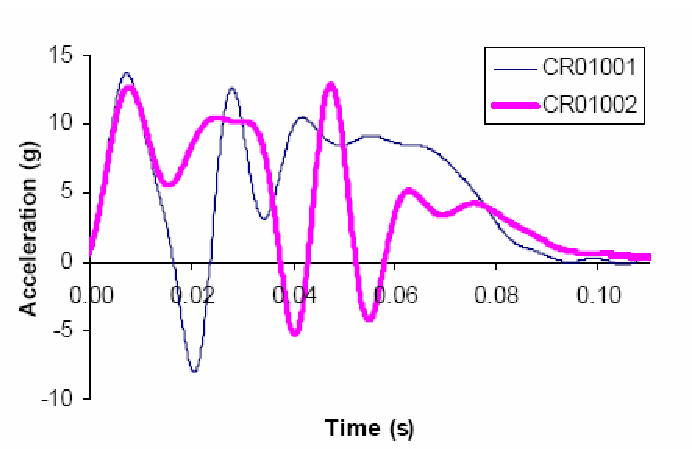

Figure 18: Car to car tests with the same make and model of vehicle for the USA and European markets at Δ*v* = 17.2 km.h^{-1} and 19.4 km.h^{-1} (Linder *et al.*, 2003)

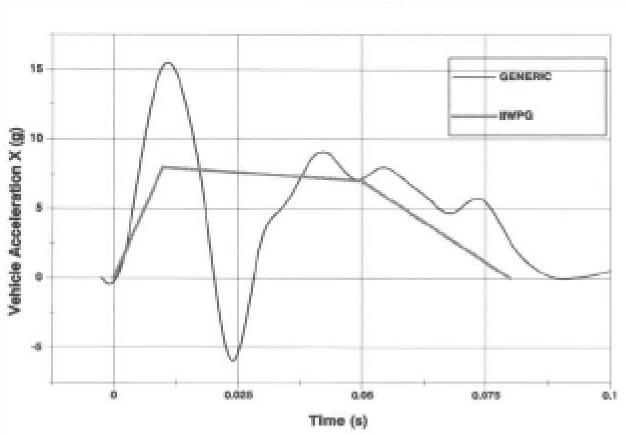

Figure 19: Generic pulse (CFC 60) and IIWPG lower pulse threshold (Avery 2001)

Zuby *et al.* (2003) give similar-looking results from far more tests (see Figure 19), that they reference to Heitplatz 2002, but which is not in the referenced paper. Zuby *et al.* note that 'many vehicle accelerations recorded in laboratory crash tests and real-world crashes have a high initial peak occurring relatively early followed by one or more smaller peaks, and rarely have a symmetric shape implied by the generalized trapezoidal pulse corridors as illustrated in Figure 4 (Heitplatz et al., 2002)'.

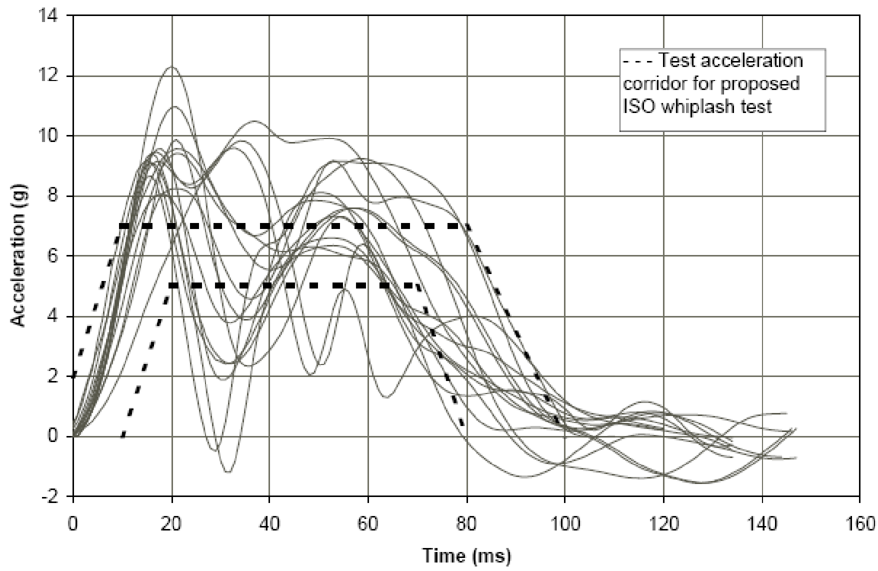

Figure 20: Typical accelerations from crash tests and a proposed trapezoidal, unimodal pulse corridor (Zuby *et al.*, 2003)

Krafft *et al*. (2000) analysed the effect of having a tow bar on injury risk. All reported rear impacts to Folksam during 1990–1993 were selected where the striking car was a Volvo 700, Volvo 240 or a Saab 900 (1979–1993). Two Volvo 240s, one with and one without a tow-bar were struck by a Volvo 240 to determine the effect of the tow-bar on the acceleration pulse of the struck vehicle. The striking cars were lowered 70–80 mm in the front to simulate pre-crash hard braking. An impact speed of 25 $km.h^{-1}$ was chosen which was expected to give a 15 $km.h^{-1}$ change of velocity of the struck car.

Krafft *et al.* found that the tow-bar increased the stiffness of the back of the car and caused a greater peak acceleration (see Figure 21), both pulses having a bimodal pulse shape. The greater peak pulse with a tow-bar corresponded to an increased risk of long-term (>1 year) symptoms by 22% in accident data set. The authors particularly noted the difference between short and long-term injuries (symptoms lasting longer than six months) in terms of the factors likely to affect the risk of these injuries. They suggested that peak acceleration could distinguish crashes causing short and long-term symptoms and that peak acceleration might be more directly related to the risk of sustaining long-term injury than Δ*v*. However, the authors were careful to note that at the time their analysis was conducted there was insufficient information available to be able to draw definite conclusions about the effect of crash pulse characteristics on injury risk.

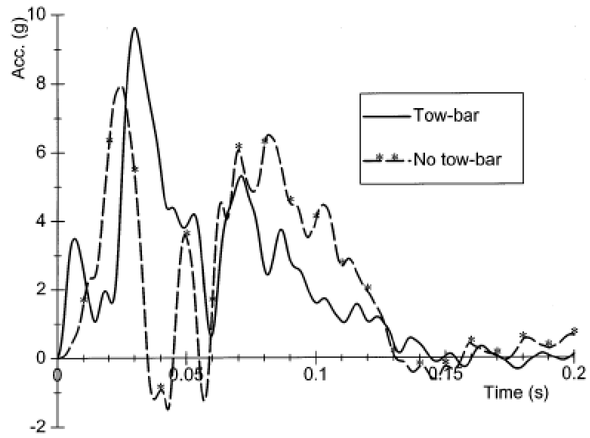

Fig. 1. Target car acceleration.

Figure 21: Mean acceleration pulses for different injury symptoms (Krafft *et al.*, 2002)

2.2.2 Pulses from Barrier-to-Car Laboratory Tests

Barrier-to-car rear impact tests are undertaken as part of insurance reparability tests. Linder *et al.* (2003) presented a series of pulses from barrier-to-car impacts, labelled OW and CR. The barrier used in the OW test had a weight of 1000 kg and the barrier used in the CR tests had a weight of 1800 kg. The vehicles were impacted at the rear with 100 % overlap. The mass of the cars used was from 1010 kg to 1966 kg. Figure 22 to Figure 26 show various pulses from this test series showing the wide range of pulse shapes from tests with a small range of vehicles and just two, well-controlled impacting objects.

