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Executive summary

Recent estimates indicate that whiplash injuries in low-speed car crashes cost the UK insurance industry over £1 billion annually, and similar costs are reported in other regions. The total cost of long-term whiplash injury in frontal and rear impact car crashes in the UK was estimated at £3 billion per annum using the Department for Transport's "willingness to pay" cost model. As a result of this, there has been considerable effort over the last decade to introduce consumer information rating schemes and regulatory tests to encourage development and deployment in the fleet of seats that reduce the risk of whiplash injury in a low-speed rear impact.

While the costs of whiplash injury are well documented, the presence of a specific injury is difficult to confirm in patients. This has led to difficulties in identifying the mechanism or mechanisms of whiplash injury, and many potential injury criteria have been proposed in the literature. However, while the exact mechanism of whiplash injury is still debated, the kinematics of occupant motion in a low-speed rear impact are well documented and research has shown that keeping the head, neck and torso in alignment greatly reduces the risk of whiplash injury. On this basis, good head restraint geometry has been identified as a basic requirement for seats that are designed to reduce the risk of whiplash injury, and a number of methods for measuring head restraint geometry have been developed for consumer information and regulatory testing. These methods assess geometry either statically or dynamically, depending on the test method.

This Insight Report summarises research conducted at TRL and elsewhere to provide a reference document and critical review of the various methods of measuring head restraint geometry that are in use or have been proposed.

Abstract

Whiplash injuries in low-speed car crashes have been identified as resulting in high associated costs to insurers and to society as a whole. For example, these injuries were recently estimated to cost the UK insurance industry over £1 billion annually. Long-term whiplash injury in frontal and rear impact car crashes in the UK was also estimated to cost £3 billion per annum using the Department for Transport's "willingness to pay" cost model. In an effort to reduce these costs, there has been considerable effort invested to introduce consumer information rating schemes and regulatory rear impact seat tests. These tests have been designed to encourage development and deployment in the fleet of seats that reduce the risk of whiplash injury in a low-speed rear impact.

As part of this effort, good head restraint geometry has been identified as a basic requirement for seats that are designed to reduce the risk of whiplash injury, and a number of methods for measuring head restraint geometry have been developed for consumer information and regulatory testing. These methods assess geometry either statically or dynamically, depending on the test method. This Insight Report summarises research conducted at TRL and elsewhere to provide a reference document and critical review of the various methods of measuring head restraint geometry that are in use or have been proposed.

1 Introduction

Evidence from the insurance industry indicates that low-speed rear impacts are the cause of a large number of whiplash injuries in the UK, Europe and worldwide. This is supported by other independent research based on hospital studies, accident data and statistics – for example, Galasko *et al*. (1996).

Whiplash injuries are most commonly considered to be due to sudden differential movement of the head and torso causing strain to the neck, although strains to other parts of the spine are also reported. The risk of sustaining a whiplash injury is highest in rear impacts, although whiplash may also be sustained in any car crash configuration (such as front or side impact). In particular, whiplash is associated with low-speed rear impacts in which other injuries are typically minor or absent. It should be kept in mind that the exact mechanism causing whiplash injuries and whiplash associated disorders is not well understood. Several injury mechanisms have been proposed in the literature, but it is very difficult to confirm the presence of an injury in patients (Bogduk, 1998). However, while the exact mechanism causing whiplash injuries may not be known, the kinematics of occupant motion in rear impacts are well understood and research has shown that keeping the head, neck and torso in alignment greatly reduces the risk of a whiplash injury being reported, even in severe impact conditions.

On this basis, good head restraint geometry has been identified as a means of mitigating whiplash neck injuries. Therefore, methods for assessing the geometry of a head restraint relative to a standard seated occupant position have been developed for regulatory and consumer information testing. The existing assessment methods either assess geometry statically or dynamically and both methods have some advantages and disadvantages. These existing methods developed for consumer groups and regulations are reviewed in this Insight Report, with consideration of the benefits and limitations of each method.

One of the main limitations with conventional static assessments of geometry is that they do not account for advanced seat technologies that react to the occupant loading in a rear impact and bring the head restraint to a more advantageous position. To assess seats incorporating such a system, a dynamic assessment of the head restraint is needed. Some options for dynamic geometry assessment methods have already been developed and implemented in regulations – for example, in the US regulation FMVSS 202a. These options, together with alternative dynamic assessment strategies, are also reviewed.

It should be noted that alongside efforts to develop robust measurement techniques for assessing head restraint geometry, research has also been conducted to develop full dynamic seat assessment techniques. This latter effort is beyond the scope of this report. However, where research serves to inform both geometric and dynamic performance strategies (e.g. in the assessment of rear impact dummies), it has been included.

This Insight Report brings together research conducted at TRL and elsewhere with the intention of providing a reference source and a critical review of the many different methods of specifying head restraint geometry that are in use or in development. Chapter 2 describes the background to whiplash injury and gives an overview of the main regulatory and consumer information test procedures that influence seat design in a manner relevant to whiplash injuries. This is followed in Chapter 3 by a summary of the costs and benefits of improving head restraint geometry requirements in the UK. On the basis that improvements in head restraint geometry would be cost-beneficial, Chapter 4 gives more information on the types of test procedure and requirements that are used in regulatory and consumer information testing. Many of these methods make static measurements of head restraint geometry, and one assesses geometry based on the movement of a crash test dummy in a dynamic test procedure.

Chapter 5 gives a critical review of the benefits and limitations of the static measurement methods, and Chapter 6 gives a critical review of the dynamic method already used in some regulations, as well as an alternative method that has been proposed by TRL. Finally, Chapter 7 summarises the current status of test procedures to control head restraint geometry and makes recommendations for further progress in this important topic.

2 Background

A number of studies using claims statistics originating from the insurance industry indicate that low-speed rear impacts are the cause of a large number of whiplash injuries in the UK, Europe and worldwide. It is suggested that whiplash injuries currently cost British insurers over £1 billion annually and account for over 80% of the total cost of personal injury claims (Thatcham, 2007). In other regions, whiplash injuries have also been estimated to have high annual costs (EEVC WG20, 2005), as follows:

- USA US$10 billion
- British Columbia, Canada C$270 million
- European Union €10 billion

In the UK, Galasko *et al*. (1996) estimated the value of the avoidance of all whiplash injuries to be approximately £2.5 billion (at 1991 costs), of which approximately 60% of the injuries were from rear impacts (£1.5 billion pro rata at 1991 costs). Welsh *et al*. (2006) found that 58% of rear impacts with new cars result in an AIS 1[1] whiplash injury and that the cost of a whiplash injury is £42,574. They also found that the risk of whiplash injury is twice as high in rear impacts as it is in front or side impacts, although the exposure to rear impacts is lower than for frontal impacts (there are more frontal impacts per year than rear impacts). Galasko *et al*. and Welsh *et al*. both used the Department for Transport's (DfT) "willingness to pay" cost model[2].

More recently, Hynd *et al*. (2007a) estimated that the cost of long-term whiplash injuries (in this case, "long-term" was defined to be symptoms lasting more than six months) to front seat occupants in frontal and rear impacts was £3 billion annually, also based on UK DfT "willingness to pay" costs.

As a result of this, there have been significant efforts in recent years to introduce regulatory and consumer test procedures that will encourage the development of seats that reduce the risk of whiplash injury in a low-speed rear impact. These have included assessments of the geometry of head restraints (i.e. how high the restraint is relative to the top of the head and how close to the back of the head), as well as dynamic tests to assess the performance of seats and head restraints in a simulated rear impact crash. This report gives an overview of the status of head restraint geometry requirements, both in static test procedures and in dynamic head restraint geometry test procedures.

2.1 Whiplash injury description

The European Enhanced Vehicle-safety Committee (EEVC) Working Group 20 (Rear Impact) undertook a review of the current state of the art in low-speed rear impact accidents and injuries (EEVC WG20, 2005). EEVC WG20 found that while the symptoms of Whiplash Associated Disorder (WAD) were well documented, the injuries causing the acute symptoms were not completely known. The relationship between acute injury and chronic pain is also not understood fully. Despite this, the kinematics of the head and neck during rear impacts are relatively well known. To date, the exact nature of the injury or injuries that lead to the symptoms known as WAD remains unknown. Some authors also refer to whiplash injuries as "soft tissue neck injuries".

Whiplash injuries have been classified in a number of ways, including using AIS (AAAM, 1990), where all whiplash injuries are rated as AIS 1, and the Quebec Task Force Scale (Spitzer *et al*., 1995), where injuries are scored from WAD 0 (i.e. no complaint about the neck and no physical signs) to WAD 4 (neck complaint and fracture or dislocation).

Within seat design, good head restraint geometry has been shown to be important in mitigating soft tissue neck injuries (e.g. Farmer *et al*., 1999), although occupant kinematic control and effective energy management have also been shown to be of importance (e.g. energy-absorbing seat backs). Hynd and van Ratingen (2005) surmised from the EEVC WG20 state-of-the-art review that for head restraint and seat systems to be effective, energy-absorbing capability could be employed to reduce occupant energy while controlling head and thorax motion. Good head restraint geometry can also contribute by controlling head kinematics early in the crash event.

Many publications differentiate between short-term and long-term whiplash injuries, and the costs associated with the two may be quite different. However, "long-term" may be defined as symptoms lasting longer than one month up to symptoms lasting longer than two years or more. The difference is often due to the differing needs of data owners or researchers. For instance, the definition of "long-term" may be based on the length of clinical evaluation that must be completed before an insurance claim can be processed, whereas it may be sufficient to use a shorter duration for some research programmes.

2.2 Factors affecting whiplash injury risk in rear impacts

There are many parameters that have been demonstrated to affect the risk of a whiplash-type injury occurring in a rear impact. These parameters relate to the occupant, the seat, the crash conditions and the vehicle.

Occupant

- Females have been reported to have a higher risk of whiplash injury for a given severity of impact than males (e.g. Krafft *et al*. (1997), Chapline *et al*. (2000) and Temming and Zobel (2000)).
- Taller drivers, front seat passengers and outboard rear seat passengers have been shown to have a higher risk of injury for a given severity of impact than shorter occupants (Jakobsson *et al*., 2000).

Seat

- Good head restraint geometry has been shown to be important in mitigating soft tissue neck injuries (Farmer *et al*., 1999 and 2003). Hell *et al*. (1998) reported that a low-positioned head restraint could be a higher risk factor than no head restraint. Ono and Kanno (1996) found that a low head restraint imposed the highest neck load in volunteer tests (i.e. higher than tests with no head restraint).

1 The Abbreviated Injury Scale (AIS) is used to code the severity of injuries arising from road traffic accidents. Injuries are ranked from AIS 0 (no injury) to AIS 6 (virtually unsurvivable).

2 Since 1993, DfT's valuation of both fatal and non-fatal casualties has been based on a consistent "willingness to pay" cost model. This encompasses all aspects of the valuation of casualties including the human costs, the direct economic costs and the medical costs associated with reported road accident injuries.

- Stiffer seat backs have been associated with an increase in whiplash injury risk (Hell *et al*., 1999). Parkin *et al*. (1995) reported that plastic deformation of seat backs reduced the risk of injury. Current research suggests that where high seat back yield strength is used in conjunction with "good" head restraint geometry and energy absorption, a reduction in injuries is observed (Jakobsson *et al*., 2000).

Crash conditions
- The change in the velocity of the vehicle (delta-v), mean acceleration and peak acceleration have all been shown to be correlated with the risk of injury (e.g. Krafft *et al*., 2002).
- Vehicle mass ratio and compatibility between the two striking vehicles (under-ride, over-ride and good engagement; full overlap or partial overlap) all affect the pulse of the struck vehicle and would therefore be expected to affect the risk of injury.