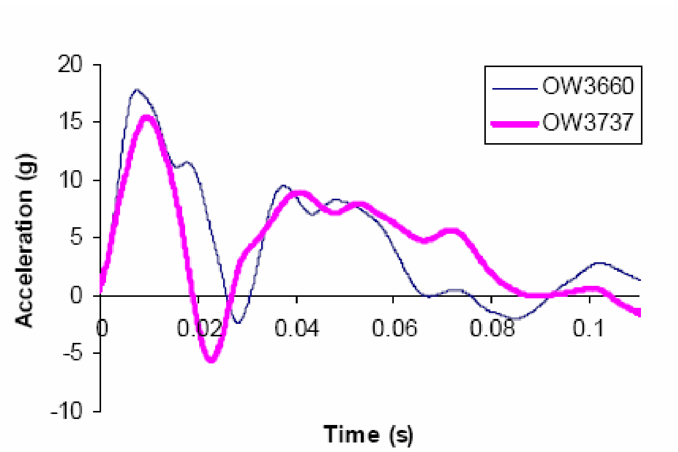

Figure 22: Pulses from two vehicles impacted with a barrier and 100% overlap,
Δ*v* = 17.2 km.h^{-1} (Linder *et al.*, 2003)

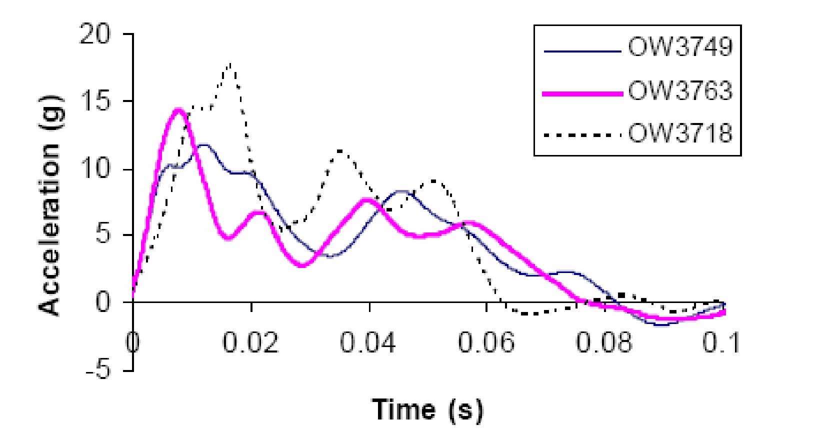

Figure 23: Pulses from three vehicles impacted with a barrier and 100% overlap, Δv = 17.2 km.h^{-1} up to Δv = 18.4 km.h^{-1} (Linder *et al.*, 2003)

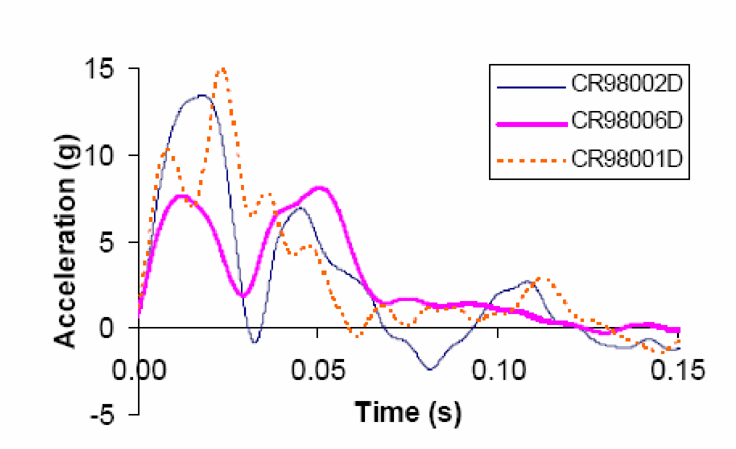

Figure 24: Pulses from three vehicles impacted with a barrier and 100% overlap, Δv = 14.4 km.h^{-1} up to Δv = 16.9 km.h^{-1} (same impact speed) (Linder *et al.*, 2003)

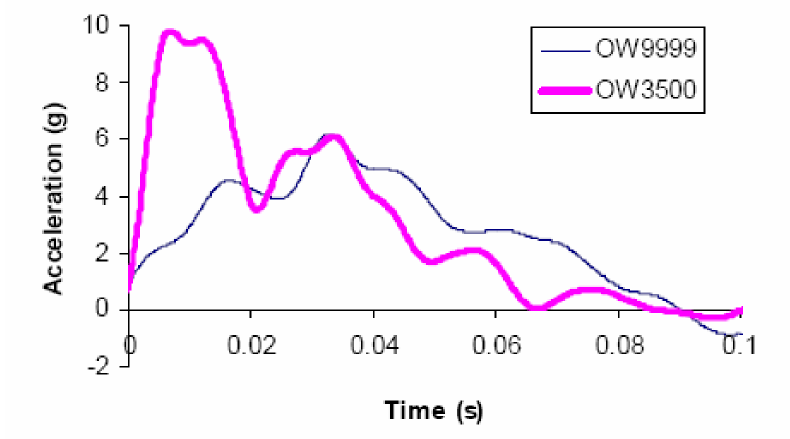

Figure 25: Pulses from two vehicles impacted with a barrier and 100% overlap, Δv = 10.2 km.h^{-1} to 11 km.h^{-1} (same impact speed) (Linder *et al.*, 2003)

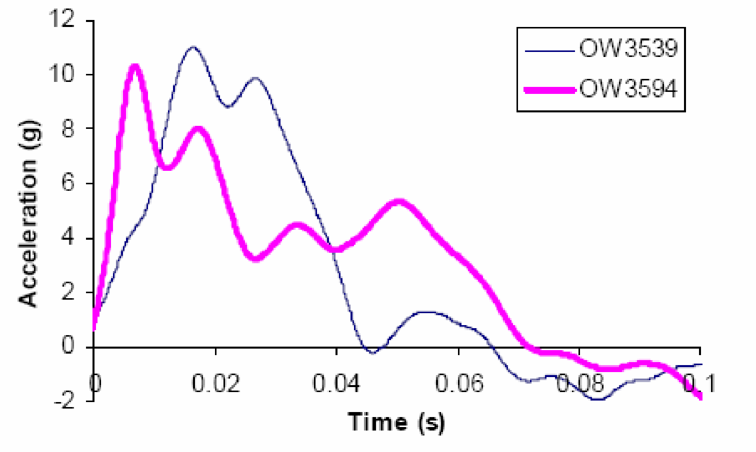

Figure 26: Pulses from two vehicles impacted with a barrier and 100% overlap, Δv = 13 km.h^{-1} to 13.3 km.h^{-1} (Linder *et al.*, 2003)

2.3 Accident Data from EEVC WG21

EEVC WG21 has recently conducted an analysis of a number of European accident databases, considering WAD injury risk with respect to a number of other parameters. Unfortunately, within each database only Δv is available as a measure of crash severity; peak and mean accelerations or actual crash pulse data are not included. Other injuries besides AIS1 neck injuries were considered in the analysis. For the GIDAS database; 35 km.h^{-1} (9.7 m.s^{-1}) corresponds to 100% of occupants sustaining only AIS1 neck injuries; 55 km.h^{-1} (15.3 m.s^{-1}) corresponds to 100% of occupants sustaining AIS1 neck injuries as well as at least one other injury. For the CCIS database; 30 km.h^{-1} (8.3 m.s^{-1}) corresponds to 90% of occupants sustaining AIS1 injuries only; 55 km.h^{-1} (15.3 m.s^{-1}) corresponds to 100% of occupants sustaining AIS1 neck injuries plus at least one other injury. (Figure 27). It should be noted that AIS1 neck injuries in this analysis may encompass more than just whiplash injuries and might also include cuts and bruises. It is likely that the CCIS data is biased towards higher Δv values due to the sampling technique used.