Vehicle
- Increased vehicle structural stiffness is considered to increase the risk of whiplash injury, because the stiffness of the vehicles affects the pulse. Vehicle structures are reported to have become stiffer since the mid-1990s and this trend in increasing stiffness is continuing (Muser *et al*., 2000; Avery and Zuby, 2001). This may be due to enhanced crash performance driven by, among other requirements, the low-speed insurance impact test and high-speed frontal impact regulatory and consumer tests, and may have led to an increase in whiplash-type injuries (Hynd and van Ratingen, 2005).
- Avery (2001) showed that rear impact pulses for nominally identical vehicles sold in different markets may vary considerably due to structural differences in the bumper systems in those markets, which is due to the different bumper requirements in different jurisdictions.

However, within all of these variables, good seat design has been found to be substantially able to reduce the risk of a whiplash injury (Farmer *et al*., 2003; Boström and Kullgren, 2007; Kullgren *et al*., 2007).

2.3 Seat technologies to mitigate whiplash
A number of seat types specifically aimed at reducing the risk of whiplash injury have been introduced to the market over the last decade. These include:
- Energy-absorbing seats – For example, the Volvo WHIplash Protection System (WHIPS) seat, which uses good fixed head restraint geometry in combination with a seat back recliner that yields plastically and thereby absorbs energy; and a retrofit yielding seat front mount that absorbs energy (Krafft *et al*., 2004).
- Reactive head restraints – These systems use the inertia of the seat occupant's body mass to move the head restraint forwards and upwards via a mechanical system in the seat back (e.g. Saab Active Head Restraint System). These systems – as with the active head restraints (see below) – allow the head restraint to be further behind the occupant's head in normal driving, but are intended to ensure that the head restraint will be much better positioned when it is needed in an impact.
- Active head restraints – Active systems use pyrotechnic or other devices triggered by a sensor to improve head restraint geometry during an impact or, with external sensors, prior to an impact occurring.

2.4 Regulatory requirements for head restraints
The following regulatory requirements relate to the provision and performance of head restraints:
- UNECE Regulation 17 – Uniform provisions concerning the approval of vehicles with regard to the seats, their anchorages and any head restraints (UNECE, 2007).
- UNECE Regulation 25 – Uniform provisions concerning the approval of head restraints (headrests), whether or not incorporated in vehicle seats (UNECE, 1997).
- Directive 74/408/EEC on the approximation of the laws of the Member States relating to the interior fittings of motor vehicles (strength of seats and of their anchorages) (EEC, 1974).
- Directive 78/932/EEC on the approximation of the laws of the Member States relating to head restraints of seats of motor vehicles (EEC, 1978).
- Directive 96/37/EC, adapting to technical progress Council Directive 74/408/EEC relating to the interior fittings of motor vehicles (strength of seats and of their anchorages) (EC, 1996).
- Directive 2005/39/EC of the European Parliament and of the Council of 7 September 2005 amending Council Directive 74/408/EEC relating to motor vehicles with regard to the seats, their anchorages and head restraints (EC, 2005).

The United Nations Economic Commission for Europe (UNECE) Regulations are adopted in many jurisdictions around the world, while the EC Directives apply only in Europe. All of the above regulations control the size, position, strength and many other parameters of head restraints. The minimum height of head restraints is defined for different seating positions, but none of the above regulations control the backset of head restraints (i.e. the horizontal distance from the rear of the head of an occupant to the front surface of the head restraint). The EC Directives are substantially the same as the UNECE Regulations and will not be considered separately hereafter. Similar regulations are in force in Australia, Canada, Japan and Korea. In addition, the USA has recently updated its regulatory requirement, Federal Motor Vehicle Safety Standard (FMVSS) 202 (US Department of Transportation, 2004), and a Global Technical Regulation has been established in the United Nations Global Registry since March 2008 (United Nations, 2008). The key elements of these regulations relating to head restraints are summarised in Section 4.1.

2.5 Consumer information rating schemes
The Insurance Institute for Highway Safety (IIHS) in the USA has been rating the geometry of head restraints since 1995 (IIHS, 2008). Since 2000, the geometric assessment has used the Research Council for Automobile Repairs (RCAR) geometry test procedure (RCAR, 2001). This procedure uses the SAE J826 H-point machine (SAE, 1995) and the Head Restraint Measurement Device (HRMD; see Figure G2 in the Glossary) developed by the Insurance Corporation of British Columbia

and RONA Kinetics (Gane and Pedder, 1999) to assess head restraint height (i.e. the height of the head restraint with respect to the head of the occupant) and backset. In the UK, the whiplash seat ratings published by Thatcham also use the RCAR geometry test procedure.

More recently, the International Insurance Whiplash Prevention Group (IIWPG) has developed a dynamic seat test procedure, which rates seats based on measurements made using the BioRID II rear impact dummy. Since 2004, Thatcham in the UK and IIHS in the USA have both published seat ratings based on a combination of the RCAR geometric rating and the IIWPG dynamic rating. Thatcham recently reported that the number of seats receiving a "Good"[3] rating rose from 16% for model year 2005 vehicles to 35% in 2008 (Thatcham, 2008). In the same period, the number of seats with a "Poor" rating fell from 35% to 16%.

In Sweden, the insurance company Folksam and the Swedish Road Administration (SRA) also publish whiplash seat ratings. These ratings use the IIWPG dynamic seat test procedure, as well as two additional dynamic tests, but do not incorporate a rating for head restraint geometry.

Euro NCAP has recently published a protocol for whiplash testing (Euro NCAP, 2008a) and the scoring system for the whiplash test results (Euro NCAP, 2008b).The whiplash tests have formed part of the overall vehicle safety rating since the new rating scheme was launched in February 2009.

Further information on consumer information whiplash seat tests can be found in Section 4.2.

2.6 European research activity

In the 1990s, no regulatory test existed in Europe to assess injury risk in rear impacts, in particular low-severity rear impacts. In 2000, the EEVC Steering Committee asked EEVC WG12 (Biomechanics) to create an ad hoc Working Group to investigate the possibility of developing an EEVC view on rear impact and whiplash associated disorders. The ad hoc group (EEVC WG12, 2002) found that there was a significant amount of research data available and that interesting and promising research projects were ongoing. It recommended that the EEVC Steering Committee start up a new activity with the aim of developing a proposal for a new European regulatory test for whiplash injury (AIS 1 neck injury) protection in rear impacts.

The EEVC Steering Committee formed a new Working Group, WG20, to develop and evaluate a test procedure, or range of test procedures, suitable for regulatory use. The test procedures should have a prime focus on neck injury reduction, but should give due regard to the potential for injuries to other body regions.

EEVC WG20 is considering the development of a geometric assessment of head restraints (which may be a static test, a dynamic test, or both) as a first stage in the mitigation of injuries in low-speed rear impacts. In the longer term, the group will develop a sled-based test procedure for the dynamic assessment of seat performance to stimulate further a reduction in the incidence of whiplash injuries.

2.7 Summary

- Evidence originating from the insurance industry indicates that low-speed rear impacts are the cause of a large number of whiplash injuries in the UK, Europe and worldwide. It is suggested that "currently whiplash injuries cost British insurers over £1 billion annually and account for over 80% of the total cost of personal injury claims" (Thatcham, 2007).
- Within seat design, good head restraint geometry has been shown to be important in mitigating soft tissue neck injuries:
  - Head restraint backset has been shown to influence injury risk.
  - Taller drivers, front seat passengers and outboard rear seat passengers have been shown to have a higher risk of injury than shorter occupants and a low-positioned head restraint could be associated with a higher risk factor than no head restraint.
- A minimum height is specified for head restraints in UNECE Regulations and EC Directives, although none of the European regulations control the backset of head restraints.
- There are requirements for both head restraint height and backset in the US regulation FMVSS 202a.
- Height and backset requirements for head restraints exist in some consumer information schemes.

3 Head restraint geometry is rated by Thatcham as "Good", "Acceptable", "Marginal" or "Poor".

3 Costs and benefits of improving the geometry of head restraints in the UK

For contribution to EEVC WG20, and on behalf of the Department for Transport, TRL undertook a cost-benefit study of geometric head restraint requirements (EEVC WG20, 2007). The study was based on UK accident data, injury costs and population height distribution, but should be representative of most of Europe. The main exception is The Netherlands, where the mean height of the population is greater than that in the UK.

The cost-benefit study was based on there being three key factors in car seat/head restraint geometry that influence whether whiplash occurs and how serious it is:

1) The head restraint height.
2) The backset of the head restraint.
3) Whether the head restraint has the ability to remain (or lock) in its set position while supporting the neck.

The cost-benefit study was concerned with the first two of these key factors and was undertaken to determine the justification for making changes to the currently legislated geometrical requirements for head restraints.

To address the whiplash injury problem, four options were considered that would amend the requirements concerning the geometrical position of the head restraint with respect to the occupant:

1) Doing nothing.
2) Increasing the current head restraint minimum height requirement from 800 mm to somewhere in the range of 800–850 mm.
3) Introducing a limit for head restraint backset somewhere in the range of 40–100 mm.
4) A combination of the two options for head restraint height and backset (i.e. options 2 and 3).

The first option considered was the option of doing nothing. This was defined as resulting in no benefit through reduction of casualties, but also no cost for UK industry. The assumption behind this eventuality was that consumer testing has already given an incentive for improved head restraint geometry over the last few years. The baseline therefore includes the current performance of the vehicle fleet, including the appropriateness of the head restraint geometry in current vehicles for reducing the incidence of whiplash injuries.

For each of the four options, the benefits were determined by evaluation of the potential casualty savings that might occur as a result of the regulatory change. The benefits were based on published information regarding the effectiveness of the head restraint in mitigating whiplash injury risk. In general terms, injury risk was expected to reduce with decreasing backset and a higher head restraint means that such benefits can be realised for a larger proportion of the population.

A monetary value was applied to the benefit by assigning a cost to each whiplash injury with long-term symptoms (for this study, “long-term” was defined as symptoms lasting more than six months). This value, which was based on the “willingness to pay” model, was calculated to be £61,326 (EEVC WG20, 2007). Application of this cost to the 2005 UK casualty data produced a total cost associated with the long-term whiplash injuries to front seat occupants in frontal and rear impacts of approximately £3 billion. The potential casualty savings were calculated as a proportion of this total cost. Long-term injuries that would be mitigated to short-term injuries by improved regulatory requirements were considered to be balanced by short-term injuries being mitigated to non-injury. Therefore, as the number of short-term injuries was assumed not to be affected by improving head restraint geometry, the costs of such injuries did not need to be considered.

To produce this figure of £3 billion, factors were derived to transform the number of casualties with a slight injury (Department for Transport, 2007) to the number of casualties with a long-term whiplash injury in the UK. These factors included under-reporting of whiplash injuries (based on a comparison of hospital and police-reported databases) in the dataset, the proportion of casualties with an AIS 1 neck injury and the proportion sustaining long-term whiplash injury symptoms (all from Galasko *et al*., 1996).

To evaluate the benefits from decreased backset of the head restraint, an injury risk function was developed based on published injury data (Olsson *et al*., 1990), as shown in Figure 3.1. Head restraint height was found to be independent of backset in this dataset, and so did not significantly affect the injury risk function. The backset injury risk function in Figure 3.1 is based on relatively old data for accidents and injuries occurring in Volvo cars from the 1980s. Since then, seat back and vehicle stiffness have increased across the vehicle fleet, and both of these factors are associated with an increase in the risk of whiplash injury. Therefore, this backset risk function was considered to be conservative and suitable for use in a cost-benefit study (EEVC WG20, 2007).