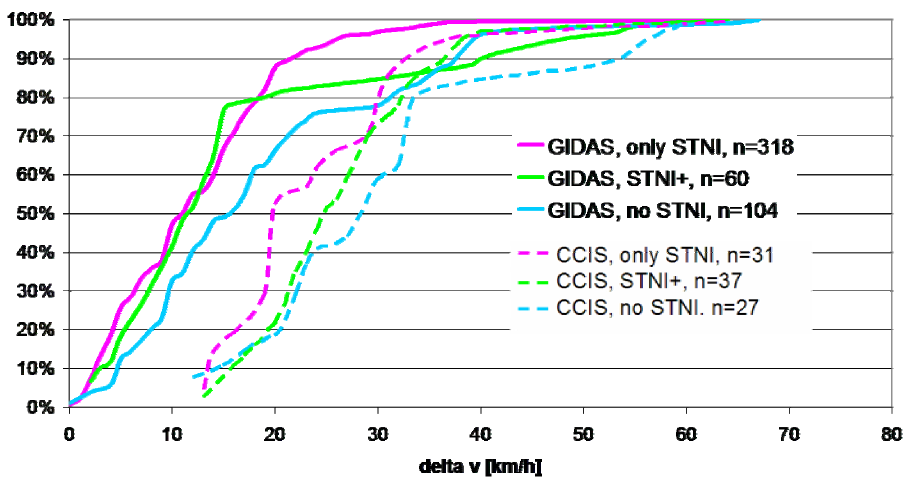

Figure 27: GIDAS and CCIS - Cars with single rear impact, cumulative Δv distribution by STNI (AIS1 Neck Injury) occurrence (taken from latest WG21 presentation)

2.4 Volunteer Testing

A number of authors have conducted volunteer tests using a low-speed rear impact scenario with a number of aims in mind, such as developing kinematic requirements for rear impact dummies or evaluating injury criteria. Not many of the papers available show the impact pulse used in detail and not all give any mention of whether all volunteers were completely exempt from any symptoms. However, many volunteer tests have now been undertaken and these can be used to give an indication of conditions which are generally non-injurious or which have very few cases of short-term symptoms (lasting less than two weeks) associated with them. Table 5 below documents the test conditions used, the number of volunteers tested and any associated symptoms of WAD following the testing.

As all of the volunteer test presented generated no injuries or (in a minority of cases) short-term symptoms, it is likely that pulse characteristics documented represent a level which is generally non-injurious and not likely to be of use in assessing seat designs for injury prevention. Figure 28 compares the Δv and mean accelerations used for volunteer testing from Table 5 with those of proposed crash pulses from the literature (Hell *et al.*, 1999; Langweider *et al.*, 2000; Langweider *et al.*, 2002; Avery, 2001; Zuby *et al.*, 2003; Cappon *et al.*, 2001; Heitplatz *et al.*, 2002; BS:ISO 17373:2005). Of the data in Table 5 for which both Δv and mean acceleration are given, the following are not included in Figure 28:

- Eichberger *et al.* (1998), as the head was already in contact with the head restraint at the start of the test;
- McConnell *et al.* (1995), as some subjects were withdrawn from further testing due to their symptoms (Δv = 10.9 km.h^{-1});
- Welcher and Szabo (2001), tests with a Volvo WHIPS seat.

Of those test series where both Δv and mean acceleration were not available (and which are therefore not shown in Figure 28), one series had volunteers with symptoms lasting more than seven days:

- Croft *et al.* (2002) - Δv 10.1 km.h^{-1}, one volunteer had symptoms lasting 10 days.

This volunteer data would suggest that, any pulse selected as being representative of injury causing conditions should have peak acceleration above 4g, mean acceleration above 3g and Δv above 11 km.h^{-1}. (Note that the volunteers are primarily young and with no pre-existing neck complaints; these pulse parameters may not indicate a low risk of injury for other groups of occupant.)

Figure 28 shows that, based on the volunteer data reviewed, some of the proposed pulse severities are likely to be too low to assess injury risk for a given seat model. However, they may be useful for ensuring that seat performance at low-severities is not compromised by efforts to improve protection at a high severity.

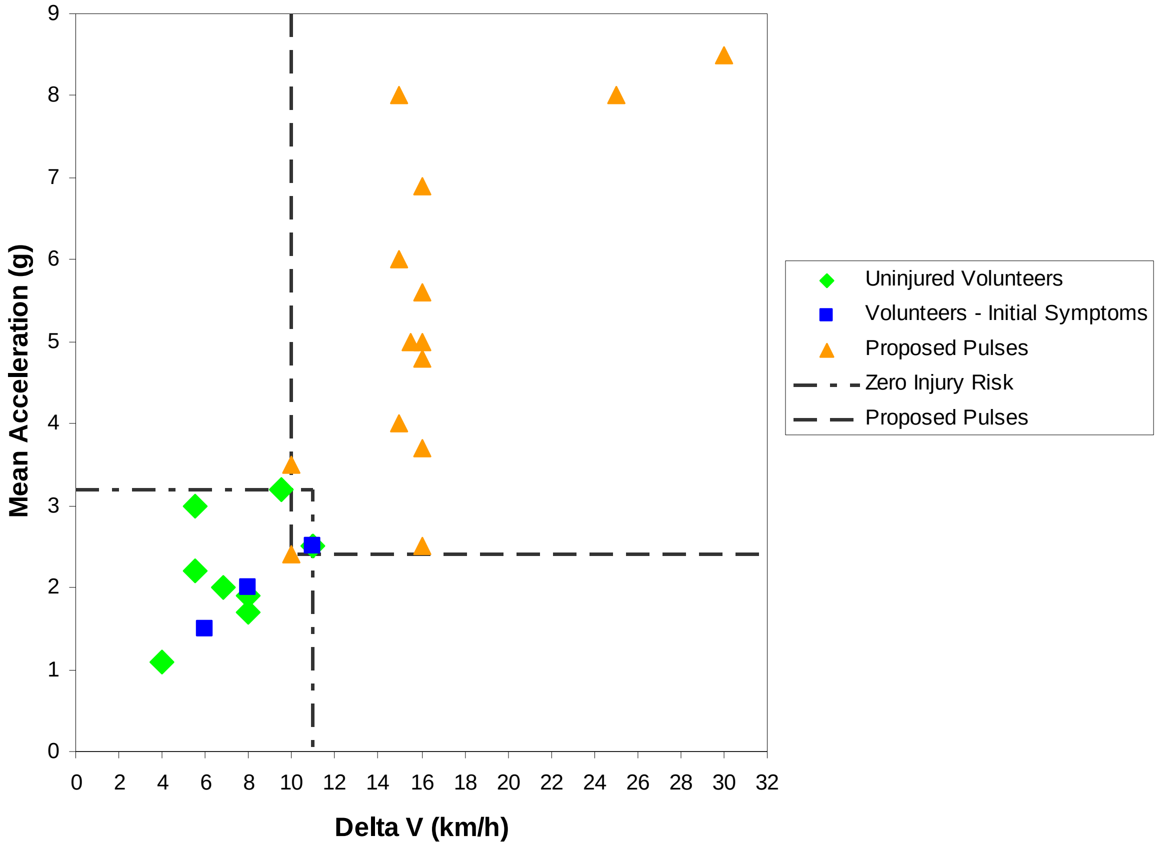

Figure 28: Comparison of volunteer data with proposed pulses

Table 5: Pulse characteristics and test conditions for a variety of low-speed rear impact volunteer tests