The protection offered by the height of the head restraint was evaluated by assuming that if the head restraint is high enough to support the centre of gravity of the head then the protection offered is adequate; otherwise, it is presumed to be inadequate. The height required included an allowance for ramping-up, whereby a person moves up the seat back during a rear impact. This assumption was combined with the height distribution of the UK population to give the proportion expected to be given adequate protection by different head restraint heights.

More factors then had to be applied to account for the proportion of whiplash injuries that result from a neck extension mechanism, the proportion of occupants who are in position at the time of the accident and could therefore benefit from a head restraint and the proportion of occupants who adjust their head restraint correctly if it is necessary for them to do so. The resulting product of the proportion of front seat occupants for whom a given head restraint height is adequate and the backset risk function gives the injury mitigation distribution is shown in Figure 3.2.

In addition to the benefits of head restraint modifications, costs for achieving such changes were also considered. For each option, costs for original equipment manufacturers to implement each of the proposed changes to the head restraint geometry were determined. These costs were based on the increase in head restraint height as justified in similar considerations by the US Department of Transportation (NHTSA, 2004). No response was forthcoming from industry for the costs associated with changing the backset of head restraints in cars, so no backset costs were used in the analysis. It was assumed that this would have no effect on the option to introduce both height and backset requirements at the same time, because backset modifications could be introduced at the same time as changes made to the seat for height requirements. However, a requirement would clearly have a greater-than-zero cost implication, although it is likely that costs would apply to a limited number of seat models and for a limited time period. This is because entirely new seats would be designed with the backset requirement in mind, and the costs would only apply to seats that had to be updated before they would normally have been superseded.

The benefit-minus-cost value of each option was then calculated along with the benefit-to-cost ratio (Figure 3.3)[4]. These comparisons were not at all revealing for backset because there were no direct costs associated with the changes. However, some inferences about backset could be obtained from the matrix of benefits and costs. It was found that the greatest benefit after subtracting the associated cost is expected with a head restraint height of 810 mm and a backset of 40 mm. The greatest benefit-to-cost ratio should occur with a small change in head restraint height and a backset of 40 mm. The minimum change in regulation expected to yield a benefit-to-cost ratio of 2 would be to adopt a backset of 70 mm.

Throughout the cost-benefit study, several assumptions were made. These assumptions are summarised in Table 3.1. It is also noted in the table whether they are considered to be conservative (i.e. tend to underestimate the benefits and/or overestimate the costs of changing head restraint geometry).

It was noted through this work that a static geometric head restraint requirement would be a first step in mitigating low-speed rear impact injuries, and additional benefit may result from appropriate dynamic seat testing.

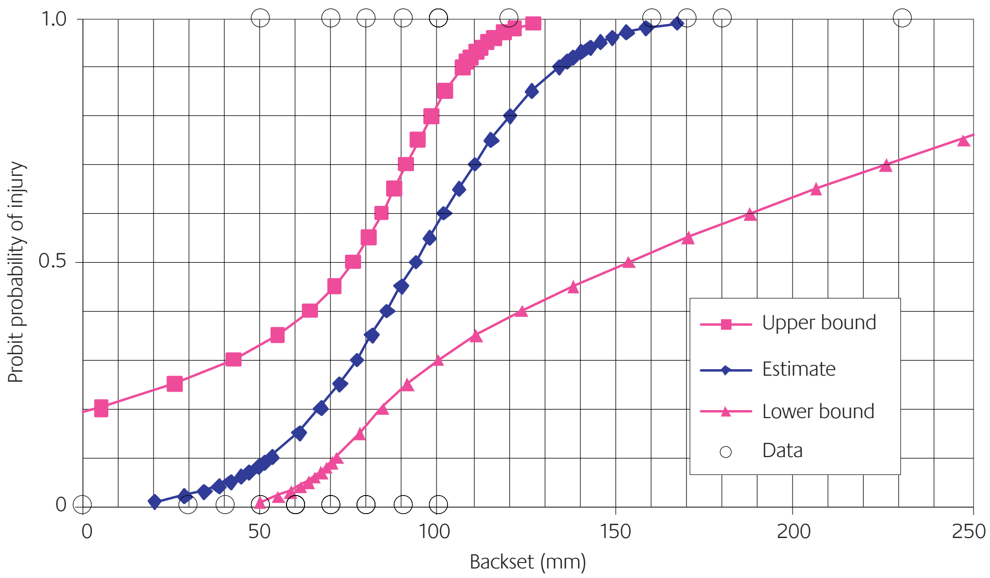

Figure 3.1 Risk of long-term whiplash symptoms (greater than six months) versus head restraint backset (based on data from Olsson *et al*., 1990)

4 This cost-benefit analysis did not use discounting to bring the values of costs or benefits in future years to their "present value" – i.e. to take account of social time preference. However, because the ratio of costs and benefits in each future year was approximately constant, this simplification to the analysis will not have affected the benefit-to-cost ratio in any important way.

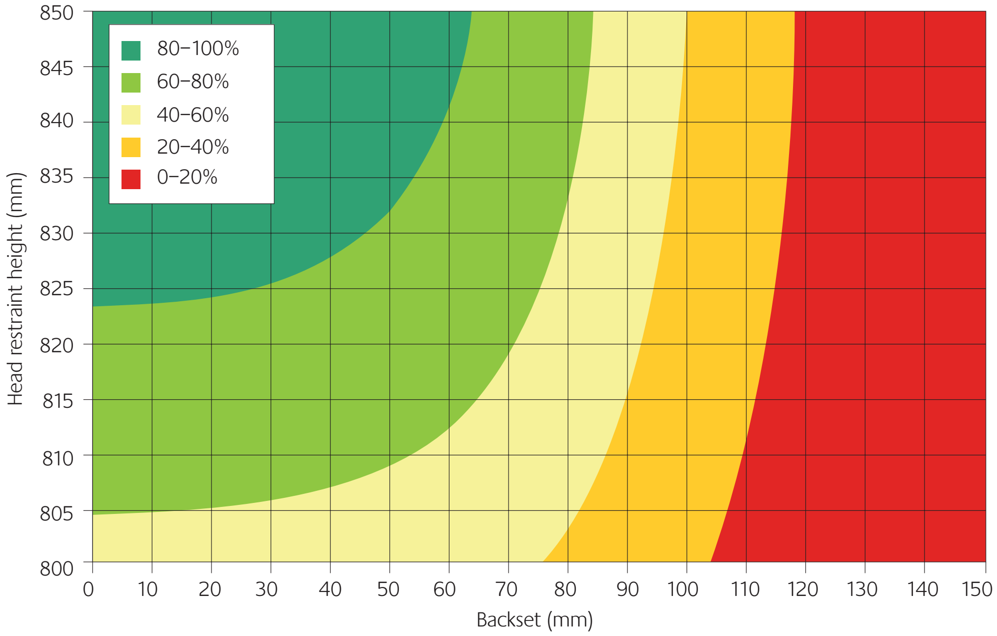

Figure 3.2 Proportion of long-term whiplash injuries in the UK adult male population that would be mitigated by setting head restraint height and backset to the values indicated (EEVC WG20, 2007)

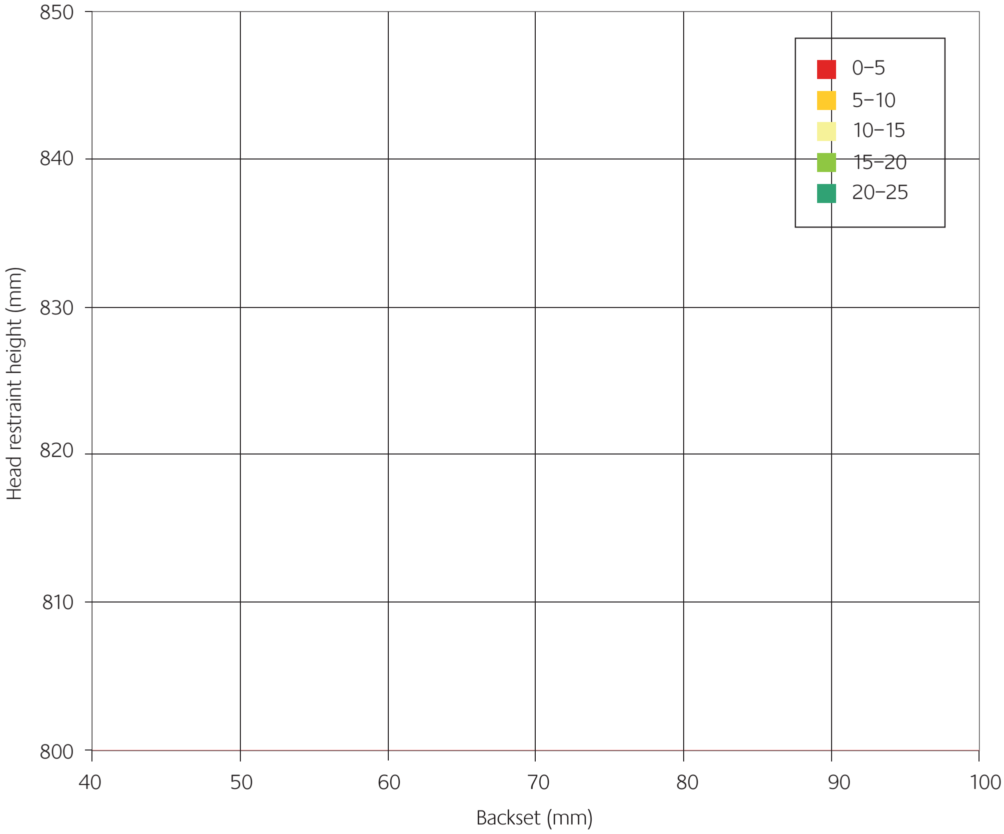

Figure 3.3 Graphical representation of the benefit-to-cost ratio for the various proposed head restraint height and backset limits (EEVC WG20, 2007)

Table 3.1 Summary of the assumptions used in this cost-benefity study

Parameter	*Assumption*	*Conservative or not?*	*Comment*
Height	Height distribution data for the UK population	Accurate for the UK	–
	Erect sitting height for the UK population	Accurate for the UK	–
	Assumed ramping-up factor	Slightly conservative	Based on volunteer test data, with cloth seats, rigid backed lab seat, and downward component to occupant acceleration pulse
Backset	Backset injury risk function	Conservative	If anything, the cars in the study would be less stiff and have less stiff seat backs than the current fleet, both of which would be expected to reduce the injury risk (EEVC WG20, 2005)
Cost – height	Full 50 mm cost applied to raising height from 800 mm to 850 mm	Conservative	Most head restraints already exceed 800 mm due to insurance industry testing
Cost – backset	No cost applied	Slightly optimistic	A proportion of seats would require a one-off tooling cost as a result of introducing a backset requirement. However, as the average backset in Thatcham testing is now 50 mm, this cost would be expected to apply only to a small proportion of seats
Cost of whiplash injuries	Frontal and rear impact whiplash proportions for male and female	Accurate for the UK	Data from STATS19 and Welsh *et al*. (2006)
	Under-reporting proportion	Accurate for the UK	Data from a large hospital study (Galasko *et al*., 1996)
	Long-term symptom proportions	Accurate for the UK	Data from a large hospital study (Galasko *et al*., 1996) supported by more recent UK insurance data
	"Willingness to pay" casualty cost for long-term whiplash injury	Accurate for the UK	From DfT "willingness to pay" costing
Proportion who could be saved by improved geometry	Proportion of rear impact occupants have a neck extension whiplash injury mechanism (i.e. they are not injured in rebound) and are sufficiently in position for the head restraint to be of benefit	Neutral	Consistent with insurance claims reductions with improved geometry
	Proportion of frontal impact occupants have a neck extension whiplash injury mechanism (from rebound) and are sufficiently in position to be saved	Little evidence, but expected to be conservative	–
	Mid-range estimate of number who would correctly adjust their head restraint, including a factor for those with fixed head restraints	Neutral	–
Other	Assumed long-term injuries mitigated to short-term are balanced by short-term injuries mitigated to no injury	Not known whether conservative or not	–

4 Head restraint geometry in regulatory and consumer testing

Head restraint geometry is measured and applied in a variety of ways in regulations and consumer information testing[5]. This section outlines the various approaches currently in use. Both static test procedures and, recently, dynamic test procedures have been proposed or implemented.