Publication	No. of Volunteers (mean age or age range)	Total number of tests	Δ*v* (km.h^{-1})	Peak Acceleration (g)	Mean Acceleration (g)	Test Conditions	Associated Symptoms
Croft *et al.* (2002)	1 male; 2 female (25-44 yo)	9	2.9 to 10.1	N/K	N/K	In vehicle simulated rear impact (9 tests) with suitable HR position.	1 volunteer had symptoms for 10 days.
Davidsson *et al.* (1999)	5 (av. 29 yo)	N/K	6.8	3.5	2 ‡	Head restraint and trapezoid pulse used.	No reported injuries.
Eichberger *et al.* (1996)	N/K	34	8 and 11	3.5	2.5	Subjects were tested in a variety of car seats using a trapezoid pulse. Efforts were made to minimise awareness of the impending impact	3 neck complaints for 24 hours. 1 cervical spine distortion symptom for 2 week. No longer-term injuries reported.
Eichberger *et al.* (1998)	12	36	5 to 5.5 (impact velocity)	4	2.5 to 3	Standard and prototype car seats. Large prototype head restraint in contact with head prior to pulse. Crash data recorder pulse used.	1 volunteer reported lumbar pain a few days after the test but this was thought to be due to an existing condition.
Geigl *et al.* (1995)	N/K (male and female 20-30 yo)	N/K	9 and 11	3	2.5	Standard car seats with head restraint, using a trapezoid pulse.	No reported injuries.
Kumar *et al.* (2000)	5 male; 9 female (24-30 yo)	N/K	N/K	0.5; 0.9; 1.1; 1.4	N/K	Laboratory seat mounted on an acceleration platform; no head restraint; subjects restrained with a 4-point harness. Some subjects aware of impending impact, others not.	None reported.
McConnell *et al.* (1995)	7 male (32-59 yo)	18	5.8 to 10.9	N/K	N/K	Modified-car to modified-car impact with standard seats. Head turned sideways in some tests.	Some discomfort leading to subjects being withdrawn from further tests.

Ono *et al*. (2006)	2 female; 4 male (23-25 yo)	6	6	4.3	1.5 ‡	Laboratory seat with no head restraint, mounted on a spring-powered sled system designed to slide backwards into a deceleration stop.	Three of the male subjects had initial symptoms which disappeared after two days or less.
Ono and Kaneoka (1997)	10 male (av. 23 yo)	13	2, 4 and 6	N/K	N/K	Standard and rigid seats, all without head restraint	No symptoms by 1 year follow-up.
Ono *et al*. (1997)	12 male (av. 24 yo)	17	4, 6 and 8	4	2	Standard and rigid seats, all without head restraint. All pulses were roughly triangular.	One subject experienced neck discomfort for a few days after the test.
Shen *et al*. (1998)	12 male and female	84	4.8 to 5.5 (impact velocity)	3	2.5 ‡	Modified driver's seat.	No reported injuries.
Siegmund *et al.* (1997)	21 female; 21 male (20-40 yo)	N/K	4 and 8	N/K	0.8 and 1.7	The subjects were seated in a target vehicle with an appropriately positioned head restraint (backset < 10 cm) and subjected to a low-speed rear impact from another vehicle. The impact pulse was not presented.	None recorded.
Tencer *et al.* (2001)	14 female; 12 male (22-64 yo)	N/K	4	3	N/K	The tests used a standard car seat with standard and modified head restraints.	None reported.
Tencer *et al.* (2004)	14 female; 12 male	N/K	4	2.5	1.1	Standard Car Seat (mid-range stiffness), mounted on a sled; subjects restrained with a 3-point belt.	None reported.
Welcher and Szabo (2001)	1 female; 2 male (21-32 yo)	30	4 and 8	1.5 and 4	0.7 and 1.9 ‡	The subjects were tested in one or more of 5 different seat types mounted in a target vehicle (1987 Plymouth Voyager), impacted by a bullet vehicle (1991 Ford Explorer). The subjects were kept unaware of the impending impact as far as possible.	"No significant Injuries".
	1 male	2	11 and 14	15	4.7 ‡	One subject was tested using a much more severe pulse and the Volvo WHIPS seat. The pulse used was a dual peak pulse, duration 80 ms.	None.

Van den Kroonenburg *et al.* (1998)	19 (17-51 yo)	43	6.5 to 9.5	3.5 to 4.5	2.3 to 3.2 ‡	43 tests were conducted with the 19 subjects. Trapezoid pulses of varying severity were used.	No reported injuries.
Wheeler *et al.* (1998)	21 male and 21 female (av. 26.8 yo)	84	4 and 8	N/K	N/K	Subjects seated in front passenger seat of 1990 Honda Accord and struck by 1983 Volvo 240.	29 % (Δv = 4 $km.h^{-1}$) and 38% (Δv = 8 $km.h^{-1}$) reported minor, short term symptoms. No long-term symptoms reported.

‡ **Mean acceleration not reported in the reference, but calculated from Δv and impact duration**

2.5 Dummy Sensitivity to Crash Pulse Characteristics

Avery *et al.* (2001) present the results of HyGe sled tests to investigate the effect of different pulse shapes on BioRID II dummy responses. The first test featured a bimodal pulse with a Δv of 16 $km.h^{-1}$, with and initial peak acceleration of 7.8 g and a second peak of 5.8 g. The second test then reversed these peak acceleration parameters, as shown in Figure 29. Avery *et al.* noted that the bimodal shape of the acceleration pulse was unclear, but that the high-low signal always gave a higher NIC and neck moment than the low-high signal. Avery *et al.* also compared the performance of the BioRID II in a generic pulse and the pulse proposed at that time by the IIWPG (see Section 2.2.1 and Figure 30) with a similar Δv (18.2 $km.h^{-1}$ and 15.8 $km.h^{-1}$ respectively). The IIWPG pulse always gave a lower injury response than the generic pulse from which it was derived. It was reported that 'when considering the NIC and neck extension moment the initial onset of acceleration and its corresponding peak may have a larger influence on dummy response than other characteristics'.

It should be noted that the performance of the current version of the BioRID II dummy, or of the RID^{3D} dummy, may be different to that reported in Avery *et al.*

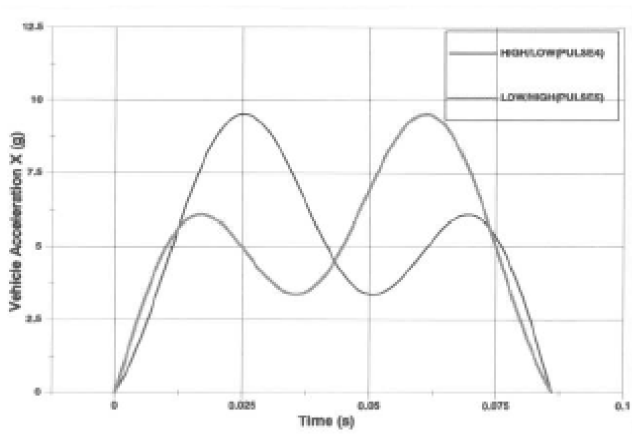

Figure 29: High-low and low-high bimodal pulses (Avery 2001)

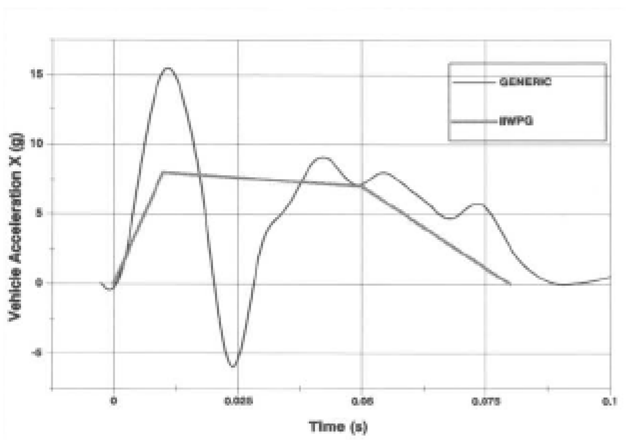

Figure 30: Generic pulse (CFC 60) and IIWPG lower pulse threshold (Avery 2001)

Siegmund *et al.* (2005) conducted a series of sled based tests in a standard seat, using a variety of "standard" pulses (i.e. square, triangular, trapezoidal, sine wave) with varying Δv, mean and peak acceleration. The objective was to assess the effects of different crash pulse parameters on injury criteria as calculated based on readings from the BioRID II. A total of 15 pulses were used, grouped together such that pulses with the same associated speed change and peak acceleration but different shape could be compared, for example. Within each group of collision pulses a one way analysis of variance was also conducted. The injury criteria compared were Upper Neck shear force (F_x) and bending moment (M_y); peak OC retraction (R_x) and peak rearward extension (θ_{rel}) relative to T1; NIC; N_{ij}; and N_{km} and all except θ_{rel} exhibited a similarly graded response across the 15 pulses. θ_{rel} also had the highest coefficient of variation across tests conducted with the same pulse. Certain parameters had a greater effect on the injury criteria values than others; increases in either mean or peak acceleration produced increases in all six criteria. When the triangular pulses (Figure 31) were considered on their own, the isosceles pulse generated higher injury criteria values. N_{ij} and N_{km} showed the greatest sensitivity to changes in pulse characteristics. The authors also assessed the correlation of NIC values with Δv and found that there was good correlation of NIC with speed changes up to 85ms after the impact.

This paper was particularly useful in illustrating the level of sensitivity the BioRID II had to different crash pulses and the effect they had on particular injury criteria. The implication is that mean and peak acceleration are the parameters most likely to affect injury criteria and that the BioRID II is sensitive to these parameters and also to the detailed shape of the pulse itself. This requires some further investigation. (There was a weak correlation between peak acceleration and NIC and Nij and a weak correlation of Δv with Nkm – Table 6, Figure 32 to Figure 34: Nkm vs Δv (Siegmund *et al.*, 2005)).

Seat Model	**Pulse**	**Δv ($m.s^{-1}$)**	**Δt (ms)**	**Peak Acceleration (g)**	**Mean Acceleration (g)**	**NIC ($m^2.s^{-2}$)**	**Nij**	**Nkm**
H	A (square)	2.2	136	1.7	1.7	6.82	0.06	0.133
H	B (sine)	2.2	136	2.6	1.64	9.57	0.083	0.172
H	C (Tri-Iso)	2.2	136	3.3	1.65	10.1	0.087	0.182
H	D (Tri-Des)	2.2	136	3.3	1.65	9.41	0.079	0.171
H	E (Tri-Asc)	2.2	136	3.3	1.65	8.39	0.075	0.155
H	F (square)	2.2	52	4.4	4.4	13.15	0.119	0.244
H	G (square)	2.2	76	3	3	12.05	0.105	0.216
H	H (square)	2.2	100	2.3	2.3	9.14	0.084	0.176
H	I (square)	2.2	180	1.3	1.3	4.98	0.043	0.119
H	J (square)	0.9	52	1.7	1.7	4.68	0.043	0.147
H	K (square)	1.2	76	1.7	1.7	6.15	0.037	0.121
H	L (square)	1.6	100	1.7	1.7	7.08	0.052	0.14
H	M (square)	2.9	180	1.7	1.7	6.66	0.06	0.131
H	N (Tri-Des)	1.9	118	3.3	1.65	8.83	0.068	0.163
H	O (Tri-Asc)	2.7	166	3.3	1.65	7.28	0.076	0.139

Table 6: Peak values of injury criteria (Siegmund *et al.*, 2005)

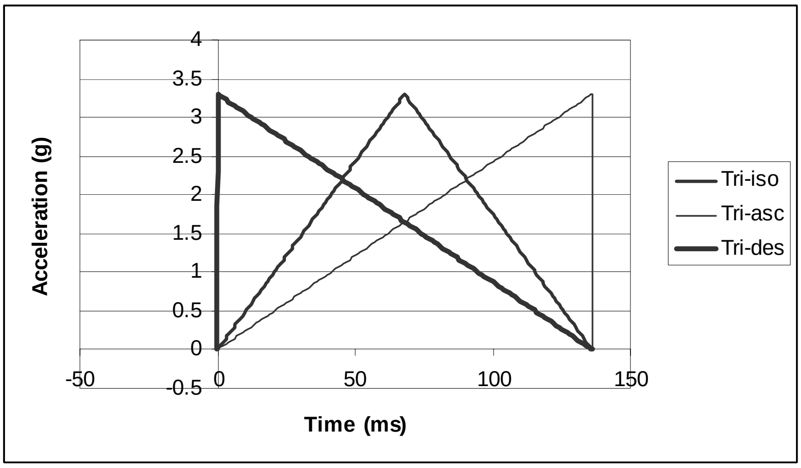

Figure 31: Triangular pulses used by Siegmund *et al.* (2005)

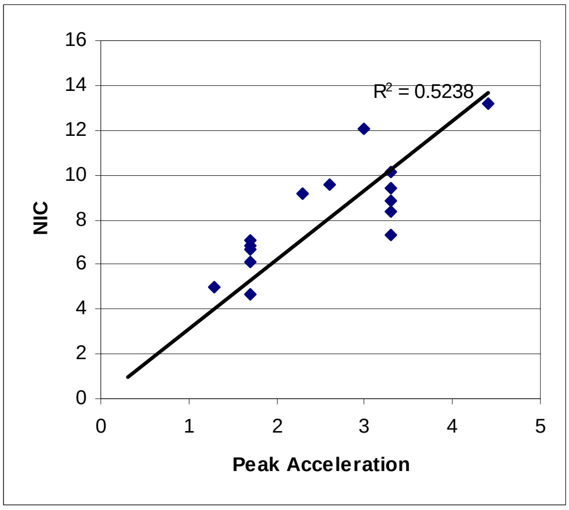

Figure 32: NIC vs peak acceleration (Siegmund *et al.*, 2005)

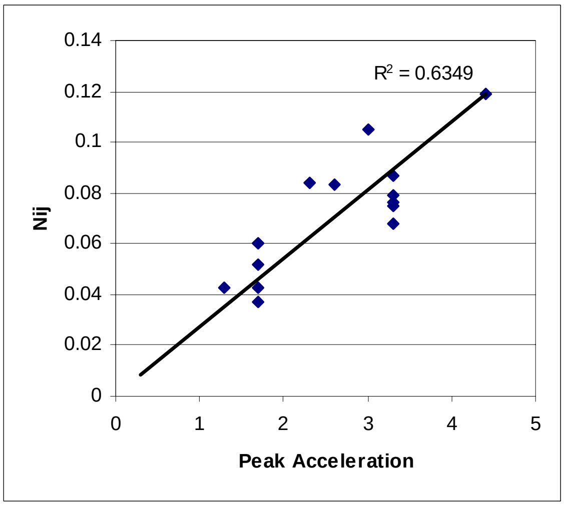

Figure 33: N_{ij} vs peak acceleration (Siegmund *et al.*, 2005)