4.1 Regulation

4.1.1 UNECE Regulation 17 and Regulation 25

Regulation 17 (UNECE, 2007) defines the minimum height, measured from the R-point of the seat (i.e. the standard H-point position as stated by the vehicle manufacturer), that head restraints should be capable of reaching for both fixed and adjustable head restraints and for various seating positions. Regulation 25 (UNECE, 1997) defines very similar requirements. Additionally, Regulation 17 defines many other requirements related to seat back strength, anchorage strength and protection from luggage loading. Neither regulation defines a backset requirement for head restraints.

The head restraint requirements defined in UNECE Regulations 17 and 25 include:

- Height of the head restraint above the R-point (800 mm and 750 mm for front and rear seats, respectively, in the highest use position for adjustable head restraints; backset and tilt are undefined).
- Height of the adjustable part of an adjustable head restraint (at least 100 mm).
- Width of the head restraint (at least 85 mm either side of the centre line).
- Allowable gap between the head restraint and the seat back (25 mm for adjustable and 60 mm for non-adjustable head restraints).
- Energy-absorption characteristics in different zones.
- Minimum radius of curvature of hard parts in different zones.

It is understood that these requirements were designed to reduce the risk of serious neck injuries (i.e. AIS 3+), not whiplash injuries (i.e. AIS 1+), and that the requirements were based on the anthropometry of the 50th percentile male. The height of the head restraint is measured from the R-point parallel to the manufacturer's torso design angle (Figure 4.1).

During the development of a cost-benefit study on head restraint geometry, Hynd *et al*. (2007a) found that the height measurement method defined in UNECE Regulations 17 and 25 overestimates the effective height of the head restraint and therefore overestimates the proportion of the population that would be protected by the head restraint. According to the calculations used in the cost-benefit study, a head restraint height of 800 mm, as required by the regulations for front seat occupants, would be expected to protect 55% of the UK male population and 98% of the UK female population. For an example seat, it was found that the effective height was overestimated by 48 mm. With an error of 48 mm in the height measurement, these proportions protected become

5 Most test procedures use either the 3-D H-point machine defined in UNECE Regulations or the SAE H-point machine (SAE J826 manikin). These test tools are very similar, though not identical. The differences are discussed in Hynd (2007a) and will not be considered further in this report.

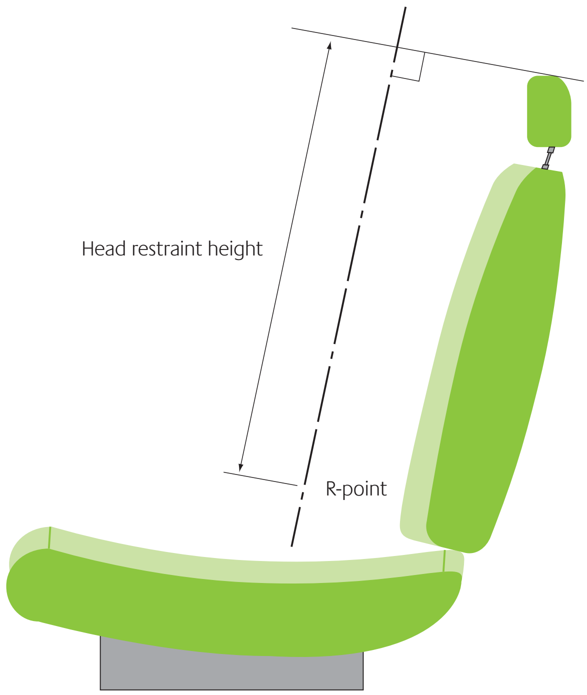

Figure 4.1 UNECE Regulation 17 head restraint height measurement example

8% and 64%, respectively. This issue was also raised by other authors in the Working Party on Passive Safety (GRSP) Informal Working Group on Head Restraints in documents HR-02-03e and HR-03-10e (available from www.unece.org). Further information on this can be found in Appendix A.

While it is acknowledged that they were not introduced for whiplash mitigation, the primary limitations of UNECE Regulations 17 and 25 with respect to whiplash mitigation are:

- Backset is not controlled.
- The effective height of the head restraint is overestimated; for some head restraints, the overestimate is substantial and the level of protection offered to the car occupant population will be much lower than expected.
- There is no dynamic assessment of whiplash performance.

4.1.2 Federal Motor Vehicle Safety Standard 202

FMVSS 202 Head Restraints (1971, as amended 1998) contains the following requirements for seat backs and head restraints:

- Dynamic test with a 95th percentile male dummy (no particular dummy is specified), with a limit on head-to-torso rotation angle of 45°; or
- Head restraint height and width requirements (backset and tilt are undefined):
  - Height of the head restraint of 700 mm above the H-point for outboard front seats with fixed or adjustable head restraints.
  - Width of the head restraint of 171 mm for individual seats and 254 mm for bench seats.
- Seat back and head restraint strength requirements.

These requirements were designed to prevent hyperextension of the neck in a rear impact. However, the National Highway Traffic Safety Administration (NHTSA) found more recent data that indicate that whiplash injury can occur without the neck moving outside its normal range of movement (NHTSA, 2000).

Therefore, FMVSS 202 was updated in 2007 to introduce more stringent requirements, and the update is known as FMVSS 202a. This standard harmonises some requirements with those of UNECE Regulation 17 and incorporates additional requirements. These include either static requirements or dynamic requirements.

Static requirements

- Height of the head restraint above the H-point (800 mm and 750 mm for front and rear seats, respectively, in the highest use position for adjustable head restraints, with the seat at a torso angle of 25°; head restraint backset and tilt are undefined).
- Backset measured with the SAE J826 H-point manikin and HRMD no more than 55 mm; compliance with the static backset requirement shall be demonstrated by taking the arithmetic mean of three measurements.
- Width of the head restraint of 170 mm for individual seats and 254 mm for bench seats.
- Allowable gap between the head restraint and the seat back (60 mm for all head restraint types).
- Head restraint height and tilt lock tests.
- Energy-absorption test similar to that in UNECE Regulation 17, but with a linear impactor rather than a pendulum.
- No minimum radius of curvature of hard parts.
- Seat back deflection requirement as in UNECE Regulation 17.

Dynamic requirements

- A low-speed dynamic rear impact test using the Hybrid III dummy, with a limit on head-to-torso rotation angle of 12° and a peak Head Injury Criterion (HIC) value of 500.

4.1.3 Global Technical Regulation 7

GTR 7 (United Nations, 2008) contains an extensive "Statement of Technical Rationale and Justification" giving the background to the recommendations made by the GRSP Informal Working Group on Head Restraints that formed the basis of the text of the GTR. The text of the GTR allows Contracting Parties (see Glossary) a certain amount of flexibility regarding the scope and applicability of the requirements, e.g. the vehicle mass range and seating positions covered by the requirements. For instance, the text recommends that the GTR applies to all Category 1-1 vehicles and Category 1-2 and 2 vehicles with a gross vehicle mass of up to 4,500 kg. However, each Contracting Party may opt to apply the requirement up to a lower vehicle mass if it decides that such a restriction of the range of application of the GTR is appropriate.

The GTR includes the following requirements:

- Dimensions of head restraints.
- Height of head restraint.
- Static backset.
- Seat back and head restraint strength.
- Energy dissipation.
- Height adjustment locking.
- Non-use position test procedure.
- Dynamic test procedure.

Static backset is evaluated by two methods:

- H-point method, using the SAE J826 H-point manikin and the HRMD.
- R-point method, using a geometric assessment (e.g. by co-ordinate measuring machine).

Each Contracting Party can allow the manufacturer the option of assessing backset using either the H-point or R-point method. For both methods, compliance with the static backset requirements shall be demonstrated by taking the arithmetic mean of three measurements and with the seat back set to the manufacturer's design torso angle. The mean of three measurements was introduced in order to achieve satisfactory reproducibility of the static backset measurement.

4.2 Consumer information

4.2.1 IIWPG rear impact seat rating

IIHS in the USA has been rating the geometry of head restraints since 1995 (IIHS, 2008). The protocol used until 1999 was very similar to the RCAR test procedure (RCAR, 2001), and in 2000 IIHS adopted the RCAR procedure, which has recently been updated (RCAR, 2008). In the UK, the whiplash seat ratings published by Thatcham (www.thatcham.org) also use the RCAR geometry test procedure. Over the last four years, the head restraint geometry rating has been combined with a dynamic rear impact test rating to give an overall seat restraint performance rating, and again these results are published on the Thatcham website.

The RCAR test procedure measures the height and backset of the head restraint using the SAE H-point machine (SAE, 1995) and a HRMD (Gane and Pedder, 1999). Together these tools provide a representation of the head position, when seated, of a 50th percentile male occupant. The height definition is somewhat different from that measured in UNECE Regulation 17 in that it is the vertical distance down from the top of the head to the top of the head restraint. Differences due to this alternative head restraint height definition are discussed in Section 5.7.

If a head restraint has height and tilt locks, the head restraint geometry is given a rating based on the backset and height at a combination of the highest locking, most forward locking, lowest and rearmost positions; otherwise it is tested in the down and most rearward position. Locks are defined as preventing inadvertent movement of the head restraint – e.g. "when a rear seat occupant uses a front seat head restraint as a hand hold to facilitate easy entry or exit from the vehicle".

Head restraint geometry is rated by Thatcham as "Good", "Acceptable", "Marginal" or "Poor", based on a combination of height and backset measurements (Figure 4.2). If static geometry measurements do not meet minimum requirements, a dynamic rating is not given.

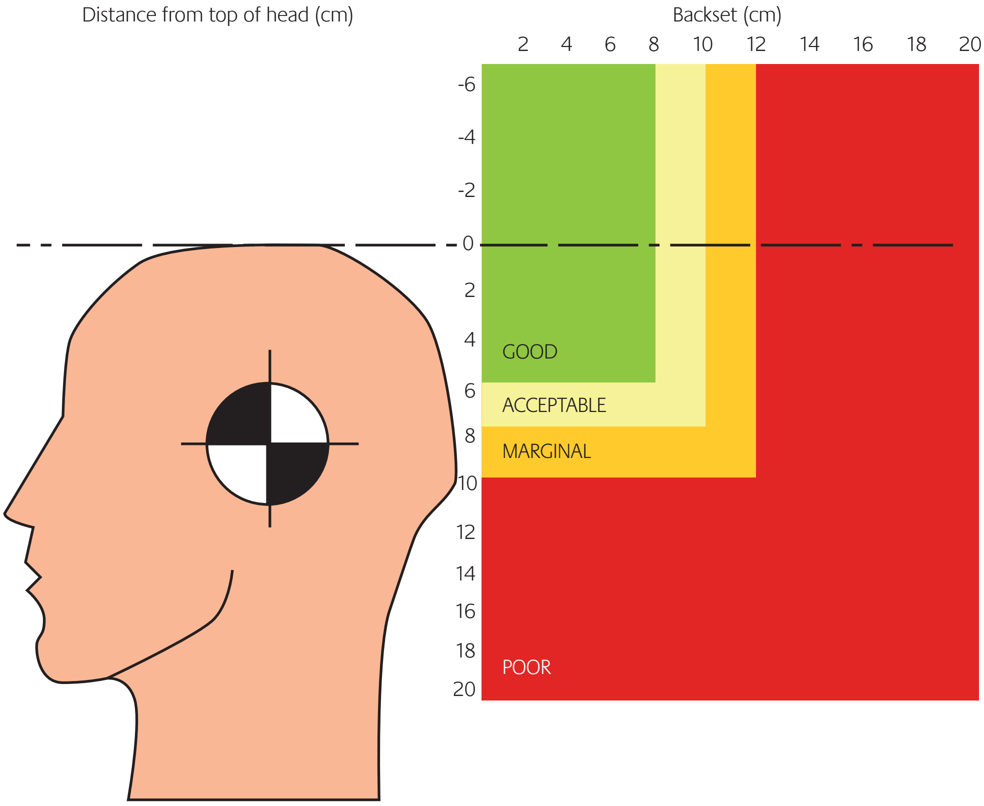

Figure 4.2 RCAR head restraint rating diagram (for adjustable head restraints) (RCAR, 2008)

4.2.2 Folksam/SRA rear impact test procedure

In the rear impact test procedure developed by the Folksam insurance company and SRA, the static geometry assessment is used as part of the BioRID positioning procedure. It is not explicitly used in the seat rating.

4.2.3 Euro NCAP

Euro NCAP has recently published a protocol for whiplash testing (Euro NCAP, 2008a) and a scoring system for the whiplash test results (Euro NCAP, 2008b). Detailed whiplash seat scores were launched in November 2008, and since February 2009 the whiplash seat scores have formed part of the overall star rating for each vehicle. The Euro NCAP whiplash tests include static geometry measurements with a 3-D H-point machine and HRMD, as well as dynamic injury assessment tests at three pulses.

The static tests are an extension of those in the RCAR procedure, but with different performance limits. The lower performance limits are 80 mm below the top height of the H-point machine and HRMD for height and 100 mm for backset (the border between “Acceptable” and “Marginal” in the RCAR test procedure). The higher performance limits are 0 mm and 40 mm, respectively (some 60 mm higher and 30 mm further forward than the minimum standard for a “Good” rating in the RCAR procedure). The static geometry of deployable head restraints can be assessed in the deployed position, provided that the manufacturer can provide suitable evidence that the deployment is consistent and stable prior to head contact with the head restraint. Reactive systems can also be assessed in a deployed position provided that suitable evidence is provided that the system will deploy and lock in a stable position prior to head contact, including with a 5th percentile female Hybrid III dummy occupying the seat.

4.3 Summary

Many regulations and consumer information tests make some measure of head restraint geometry, and most of these measures are made using one of several static test procedures. UNECE Regulations 17 and 25 control the height of head restraints, but there is no backset requirement. The static test option in FMVSS 202a and GTR 7, as well as IIWPG and Euro NCAP consumer information testing, have requirements for both height and backset.

The only dynamic test procedure for head restraint geometry currently in use is the test in FMVSS 202a. This test has recently been adopted in GTR 7, but has not been applied in local regulations outside the USA.

5 Critical review of static head restraint geometry measurement methods

5.1 Introduction

Chapter 4 identified a range of regulations and consumer information tests that make requirements on head restraint geometry, using a number of different test methods. The following sections provide a critical review of each of the static geometry test methods and requirements, giving an overview of the advantages and disadvantages of each. Dynamic geometry methods are considered further in Chapter 5.

5.2 UNECE Regulation 17 and Regulation 25

The UNECE Regulation 17 and Regulation 25 height measurement method was reviewed by EEVC WG20 (Hynd, 2007a). The Working Group agreed that the Regulation 17 height measurement method was straightforward to implement and had the advantage of not requiring the use of the combined 3-D-H machine and HRMD (see Section 5.3). However, concerns were raised that the measurement method overestimates the effective height of the head restraint and therefore overestimates the benefit arising from the regulation (see Appendix B of the UK cost-benefit report (EEVC WG20, 2007); see also GTR documents HR-02-03 from The Netherlands and HR-03-10 from the Alliance of Automobile Manufacturers).

The height measurement error is detailed in Appendix A. For the seat reviewed by EEVC WG20, the height measurement using the Regulation 17 method was approximately 48 mm greater than the effective height of the head restraint. According to the calculations used in the WG20 cost-benefit study, a head restraint height of 800 mm would be expected to protect 55% of the UK male population and 98% of the UK female population. With an error of 48 mm in the height measurement, these proportions become 8% and 64%, respectively.

A revised Regulation 17 height measurement method has been drafted by The Netherlands that defines the effective height of the head restraint. This seeks to define and measure the height of those parts of the front face of the head restraint that will support the centre of gravity of the head in a rear impact or when an occupant is rebounding following a frontal impact. The Dutch proposal retains the advantage of not using the 3-D H-point machine and HRMD, while addressing the concerns regarding the overestimation of the effective height. EEVC WG20 recommended that this method should be combined with its backset measurement method (see Section 5.6) so that only one test apparatus is required to perform both measurements. However, to date the Dutch proposal has not been widely evaluated and further work is necessary before it could be recommended for regulatory testing.

5.3 RCAR-style methods using the 3-D H-point machine and HRMD

The RCAR test procedure (RCAR, 2001) is used by IIWPG, and a very similar approach is used by Euro NCAP and for backset measurements in the FMVSS 202a and GTR 7 static test options.

EEVC WG20 developed a draft head restraint geometry test procedure based on the RCAR test procedure. This procedure measures the height (relative to the top of the head) and the backset using the 3-D-H machine and the HRMD, which are shown in Figure G2. Refinements were made to the text of the RCAR procedure to improve the consistency with which the test procedure was interpreted and to introduce the application of a small load to the backset measurement tool to discourage overly soft head restraints.

The draft WG20 test procedure was evaluated for repeatability, reproducibility and usability by four laboratories (TRL, Thatcham, BASt and IDIADA) using three test tools (two manufactured by Automotive Accessories in the UK and one by TechnoSport for the SAE in the USA) and four car seats. The test procedure and the evaluation programme were reported in EEVC WG20 report – document no. 123 (Hynd *et al.*, 2006).

Overall, the results suggested that seat design may be the most important source of test variability, but that it is possible to design a seat that has relatively good test reproducibility as well as a wide range of comfort adjustments.

With a tightening of the torso angle specification from 25° ± 1° to 25° ± 0.5° and improvements in the reproducibility of the 3-D-H machine, the results of this test programme indicate that the draft WG20 RCAR-based test procedure could have sufficient repeatability and reproducibility for a regulatory test procedure.

During the development and evaluation of the draft WG20 RCAR-based test procedure, WG20 raised a number of concerns regarding the specification of the test tool used in the test procedure (the 3-D H-point machine). These concerns were reported in detail in Appendix A of the EEVC WG20 report on static geometry test procedures (Hynd, 2007a). In summary, the main concerns were:

- The geometry of the interface between the 3-D H-point machine and the seat is not sufficiently well controlled for use in evaluating the geometry of head restraints without additional calibration of the tool being undertaken. This is undesirable for a regulatory test tool, but in practice may not affect the current application of the 3-D H-point machine in regulation. However, it is not acceptable for measurement of head restraint geometry, which is more sensitive to differences in the geometry of the test tool. It should be noted that additional calibration procedures for the 3-D H-point machine and HRMD are being developed within the insurance industry whiplash protection initiative.
- The geometry of the interface between the 3-D H-point machine and the seat is not representative of any particular specification, such as the University of Michigan Transportation Research Institute 50th percentile male external geometry, so it is not clear how well it represents any particular occupant group.
- The 3-D H-point machine has rigid seat and back pans, with just a hip joint representation to allow rotation between the two pans. This means that the tool is unable to conform to the seat in the way that a human occupant would (e.g. to local structures such as lumbar support or narrow side bolsters in a sports-style seat). This means that the measured backset and height may be unrealistic for some seats, which could mean that adequate seat designs (for human occupants) are failed or that inadequate seat designs pass a given test procedure.

It should be noted that the additional calibration procedures for the 3-D H-point machine alluded to by EEVC WG20 have been completed and are incorporated in the Euro NCAP whiplash assessment procedure (Euro NCAP, 2008a). This controls the position and alignment of the torso weight hangers on the 3-D H-point machine with the objective of reducing variability in backset measurements. However, the calibration does not control the geometry of the seat and back pans of the 3-D H-point machine, which form the interface between the tool and the seat. Potential interaction of the 3-D H-point machine with local seat structures such as lumbar support or side bolsters, which may lead to an inappropriate assessment of head restraint geometry, remains a problem with this method.

5.4 Federal Motor Vehicle Safety Standard 202a

FMVSS 202a uses a RCAR-style measurement method for the head restraint backset and a UNECE Regulation 17- and Regulation 25-style measurement for the height. For both measurements, the seat back angle is set to give a torso angle (see Glossary) of 25° measured with the 3-D H-point machine; for some seats, this will result in a different torso angle than the UNECE Regulations, where the torso angle is set to the manufacturer's design torso angle. In practice, many cars have a design torso angle of 25°. EEVC WG20 found that, of 41 car and seven van models produced by eight manufacturers, 31 models had a design angle of 25° (Hynd, 2007a) (Figure 5.1).

The comments in Section 5.3 regarding backset measurement with the 3-D H-point machine apply equally to FMVSS 202a.

The height measurement in FMVSS 202a is similar in concept to that of UNECE Regulation 17 and Regulation 25, except that the H-point is used as the reference rather than the R-point, and the torso angle may be different. Height measurements may therefore be different for FMVSS 202a and UNECE Regulation 17. The height measurement error discussed in Section 5.2 will apply also to the method used in FMVSS 202a, which may lead to a marked reduction in the benefit arising from implementation of the regulation.

5.5 Global Technical Regulation 7

As noted in Section 4.1.3, GTR 7 allows Contracting Parties a certain amount of flexibility in selecting the method by which head restraint backset is assessed. One of two methods may be used:

- H-point method, using the 3-D-H machine and the HRMD.
- R-point method, using a geometric assessment (e.g. by co-ordinate measuring machine).

The H-point method is essentially the same as that used in the RCAR test procedure (see Section 5.3) and FMVSS 202a (see Section 5.4) and the same concerns apply here. The R-point method is similar to that proposed by UTAC and simplified by EEVC WG20 (see Section 5.6).

The GTR 7 height measurement method is essentially the same as that used in UNECE Regulation 17 and Regulation 25, and will therefore be subject to the same concerns (see Section 5.2).