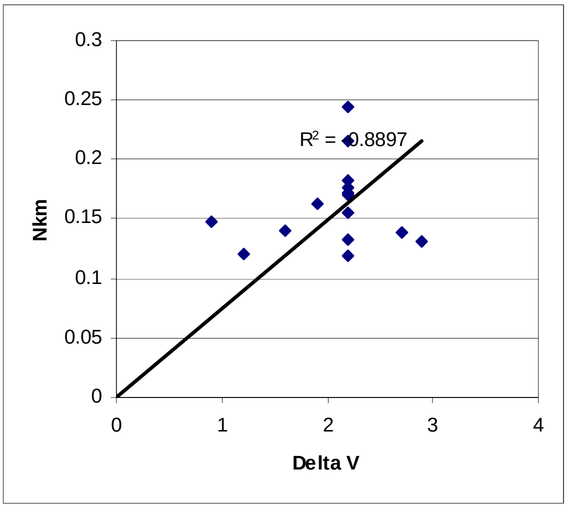

Figure 34: Nkm vs Δ*v* (Siegmund *et al.*, 2005)

Zuby and Avery (2002) conducted 21 sled tests with three different car seats and seven different crash pulses, using the BioRID II with the aim of assessing its sensitivity to the different pulse characteristics and seat geometries used. Three half-sine pulses were used, two simplified bimodal pulses, the proposed IIWPG trapezoid pulse and a "generic" crash pulse with various oscillations. Although the pulses themselves were presented in detail, such that Δv, peak and mean accelerations could be calculated, the results were only given in terms of the maximum values of certain injury criteria. A variety of injury criteria were calculated and compared across all tests. The maximum injury criteria values varied considerably and combinations of changes in seat geometry and crash pulse appeared to have a much greater effect than either change in isolation. (There is little or no correlation between pulse characteristics and either NIC, Nij or Nkm for these tests – Table 7). The authors found that none of the injury measures consistently ranked all the seats in the same order for all pulses and suggested that this was because the seats were quite close together in performance. It should also be noted that the pulses used did not represent a wide range of severities or shapes, as the bimodal pulses had secondary peaks that were approximately 70% of the maximum peak and troughs that were approximately 35% of the peak – hence these pulses were close to triangular in shape.

Zuby *et al.* (2003) tested the BioRID II with three similar pulses of varying shape but with the same mean and peak acceleration and Δv. The objective was to compare the effect of pulse shape alone on BioRID II response and hence the injury criteria calculated from it. The pulses consisted of a similar pulse to the high-low pulse used in the previous study by the same authors and two triangular pulses. As was noted above, the pulses did not vary widely in shape, and greater differences in shape could have been achieved whilst still maintaining the same peak and mean acceleration and Δv. The authors found that the dummy's head consistently contacted the head restraint later in the tests using the "late peak" pulse but that the peak values of various parameters measured were also significantly lower for this pulse. The "late peak" pulse also produced greater retraction in the dummy but this has not been investigated further. The authors analysed the seat rankings obtained based on different injury criteria and pulse shape and found that pulse shape only affected the ranking order of the seats, using NIC, when the head restraint was positioned in its "full-down" position. As this is not the position for optimum protection it is likely that these types of difference in pulse shape alone would not affect seat rankings. However, the objective of a regulatory test programme is not merely to rank cars or car seats for safety but to ascertain that a minimum level of protection will be provided to the occupant, regardless of how the seat performs against its competitors. At this stage, injury criteria have not been selected for the regulation and injury risk functions for particular dummies have not been verified. Hence any effect of crash pulse characteristics on any injury criterion should be noted until that criterion has been ruled out as usable in a regulatory procedure.

Table 7: Peak values of injury criteria (Zuby and Avery, 2002)

Seat Model	Pulse	Δv	Δt	Peak Acceleration	Mean Acceleration	Summary of Injury Measures							
									NDC Parameters				
						NIC	Nij	Nkm	Maximum Flexion Angle	Maximum Rearward Displacement of OC	Maximum Vertical Displacement of OC	Head to HR Contact Time	Seatback Deflection Angle
B	Baseline (half-sine)	4.4	70	9.5	6	22	0.13	0.45	17	2	6	83	14
B	High DV (half-sine)	5.6	105	9.5	6	18	0.15	0.51	18	12	9	84	17
B	Low g (half-sine)	4.4	90	7	4.5	13	0.1	0.39	9	6	6	85	11
B	High-Low Bimodal	4.4	85	9.5	5	16	0.12	0.45	13	10	4	84	15
B	Low-High Bimodal	4.4	90	9.5	5	12	0.11	0.43	12	13	3	78	15
B	IIWPG	4.4	80	8	6	17	0.11	0.39	8	5	4	77	19
B	Generic	5.7	80	14	7.5	19	0.1	0.5	8	12	7	78	18
C	Baseline (half-sine)	4.4	70	9.5	6	23	0.19	0.59	13	0	8	90	11
C	High DV (half-sine)	5.6	105	9.5	6	21	0.21	0.68	11	0	8	95	14
C	Low g (half-sine)	4.4	90	7	4.5	17	0.16	0.47	17	0	10	95	12
C	High-Low Bimodal	4.4	85	9.5	5	19	0.18	0.69	12	0	8	92	12
C	Low-High Bimodal	4.4	90	9.5	5	15	0.17	0.51	18	0	7	91	13
C	IIWPG	4.4	80	8	6	18	0.26	0.61	8.3	0	7	89	16
C	Generic	5.7	80	14	7.5	26	0.29	0.77	11.6	0	9	94	18

D	Baseline (half-sine)	4.4	70	9.5	6	19	0.17	0.59	17	13	6	99	17
D	High DV (half-sine)	5.6	105	9.5	6	17	0.21	0.61	15	10	5	104	25
D	Low g (half-sine)	4.4	90	7	4.5	15	0.16	0.61	14	11	5	104	14
D	High-Low Bimodal	4.4	85	9.5	5	14	0.16	0.56	18	11	4	95	14
D	Low-High Bimodal	4.4	90	9.5	5	17	0.17	0.62	12	15	4	110	17
D	IIWPG	4.4	80	8	6	18	0.18	0.58	16	13	5	94	21
D	Generic	5.7	80	14	7.5	16	0.25	0.64	13	14	6	105	25

3 Discussion

3.1 Suggested pulse shape and severity from real-world data

3.1.1 Pulse Shape

It is apparent from the data reviewed in Section 2.1.1 that a large variety of crash pulses for a specific Δ*v* will be produced in the same car model (e.g. Linder *et al.*, 2003). The data in Section 2.2.1 shows that well controlled laboratory car-to-car tests produce a similarly wide range of crash pulses (e.g. Linder *et al.*, 2003; Heitplatz *et al.*, 2002). Some impacts give biomodal, or multimodal, pulses, whilst others give a generally triangular response, with a steep leading edge and a more gradual drop-off in acceleration. Many other pulse shapes are also presented, but trapezoidal pulses of the form selected for some sled test programmes are not often reported in the literature Results from insurance industry barrier-to-car tests show a similar degree of variability. However, the data are available for only a limited range of vehicles, for instance the Folksam insurance crash pulse recorder database with a limited range of Toyota car models (with a wide range of striking vehicles) and car-to-car laboratory tests with Ford-group cars. It is apparent from this review that real-world pulses will depend on parameters such as:

- The mass ratio, stiffness and structure of the crash partners;
- The degree of overlap;
- The level of engagement of the two bumper systems;
- The type of bumper energy absorber fitted, and
- The presence of a tow-bar on the struck vehicle

The number of factors involved and their variability suggest that the total variability of real-world low-speed rear impact pulses would be greater than shown in the data reviewed here. This large range of pulse shapes, together with the difficulty of reproducing complex, multimodal pulse shapes in the laboratory, may be why simple trapezoidal or triangular pulses have been proposed by most groups. However, it is not understood whether the detailed shape of a pulse is correlated to the risk of injury, or whether only the general characteristics of the pulse (such as Δ*v*, mean acceleration and peak acceleration) are important. A much larger real-world crash pulse recorder database than currently available would be required to determine a definite link between injury risk and specific pulse features.

Given that the information reviewed in this study is not sufficient to recommend one specific pulse shape as correlating with injury, another approach to determining which pulse shape to use for low-speed rear impact seat testing is required. If the information in Heitplatz *et al.* (2002) is correct, many crash pulses would be expected to have a bimodal shape, with a steep rise and large first peak, followed by a smaller second peak and more gradual drop-off in acceleration. The crash pulse recorder data from Folksam (e.g. Linder *et al.*, 2003) indicates that a triangular pulse with a steeper initial rise in acceleration and more gradual drop-off is prevalent (although only a very small sample of the crash pulse recorder pulses are presented in the literature). One approach would be to evaluate both pulse shapes at a chosen Δ*v* and mean acceleration with the recommended rear impact dummy and injury or seat performance criteria. If one pulse shape consistently classifies seats as having a lower performance, this pulse should be used as the use of the less severe pulse may cause the benefit arising from the introduction of the test procedure to be underestimated. If both pulses give similar classifications, or if the classification is inconsistent, consideration could be given to selecting the pulse shape that is easiest to implement on typical laboratory sled test equipment, which is likely to be a unimodal pulse shape.

The wide range of vehicle crash pulses observed in car-to-car rear impacts may indicate that the design of the seat would have the largest potential to reduce the risk of whiplash-type neck injury. However, it may also indicate that better standardisation of the pulse, through improved compatibility of the front and rear structures of cars, could contribute to controlling the whiplash injury problem.

3.1.2 Pulse Characteristics

Given that the information reviewed does not allow a particular pulse shape, or the characteristics of particular pulse shapes, to be definitively correlated with injury (or claim of injury), most studies have evaluated the correlation between injury or claim rates and pulse characteristics such as Δv, mean acceleration and peak acceleration. These parameters may be calculated directly from crash pulse recorder data, which should provide the most accurate data available. Alternatively, the Δv and mean acceleration can be estimated from accident investigation data such as vehicle intrusion measurements or photographs of the damage to the vehicles (this latter will be the least accurate method), although the accuracy of such estimates for low-speed rear impact is not clear. In particular, the computer programmes used to calculate Δv from damage profiles (either measured or estimated from photographs) are not suitable for under-run (or, presumably, over-run) impacts and should not be used for these cases (Lenard *et al.*, 1998). Many of the laboratory crash tests reviewed feature either under-run or over-run and it is not clear that such cases have been excluded from accident investigation estimates of low-speed rear impact crash pulse characteristics. However, the results from these accident investigation studies may lend support to the findings from pulse characteristics determined from crash pulse recorder data.

The most recent of the studies using the Folksam crash pulse recorder data, and therefore with the largest dataset and most reliable results, shows a correlation between crash severity and duration of symptoms (Krafft *et al.*, 2005). This study showed a correlation between injury risk and both Δv and mean acceleration: The risk of symptoms lasting more than one month was 20% at a Δv of 18 km.h^{-1}, and a mean acceleration greater than 5g. This is supported, within the limitations discussed above, by the information in the accident investigation papers reviewed. For example, Langwieder and Hell (2002) reported that the majority of whiplash injuries in their database occurred with a Δv below 15 km.h^{-1}, but that when potentially fraudulent low-speed cases were removed the 15-25 km.h^{-1} group was the largest.

A Δv of 16 km.h^{-1}, as proposed for a number of test procedures in existence or under development, therefore seems to be reasonable, although any Δv between 15 and 20 km.h^{-1} could be equally well supported and the Folksam data suggests that a pulse at the high end of that range would be closer to a significant increase in the risk of longer term injuries (greater than one month). The data in Krafft *et al.* (2005) using the Quebec Task Force WAD classification scale (Spitzer *et al.*, 1999) indicates that a Δv in the 20 to 25 km.h^{-1} range may be more appropriate for more severe whiplash injuries. If longer-term whiplash injuries are to be targeted by a test procedure, it would seem from the information reviewed that a Δv of 20 km.h^{-1} with a mean acceleration of 5-6 g would be the most reasonable pulse characteristic. The UK static-geometric cost-benefit study [WG20 document number WD167] indicates that long-term whiplash injuries (from both rear and front impact) cost the UK economy approximately £3 billion pounds per annum, based on the Department for Transport 'Willingness to Pay' costing method.

This would be well outside the range of pulse characteristics for volunteer tests where no injury or only minor, short-term injury occurred, but would be more severe than most of the test procedures currently proposed (see Figure 28). (It should be noted that the pulse shape in the volunteer tests may not be representative of a vehicle pulse and volunteer sample is unlikely to be representative of the vehicle front seat occupant population - the volunteers were typically younger, often male, of average height, and with no previous history of neck problems.) In addition to the pulse described above, a lower severity pulse may be useful to ensure that the low risk of injury at a lower pulse is not compromised by efforts to meet a more severe pulse test.

3.1.3 Corridor Definition

The sections above define a typical pulse shape and characteristics:

- Δv of 20 km.h^{-1} with a mean acceleration of 5-6 g, either
  - Bimodal, with a steep rise and large first peak, followed by a smaller second peak and more gradual drop-off in acceleration, or
  - A triangular pulse with a steeper initial rise in acceleration and more gradual drop-off in acceleration

This defines an ideal pulse, but for the pulse to be implemented in a laboratory test procedure, acceptable limits must be defined within which the pulse must be reproduced. This is usually achieved by defining a corridor either side of the ideal pulse. Two conflicting considerations are of primary importance in defining such a corridor:

- Achievability of pulse - for a test procedure to be cost effective, the corridor should be wide enough that it is possible to achieve the pulse within the specified tolerance corridor at a number of different laboratories, preferably using different types of sled equipment (e.g. deceleration sled and acceleration (or HyGe) sled)
- Reproducibility of test results - the corridor should be narrow enough that no pulses that lie within the corridor lead to significantly different assessment of seat performance than any other pulse that lies within the corridor

There is little information in the open literature regarding the achievability and reproducibility of pulses for low-speed rear impact testing. However, this is currently being evaluated for consumer seat testing and the results, when available, should be used to define the corridor for the pulse recommended in this report. It should be noted that the recommended pulse is at a higher severity than is being investigated for consumer testing. It is therefore recommended that the achievability and reproducibility of the pulse is confirmed through additional testing before being implemented in the WG20 test procedure.

3.2 Dummy Sensitivity

Evidence documented from publications available to-date suggests that BioRID II is sensitive to both pulse shape and severity, but that there is no linear relationship between a particular injury criterion and one pulse characteristic (e.g. Δv or peak acceleration). It is not clear whether this is the case for the current version of the BioRID II dummy or for the RID^{3D} rear impact dummy. More information is needed for any injury criterion correlated to actual injury risk as selected by EEVC WG12 as to whether it is affected by the shape of the pulse and whether the pulse characteristics known to affect injury risk produce a suitable range of values in the selected criterion to be able to assess seat design for injury prevention.