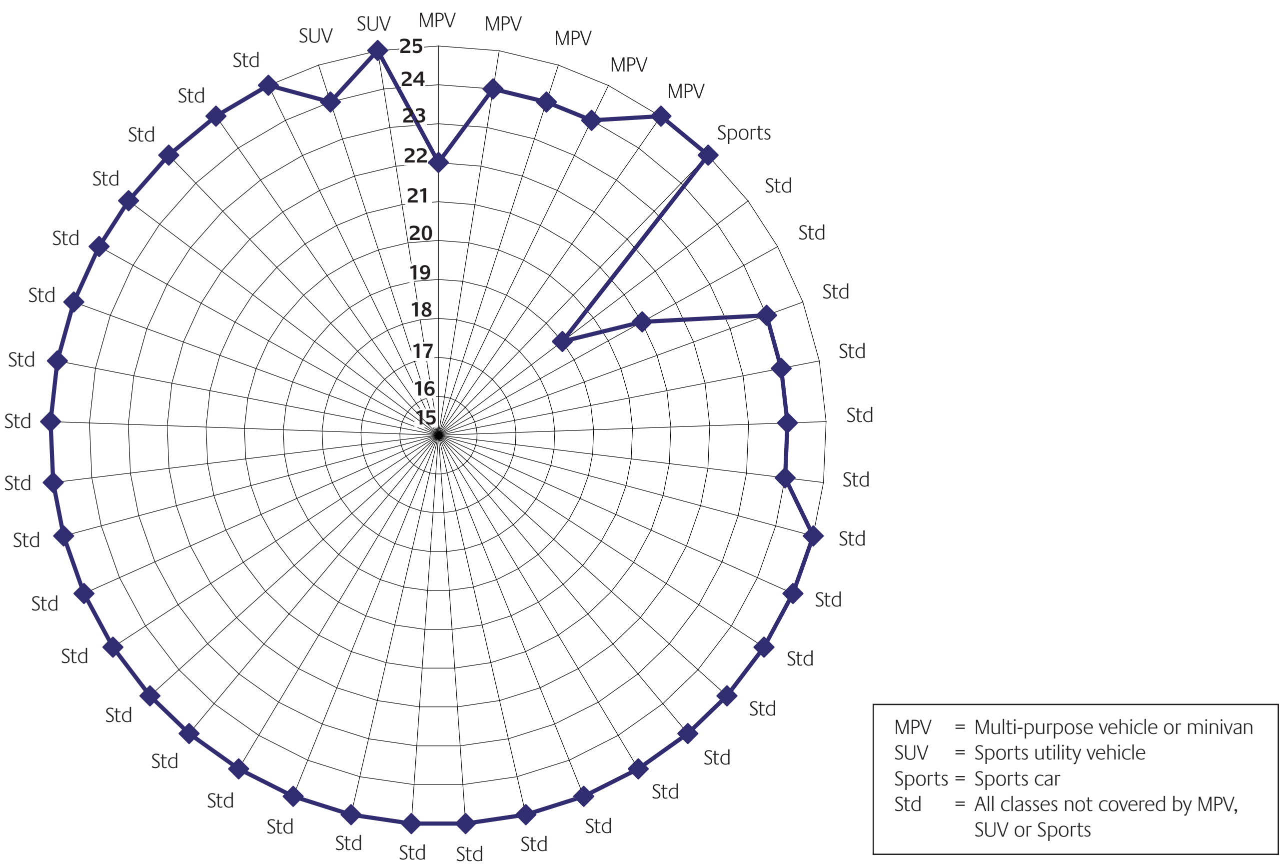

Figure 5.1 Manufacturer's design torso angles for a subset of the cars and vans from the European fleet

5.6 EEVC WG20 proposal

As a result of the work summarised in Section 5.3, EEVC WG20 investigated alternative methods of assessing head restraint geometry. For backset measurement, the following alternatives were considered:

- The proposed EuroNCAP protocol using:
  - SAE J826 H-point manikin (very similar to the 3-D-H machine).
  - HRMD.
  - No preload to head restraint.
- The draft EEVC WG20 RCAR-based test procedure:
  - Similar to EuroNCAP, but with 10 N preload to backset probe.
- An alternative proposal from UTAC (see GTR documents HR-06-03 and HR-06-06 from www.unece.org):
  - Replaces the 3-D H-point machine with a simple three-link mechanism located at the H-point (see below).
- Co-ordinate measuring machine (e.g. 3-D FARO arm) measurement without the HRMD:
  - Like the UTAC proposal, but with the seat loaded with the SAE manikin.
- Co-ordinate measuring machine measurement without the HRMD and without the 3-D-H machine:
  - Like UTAC without preload.
  - Like UTAC with 10 N preload to backset probe.

In the UTAC proposal, the 3-D H-point machine and the HRMD are replaced with a three-link mechanism, the links representing the "torso" of the 3-D H-point machine, the "neck" of the HRMD and the "head" of the HRMD. These links are used to place the backset probe (as found on the HRMD) in the correct position for the backset measurement to be made.

In the WG20 backset test procedure, the UTAC method is simplified further by replacing the physical three-link mechanism with a calculation that defines the location of the backset probe relative to the R-point. The probe is held in place by a framework, known as a portal, that allows the backset probe to translate in a fore–aft direction so that the backset measurement can be made (Figure 5.2). The 3-D-H machine is installed in the seat only to check that the R-point and seat back torso angle are within the specified limits for the seat. The backset probe is then positioned relative to the R-point using a co-ordinate measuring machine, which gives very accurate measurements of the positions of objects in three dimensions.

All five methods were evaluated by TNO and the results reported by EEVC (Hynd, 2007a). It was concluded by WG20 that:

- The variation caused by the individual seats (one type of reproducibility) and SAE manikin positioning (repeatability) is larger than the deviation caused by a change of measurement method.
- The positioning of the 3-D-H machine (including seat back angle setting) mainly determines head restraint distance.
- Head restraint distance varies with seat back angle and H-point location. This relation is not similar for all seat types.
- Within the test procedure specifications, small differences in H-point location may result in large changes of the head restraint distance. For example, in one seat the H-point location varied by 5 mm and the backset changed by 15 mm.
- No method gave more accurate results than any other method, so there is no preference for any method with regard to these results.

Figure 5.2 HRMD backset probe held in position using the adjustable portal arm

The following recommendations were also made:

- The measurement method is intended to be used for regulatory testing. This means that an easy-to-use and straightforward method will be preferred by the Type Approval engineer. The mathematical co-ordinate measuring machine (e.g. 3-D FARO arm) method without the HRMD and, if possible, even without the 3-D-H machine is therefore likely to be preferred to the method with manikin and HRMD.
- For this type of measurement (i.e. head restraint geometry), there is a need for tighter requirements on the positioning of the 3-D-H machine. Alternatively, a more straightforward point in the car, such as the R-point, could be used. The latter option does not need a 3-D-H machine, as long as there are other means to properly verify the seat back angle. Not using a 3-D-H machine can make the procedures more robust, since errors in positioning are diminished.
- The influence of each of the parameters determining the measured head restraint distance can be investigated more thoroughly using a larger sample size of measurements.

It was noted by WG20 that a simple (co-ordinate measuring machine-based) method could easily be extended to other occupant sizes, e.g. 95th percentile male. Based on this investigation, the simple co-ordinate measuring machine method was adopted by WG20 for backset measurement.

5.7 Discussion

All of the static measurements of head restraint geometry reviewed above have advantages and disadvantages. For backset, two principal methods have been used: the RCAR-style method using the 3-D H-point machine and the HRMD; and a simplified approach using the geometry of these test tools but without any interaction with the seat. The RCAR-style approach has the advantage that the seat is loaded in a manner that is intended to be representative of a 50th percentile occupant, but the disadvantages that the interface between the 3-D H-point machine and the seat is not well controlled, and that the interaction with the seat is not human-like as the machine cannot conform to the shape of the seat. This is particularly an issue for seats with prominent lumbar support or narrow side bolsters. These issues mean that the backset measurement may not be representative of that for a human occupant, and that there may be practical difficulties in making the measurements with some seat types. If nothing else, this may be design restrictive for seat manufacturers, without any benefit for the seat occupant.

The simplified approaches recommended by EEVC WG20 and adopted as an option in GTR 7 have the advantages that the measurements are quick and easy to make, and are equally applicable to all seat shapes. The measurements are different to those obtained with the RCAR-style method, but the review by WG20 indicated that the results of both are consistent and that with an appropriate backset threshold each can provide an equivalent assessment of head restraint backset.

All of the backset measurement methods have three further disadvantages:

1) The head restraint may be forced backwards by the head during an impact and therefore offer less protection than is implied by the static backset measurement.
2) It is difficult to assess some dynamic head restraint systems, particularly reactive head restraints that are deployed by the inertia of the occupant during a rear impact acting on a mechanism inside the seat.
3) Static tests may be perceived to be design restrictive as equivalent protection may be offered by dynamic head restraint systems.

FMVSS 202a and GTR 7 offer an alternative to the static backset measurements: a dynamic test of head restraint geometry. These alternatives are intended to allow innovative head restraint design solutions, while ensuring that the head restraint provides good support to the head early in a rear impact event. These test methods, along with a proposed alternative, are reviewed in Section 6.

The height measurement methods also fall into two categories: the RCAR-style method and the UNECE Regulation 17-style method. The RCAR-style method again has the disadvantages associated with the interaction of the test tools with the seat, and it measures to the highest point on the head restraint, which may be higher than the effective height of the head restraint (i.e. the highest point that will offer support to the centre of gravity of the head). The Regulation 17-style method has been shown to overestimate the effective height of the head restraint, in some cases markedly so. This means that the method will offer protection to a much lower proportion of the population than intended, and the cost-benefit of the test procedure will be adversely affected.

Several proposals have been made for alternative methods to measure the effective height of head restraints, but none are yet fully developed. It is also not clear how these, or existing height measurement methods, will work with the dynamic head restraints that are becoming more common, or future designs that may be developed to meet dynamic backset requirements.

If an appropriate dynamic test of backset were used instead of the static measurements reviewed above, the height of the head restraint would have to be at least adequate for the height of dummy used, typically representing a 50th percentile male. If it were decided that the height should be adequate for a greater proportion of the population, then additional height measures would be required.

6 Critical review of dynamic head restraint geometry measurement methods

As mentioned in Section 5.7, FMVSS 202a and GTR 7 include options for the dynamic assessment of head restraints. This test is intended to overcome some of the difficulties with static geometry test methods, particularly relating to active and reactive head restraints. Sections 6.1 and 6.2 below outline the dynamic test method and summarise the critical review of the method published by EEVC. Section 6.3 gives an overview of the work undertaken by TRL on behalf of the UK Department for Transport to develop an alternative dynamic backset test procedure as part of the UK contribution to EEVC WG20. This includes the evaluation of several options, the selection and preliminary validation of a proposal for an alternative test procedure and recommendations for further work to validate fully the draft procedure.

6.1 Federal Motor Vehicle Safety Standard 202a

The dynamic test option in FMVSS 202a facilitates the development of active and reactive head restraints that have a greater backset in normal use than is allowed by the static backset requirement, but which deploy during a rear impact to provide improved geometry when it is needed. The dynamic test involves mounting the whole vehicle on a sled, with all unsecured components removed (e.g. tyres, wheels and fluids) and with elements such as the engine, transmission, axles and exhaust rigidly secured so that they do not affect the pulse applied to the seat.

The dynamic test uses the 50th percentile male Hybrid III dummy, with a head-to-torso angle limit of 12° and a HIC15 limit of 500. However, many groups have questioned the appropriateness of both the dummy used and the head-to-torso rotation angle limit. These issues will be discussed further in Section 6.2.

6.2 Global Technical Regulation 7

As an alternative to the static backset assessment in GTR 7, a dynamic test is described. This facilitates the development of active and reactive head restraint systems. The default test procedure is that of FMVSS 202a with the same requirements of 12° on head-to-torso rotation angle and a HIC15 limit of 500, measured with the Hybrid III 50th percentile male dummy. Each Contracting Party has the option to adopt an alternative test using the BioRID II dummy from their national regulation or an updated version of GTR 7 or, if such a national regulation does not exist, to not adopt a dynamic test at all. Where a dynamic test is allowed by a Contracting Party, the option of whether to perform a static or dynamic test is left to the manufacturer and is not dependent on the type of head restraint.

The "Statement of Technical Rationale and Justification" in the GTR text "acknowledges differing views associated with the use of the Hybrid III dummy". In Europe, EEVC had co-ordinated extensive research to develop biofidelity requirements for crash test dummies used in low-speed rear impact test procedures, where the performance of the dummies was compared with four sets of target corridors based on volunteer tests, and one set of target corridors based on Post Mortem Human Subject (PMHS) tests (Hynd *et al*., 2007b). The performance of the Hybrid III, RID3D and BioRID II dummies was subsequently assessed to these biofidelity requirements (Carroll *et al*., 2007). EEVC recommended that the Hybrid III dummy is not of sufficient biofidelity for use in low-speed rear impact test procedures. In addition, EEVC reviewed the literature on the biofidelity of the Hybrid III dummy in low-speed rear impacts, including the information presented to the GRSP Informal Working Group on Head Restraints[6], and considered the wider implications of the possible use of the Hybrid III dummy in low-speed rear impact test procedures (Hynd, 2007b and 2007c).