3.3 The Need for Other Pulses

Section 3.1 makes a recommendation for a pulse that would be suitable for targeting long-term injuries arising from low-speed rear impacts. The delta-v of the pulse is roughly in the middle of the range reported for long-term whiplash injuries and should therefore be best able to cover the range of interest. Currently, the majority of rear impacts occur below the 16 to 25 km.hr^{-1} Δv range and the majority of these lower-severity impacts result in short-term symptoms. In addition to the 20 km.hr^{-1} pulse described above, it is therefore recommended that a low-speed pulse is used to ensure that the current good performance of seats in low-Δv impacts is maintained. In particular, this would ensure that seat back stiffness, reactive head restraint actuation and active head restraint triggering are not optimised for a high severity pulse alone. WG20 has not investigated this in detail to date, but approximately 10 $km.hr^{-1}$ seems to be indicated.

If a single pulse is to be used, some members of the WG recommended that a mid-severity pulse be used, such as the a 16 $km.hr^{-1}$ pulse, so that the assessment of seats isn't biased too strongly to either end of the severity range. A single pulse would, however, carry the risks of not maintaining current good performance at the frequently occurring, low-severity impact range, nor providing adequate incentive to provide good protection across most of the long-term injury severity impact range.

4 Conclusions

- Pulses in low-speed car-to-car rear impacts are very variable and depend on (amongst others):
    - The mass ratio, stiffness and structure of the crash partners;
    - The degree of overlap;
    - The level of engagement of the two bumper systems (over-ride, under-ride, bumper-to-bumper engagement);
    - The type of bumper energy absorber fitted (e.g. crush tubes or hydraulic energy absorbers), and
    - The presence of a tow-bar on the struck vehicle

- There are a number of limitations of the accident data with crash pulse data available to-date:
    - Crash pulse data is only available for a limited number of car models from one manufacturer;
    - The position of the head restraint for each injured and uninjured occupant is not known for certain;
    - Physical injury and the resulting symptoms may be exacerbated by psychological factors. In some cases, symptoms may be entirely psychological.

- It is currently not possible to correlate detailed pulse shape, such as the number of peaks and shape of the pulse, with injury risk at present and this would require a great deal more data to achieve. In the absence of this link, it is recommended that any pulse used should be representative of real-world impacts in which injury (or symptoms) occurs.

- From the evidence reviewed, there is no one typical pulse shape for a low-speed rear impact. However, the following two pulse shapes seemed to be the most supportable:
    - A bimodal shape, with a steep rise and large first peak, followed by a smaller second peak and more gradual drop-off in acceleration;
    - A triangular shape, with a steeper initial rise in acceleration and more gradual drop-off in acceleration.

- From the evidence reviewed, the trapezoidal pulse proposed for a number of rear impact test programmes does not appear to be representative of real-world pulses.

- Increasing Δv and increasing mean acceleration have both been found to correlate with an increased risk of reported symptoms.

- If longer-term whiplash injuries are to be targeted by a test procedure, it would seem from the information reviewed that a Δv of 20 $km.h^{-1}$ would be the most reasonable pulse characteristic, with a mean acceleration of 5-6 g.
    - 20 $km.hr^{-1}$ is approximately the mean Δv indicated in the literature for long-term injuries, with a typical range of 16 to 25 $km.hr^{-1}$.

- Long-term injuries cost approximately £3 billion pounds annually in the UK alone, using the UK Department for Transport 'Willingness to Pay' costing method [WG20 document number WD167].

- It should be confirmed that any dummy chosen for rear impact testing is robust, repeatable and reproducible at the above pulse.

- In addition to the pulse described above, a lower severity pulse is recommended to ensure that the current low risk of injury at the more frequent lower-severity pulses is not compromised by efforts to meet a more severe pulse test.
  - This would ensure that seat back stiffness, reactive head restraint actuation and active head restraint triggering are not optimised for a high severity pulse alone.
  - WG20 has not investigated this in detail to date, but approximately 10 $km.hr^{-1}$ seems to be indicated.
  - If a single pulse is to be used, some members of the WG recommended that a mid-severity pulse be used, such as the a 16 $km.hr^{-1}$ pulse, so that the assessment of seats isn't biased too strongly to either end of the severity range. A single pulse would, however, carry the risks of not maintaining current good performance at the frequently occurring, low-severity impact range, nor providing adequate incentive to provide good protection across most of the long-term injury severity impact range.

- The BioRID II dummy is sensitive to changes in the Δv, peak and mean acceleration of a given crash pulse. It appears to be affected by the shape of the pulse, in terms of the timing of the peak or peaks as well. Various injury criteria, including NIC and Nkm, are also affected by the timing of peak acceleration, Δv and mean acceleration values when calculated using readings taken with the BioRID II. This should be verified for the latest version of the low-speed rear impact dummy that is recommended by EEVC WG12.

- There has been a great deal of volunteer testing conducted during the last 10-15 years and most of these tests suggest with a Δv below 11 $km.h^{-1}$, a mean acceleration of 3g and a peak acceleration of 4g will have a low risk of short-term whiplash symptoms and a very low risk of longer-term symptoms (greater than 1 month).
  - The volunteers used are primarily young and with no pre-existing neck complaints; these pulse parameters may not indicate a low risk of injury for other groups of occupant.

5 Recommendations

- Real-world low-speed rear impact pulses are very variable and the available data is limited. It is currently not possible to correlate detailed pulse shape with injury risk, and the evidence for a link between pulse characteristics (such as Δv and mean or peak acceleration) and injury (or claims) is weak. However, within these limitations it is recommended that the following pulse is used to target longer-term whiplash injuries:
  - Δv of 20 km.h^{-1}, with mean acceleration of 5-6 g, either
    - Bimodal, with a steep rise and large first peak, followed by a smaller second peak and more gradual drop-off in acceleration, or
    - Triangular, with a steeper initial rise in acceleration and more gradual drop-off in acceleration.

- As this pulse is more severe than those currently used in consumer testing, it is recommended that testing is undertaken to confirm that the dummy chosen for rear impact testing with this pulse is robust, repeatable and reproducible at this higher pulse severity.

- In addition to the pulse described above, a lower severity pulse may be useful to ensure that the current low risk of injury at a lower pulse is not compromised by efforts to meet a more severe pulse test.

- In order to choose between a bimodal and a triangular pulse shapes Δv and mean acceleration, it may be possible to evaluate both pulse with the recommended rear impact dummy and injury or seat performance criteria from EEVC WG12 on the following basis:
  - If one pulse shape consistently classifies seats as having a lower performance, this pulse should be used as the use of the less severe pulse may cause the benefit arising from the introduction of the test procedure to be underestimated;
  - If both pulses give similar classifications, or if the classification is inconsistent, consideration could be given to selecting the pulse shape that is easiest to implement on typical laboratory sled test equipment, which is likely to be a unimodal pulse shape.

- There is little information in the open literature regarding the achievability and reproducibility of pulses for low-speed rear impact testing. However, this is currently being evaluated for consumer seat testing. It is recommended that the results, when available, should be used to define the corridor for the pulse recommended in this report.

- It should be noted that the recommended pulse is at a higher severity than is being investigated for consumer testing. It is therefore recommended that the achievability and reproducibility of the pulse is confirmed through additional testing before being implemented in the WG20 test procedure.

Acknowledgements

The authors are grateful to the members of WG20 for the information and views they have provided, which have contributed to the formation of this document.

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