EEVC reported that the evidence reviewed showed that the Hybrid III dummy is not biofidelic in low-speed rear impacts and should not be used to test seats in these conditions. For some seat designs, some head-neck motion and force parameters are reasonably comparable to those of a human occupant, but this is dependent on the particular interaction between the Hybrid III back (the shoulders and/or the thoracic spine) and the seat back. All studies that have specifically examined the interaction between the Hybrid III dummy and the seat back have found that the interaction is not at all human-like due to the rigid thoracic spine of the dummy. Most importantly, evidence was reviewed that showed a reactive head restraint being actuated very effectively (i.e. moving the head restraint substantially forward, thereby giving a small backset) when tested with the Hybrid III dummy, but actuating poorly with the more biofidelic BioRID II dummy. The implication from this is that seats tested using the Hybrid III dummy may offer much lower protection to a human occupant than would be assumed from the dummy test results. It was also found that the Hybrid III dynamic test with a 12° head-to-torso rotation limit would fail the Volvo WHIPS seat (see GTR documents HR-05-12 and HR-07-13 from www.unece.org), which has been shown to be one of the most effective seats on the market at reducing the risk of whiplash injury in a rear impact (Kullgren *et al*., 2007).

EEVC recommended that in order to ensure that the dummy interacts with the seat in the same way as a human in a low-speed rear impact, and thereby to ensure that the assessment of the seat is reliable and the prediction of injury savings is robust, the dummy used should have a more flexible spine than the Hybrid III.

6.3 EEVC activity

As introduced above, one of the terms of reference for EEVC WG20 is to deliver a procedure and metric that could be used to evaluate the geometry of head restraints in a dynamic test. This is considered to be particularly beneficial for assessing the geometry of active and reactive head restraints. As a contribution to this objective, TRL (under contract to the UK Department for Transport and as part of the UK contribution to EEVC WG20) evaluated several concepts for dynamic head restraint geometry test procedures and metrics (Hynd and Carroll, 2008). These concepts had been proposed in WG20 and other fora, used in the development of existing test procedures, or were developed specifically as a contribution to WG20.

6 Available from the UNECE website, www.unece.org.

The TRL project took three main technical approaches to the development of a dynamic head restraint geometry metric:

- Review dummy metrics from consumer information test programmes, and elsewhere if other sources of data could be identified, and correlate the metrics with head restraint geometry.
- Using existing BioRID II seat test data, make recommendations for metrics using the method used to develop the head-to-torso angle criterion used in the Hybrid III dynamic test in FMVSS 202a.
- Analyse existing rear impact seat test footage to determine whether dynamic metrics from marker tracking are feasible and reliable.

6.3.1 Control of head restraint geometry based on BioRID II measurements

In lieu of a recommendation on a preferred dummy from WG12, and given that the Hybrid III is not considered by WG12 or WG20 to be an appropriate test tool for low-speed rear impact testing, only the BioRID II and RID3D dummies could be considered for use in measuring head restraint geometry dynamically. Furthermore, few test data were, or are, available for the RID3D compared with the BioRID II. This work item therefore aimed to make recommendations on metrics that could be used with the BioRID II, should that dummy be recommended in the future by WG12, based on existing test data from WG20 partners and other organisations. The focus was on evaluating metrics that would correlate with head restraint geometry in a static test procedure, rather than with a particular risk of injury.

To assist in this task, Thatcham provided a database of results from several hundred IIWPG consumer information seat rating tests. The IIWPG database provided static geometric measurements for the seats, using the RCAR protocol with the SAE J826 H-point manikin and the HRMD headform. It also provided BioRID sensor measurements (such as neck forces and accelerations) and, where required in the test specification, BioRID external measurements (such as head restraint contact time) from dynamic tests with the same seats. An initial review of the options was based on plotting each of the BioRID measurements against the head restraint geometry for that seat. The correlation between the two parameters was then derived.

The best two measurements based on the Thatcham database were upper neck shear force F_x and NIC (Neck Injury Criterion). The corresponding R^2 values were 0.28 and 0.26, respectively, when looking at the seats with passive head restraints with good or adequate height. Neither of these parameters differentiated well between seats with different static backset measurements. For instance, a threshold of just 50 N on upper neck shear, which would fail many seats with a “Good” IIWPG rating, would still allow a seat with a static backset of over 80 mm to pass.

It was concluded that static head restraint geometry was not well correlated with any of the BioRID II dummy measurements or derived seat performance criteria and that these measurements and criteria would not be suitable for controlling head restraint geometry in a dynamic test. Therefore, further statistical analysis was conducted to see if a combination of measurements provided a better model for the geometry.

The statistical analysis developed multiple-parameter models that had a much higher R^2 value (up to $R^2 = 0.62$) than the single-parameter models above. However, even the “best” model had too much scatter to enable it to be used to control backset to the level in the GTR (55 mm). The model was also very complex and would be very difficult to use as a design target for new seat development.

Overall, Hynd and Carroll (2008) concluded that it was not feasible to control static head restraint backset using existing BioRID II instrumentation measurements or external measurements such as head restraint contact time. Strictly, this conclusion is only valid for the IIWPG test procedure, dummy measurements and seat performance criteria, as these were the only ones assessed in detail. However, experience with the dummy and review of the UNECE GRSP/GTR documentation suggest that similar results would be expected for other test conditions and dummy measurements.

6.3.2 Development of a head restraint geometry metric using the NHTSA 202a method

The approach used to develop the head-to-torso angle criterion used in FMVSS 202a was reviewed in detail by Hynd and Carroll (2008). There has been much criticism of the use of the Hybrid III high-speed frontal impact dummy for low-speed rear impact testing in this test procedure. However, it was considered that the underlying approach for developing the criterion may be applicable to developing new criteria for rear impact dummies.

NHTSA had compared measurements taken with a Saab 9-3 seat featuring the Saab Active Head Restraint System with those from the equivalent previous model, the Saab 900. Real-world effectiveness data were available for both of these vehicles (Viano, 2002). NHTSA used a logistic regression analysis on the two data points that this approach provides to develop an injury risk function for Hybrid III head angle in low-speed rear impacts. Underlying this is the understanding that the vehicle structure of the Saab 900 and 9-3 v1 were identical and that the only difference between the whiplash injury risk of the two models would be due to the change of seat design.

It was originally intended to repeat this approach using existing BioRID II dummy test data, comparing instrumentation readings (such as neck loads) and derived seat performance criteria (such as N km) in the same vehicle seats, knowing the real-world performance of the two seats. The method could also be applied to Volvo V70 seats with and without the WHIPS. However, despite the expectation that equivalent test data with the BioRID on these Saab and Volvo seats would be available, these data could not be obtained during the period of this work.

In addition, an initial review conducted by Hynd and Carroll (2008) found that there was considerable criticism of the approach in the literature, most significantly:

- Only two data points are used, from just one car model (in terms of the underlying structure), and it is not clear that this would be representative of the risk in the fleet in general or whether this is a function only of the two seat designs used.

- The head-to-torso angle threshold of 12° fails the Volvo WHIPS seat, which is generally agreed to be one of the best for real-world injury reduction.

It was therefore recommended that this approach is not used to develop dynamic head restraint geometry metrics at this time.

6.3.3 Dynamic backset measurements from film analysis

Finally, as part of the TRL project reported by Hynd and Carroll (2008), a large study was undertaken to establish the feasibility of using film analysis of markers placed on the seat, head restraint and dummy to control head restraint backset. No new testing was undertaken for this work, so feasibility was assessed using film from existing rear impact seat tests. Due to the good availability of existing data, all of the films analysed used the BioRID II dummy and test procedures based on that developed by IIWPG.

Extensive analysis of films from a recent Euro NCAP Technical Working Group (TWG) test programme was undertaken using 2-D marker tracking software. Based on a preliminary analysis, two main dynamic test metrics were evaluated in detail:

- Calculation of the rearward motion of the occipital condyle (OC) pin (at the top of the neck of the BioRID II dummy) relative to the T1 (first thoracic vertebra, at the base of the neck); and
- Calculation of the forward motion of the head restraint up until head-to-head-restraint contact time.

It was found that both metrics were feasible, and tracking of head restraint motion could be used to develop a metric that would be directly equivalent to static measurements of head restraint backset. However, some head restraints were observed to have considerable rearward motion after head contact with the head restraint, which would not be accounted for and which may be expected to increase the whiplash injury. The first metric, known as dynamic backset, was able to account for this additional rearward motion and was therefore evaluated in more detail. A description of the marker tracking process and the dynamic backset measurement are provided in Appendix B.

The Euro NCAP TWG tests were undertaken independently of this investigation and for reasons other than the development of marker-based head restraint geometry metrics. As a result, marker positions varied somewhat from laboratory to laboratory and even from test to test. Also, a range of other factors was expected to increase the variability of the results. For example:

- Some sleds were acceleration sleds and some were deceleration sleds.
- Some laboratories used on-board cameras and some used off-board cameras.
- Each laboratory used its own BioRID dummy, so data were obtained from five different dummies at five different laboratories.
- The lighting was set up to enable tracking of the seat and head, but was not always good for tracking the neck pins.
- The films provided were compressed.

Overall, this should provide a worst-case test of the reproducibility of any metrics calculated from the marker tracking data. The dynamic backset was found to have a unique shape and magnitude for each of the three seats and reasonably good reproducibility across the different laboratories, dummies, sled and camera configurations. An example of the results for one of the seats is shown in Figure 6.1.

In parallel with this, IIHS provided BioRID II films of the four seats used by NHTSA as additional validation of the FMVSS 202a test procedure (Voo *et al*., 2007). Three of the four seats were rated by IIWPG as “Good” and one as “Adequate”, and Voo *et al*. found that the Hybrid III head angle metric gave a similar ranking to the seats. In a similar way, the dynamic backset metric grouped the three seats with “Good”

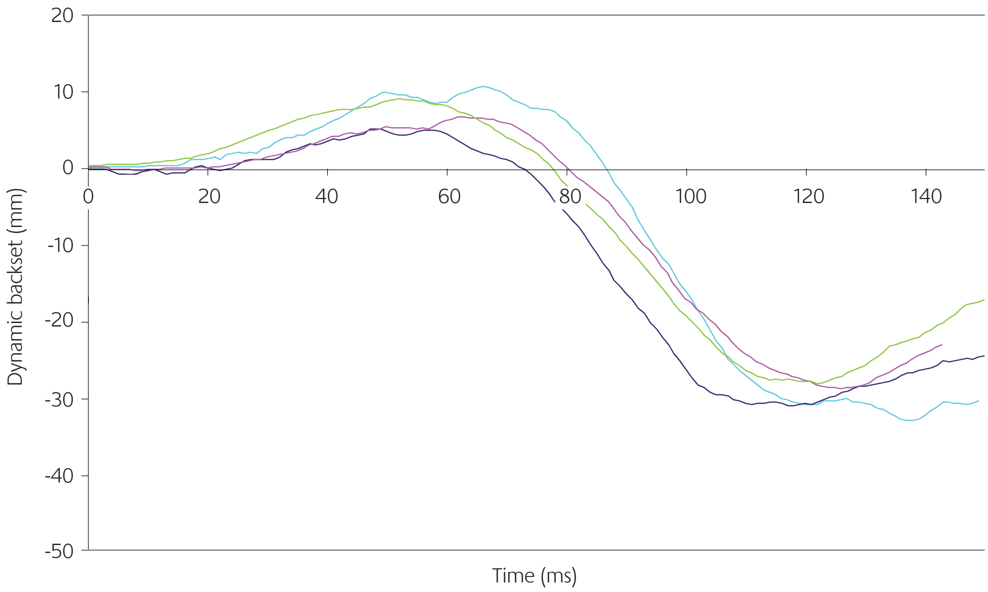

Figure 6.1 Dynamic backset with respect to T1 in a seat back co-ordinate system
BioRID dynamic backset – four laboratories and BioRID IIs: two deceleration sleds, two HyGe (one on-board camera, three off-board cameras)

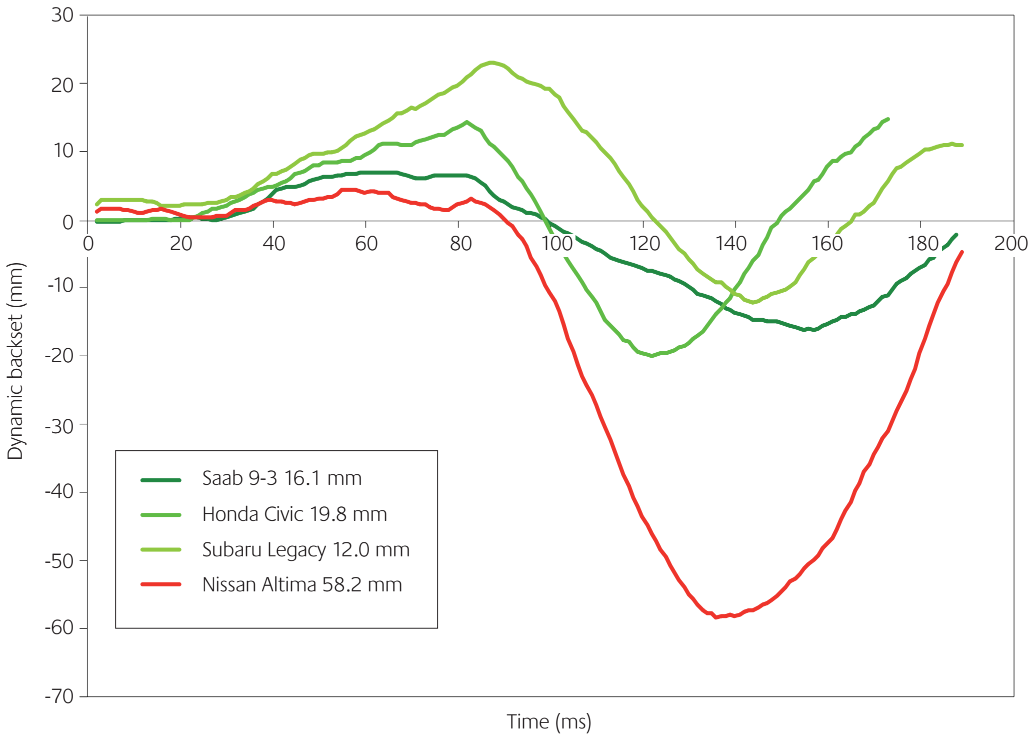

Figure 6.2 Dynamic backset with respect to T1 for the four seats used in Voo *et al*. (2007)*
* The Nissan Altima was rated “Acceptable” by IIWPG, while the three other seats were rated “Good”

ratings together, with very low dynamic backsets, and the seat rated average had a much larger dynamic backset (Figure 6.2).

Together, these results suggested that the dynamic backset metric is very promising as a criterion for controlling head restraint backset in a dynamic test procedure (full evaluation results are reproduced in Appendix B). The calculation of head restraint movement also worked well, and would be directly equivalent to the static backset measurement of standard head restraints. However, it was considered to be less likely to correlate with real-world performance as the head restraint may be forced backwards after head contact, which is expected to increase the risk of whiplash injury. As a result, it was recommended that the head restraint movement metric should not be taken forward at this time.

The proposed dynamic backset metric was presented to EEVC and to the Informal Working Group on Head Restraints that developed GTR 7. The method has also been further evaluated by the Japanese delegation to GRSP and was proposed by Japan as an update to UNECE Regulation 17 at GRSP in May 2008 (JASIC/Japan, 2008).

Hynd and Carroll (2008) recommended that the dynamic backset method be developed further as a dynamic alternative to existing static backset test procedures. The following tasks were recommended in order to achieve this:

Improved validation

- It was not possible with the marker tracking software available to correct for the distance between the markers that were tracked and the focal plane of the camera. It is expected that such depth correction would improve the reproducibility of the dynamic backset metric.

Performance specification

- The indications from this work programme are that it is possible to use marker tracking to give a reproducible assessment of OC–T1 relative motion, among other potential metrics. However, it is also possible to perform poor marker tracking, even when using good-quality equipment (cameras, lenses, lighting, marker tracking software and so forth). It is recommended that a performance specification is developed so that laboratories can confirm that they are able to perform marker tracking to a suitable standard.

Development of a threshold

- It is recommended that comparison of the dynamic backset metric with the known real-world performance of certain seats should be undertaken to develop a threshold for the metric.

7 Conclusion

Although classified as minor injuries, whiplash associated disorders frequently result from car crashes and the cost of long-term whiplash injuries in the UK alone has been estimated at £3 billion per year. Good head restraint geometry is considered to be a basic requirement in the design of seats to mitigate whiplash injuries. As a result, numerous regulatory and consumer information test procedures measure the height of head restraints and many of them also assess the backset of the head restraint.

The procedures used to measure the height and backset of head restraints in a static test procedure are varied, and each approach has benefits and drawbacks related to the test tools and measurement methods used. It has been identified that the height measurements that are used overestimate the effective height of the head restraint, and will therefore tend to underestimate the proportion of the population that would be expected to receive protection from the height of the head restraint. This is particularly so for the method used in UNECE Regulation 17 and Regulation 25. Several proposals have been made for alternative measurement methods that will estimate the effective height of the head restraint – i.e. the height that will provide adequate support to the centre of gravity of the head. It is unclear how these, or existing height measurement methods, will work with the dynamic head restraint designs that are becoming more common, or future designs that may be developed to meet dynamic backset requirements. It is important that an appropriate method is devised in order to ensure that head restraints are designed such that they can be adjusted to a suitable height for the large majority of the population.

Static measurement of backset is also problematical for dynamic head restraints, because the head restraint is designed to have a large backset in normal use and only deploy to a position with a small backset during (or immediately prior to) a rear impact. One alternative is to test the backset dynamically, and several options have been reviewed in this report.

For a dynamic rear impact seat test to be reliable, and thereby encourage seat designs that will result in the predicted reduction in whiplash injuries, it is very important that the dummy used in the test interacts with the seat in a biofidelic manner. EEVC reviewed three candidate dummies for low-speed rear impact seat tests: Hybrid III, RID3D and BioRID II. EEVC reported that the Hybrid III was not of sufficient biofidelity for use in low-speed rear impact test procedures. In particular, the interaction with the seat back was not at all biofidelic due to the rigid thoracic spine of the dummy. Most importantly, evidence was reviewed that showed a reactive head restraint being actuated very effectively (i.e. moving the head restraint substantially forward, thereby giving a small backset) when tested with the Hybrid III dummy, but actuating poorly with the more biofidelic BioRID II dummy. Overall, EEVC recommended that the BioRID II was the most biofidelic dummy in terms of its head-neck kinematics and seat interactions.

A dynamic rear impact test using the Hybrid III frontal impact dummy is incorporated in the US regulation FMVSS 202a and in the recently agreed GTR 7. Due to the concerns regarding the use of the Hybrid III dummy in low-speed rear impacts, an alternative test procedure using the BioRID II has been developed at TRL. This procedure has been presented to EEVC and has been proposed as an update to UNECE Regulation 17 at GRSP by the delegation from Japan.

A key advantage of this test procedure is that it assesses not just static backset, but also gives an assessment of how far rearwards the head restraint is pushed when it is loaded by the head. This will typically result in a larger dynamic backset than the static backset that would be measured for conventional seats. The method also means that the assessment of seats with conventional head restraints and seats with dynamic head restraints can be compared directly.

It is recommended that further work is required to refine this test procedure, particularly in terms of validating the accuracy of the marker tracking camera system that is used for the measurements, and to recommend a performance threshold for the dynamic backset measurement.

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Glossary of terms and abbreviations

3-D-H machine The name that is used for the H-point tool (see SAE J826) as it is used in UNECE Regulations.

AIS The Abbreviated Injury Scale is a standard system for categorising injury type and severity. It arose in the mid-1960s alongside multidisciplinary motor vehicle crash investigation teams. Specialists in engineering, medicine, anatomy/physiology and crash investigations made up these teams, which were organised to collect epidemiological data from crashes. The AIS was developed to code trauma for impact injury assessment using a standard scale that all of the specialists could employ and relate to.

Backset The backset for a head restraint is the horizontal distance from the rear of the head of an occupant to the front surface of the head restraint (Figure G1). The measurement is usually taken longitudinally rearwards from the centre of gravity of the head of an occupant (or occupant surrogate). To provide a standard physical measurement tool throughout the industry, the Head Restraint Measurement Device (see HRMD) was introduced as an addition to the H-point manikin.

Contracting Party Any country member of the United Nations, and any regional economic integration organisation set up by country members of the United Nations, may participate fully or in a consultative capacity in the activities of the United Nations World Forum for Harmonisation of Vehicle Regulations (WP.29) and become a Contracting Party to the agreements administered by WP.29.

FMVSS Federal Motor Vehicle Safety Standard. The US regulations relating to motor vehicle safety.

GRSP Working Party on Passive Safety.

GTR Global Technical Regulation.

H-point Defined as the position of the mechanical hinge between the thigh and torso of the standard H-point manikin (3-D H-point machine, SAE J286), when correctly installed. It is meant to represent the approximate position of the hip of an average human occupant. It is used to provide a standard reference point when installing occupant surrogates such as test dummies, against which their seating position can be referenced.

HRMD The Head Restraint Measurement Device was introduced as an add-on to H-point manikins in order to be able to measure head restraint height and backset in relation to the top and back of an occupant surrogate's head, respectively. An example of the device, being used, is shown in Figure G2.

IIHS Insurance Institute for Highway Safety, a US member of IIWPG.

IIWPG International Insurance Whiplash Prevention Group, a consortium of research groups supported by the insurance industry.

NHTSA National Highway Traffic Safety Administration, part of the US Department of Transportation.

R-point The standard H-point of the seat, as defined by the vehicle manufacturer.

RCAR Research Council for Automotive Repairs.

SAE J826 Society of Automotive Engineers Standard J826. This standard defines the H-point manikin (also known as a 3-D H-point machine or H-point machine) that is used to confirm that the H-point (i.e. the centre of the hip of the occupant of a car seat) of a car is correct. The J826 H-point tool is also used to set the seat back angle and in some standards is used with the HRMD to measure head restraint height and backset. The SAE J826 manikin is shown in Figure G3.

SRA Swedish Road Administration.

Thatcham Motor Insurance Repair Research Centre, a UK member of IIWPG (mostly referred to as Thatcham).

Torso angle The angle of the torso of the 3-D H-point machine when correctly positioned in a car seat, used to set the angle of the seat back in some test procedures.

UNECE United Nations Economic Commission for Europe. The transport division of UNECE is responsible for publishing the Vehicle Regulations for Europe. Since 1958, there has been an agreement that each country within Europe will do their part in adopting these Vehicle Regulations into their national legislation. The regulations therefore provide uniform technical prescriptions throughout Europe.

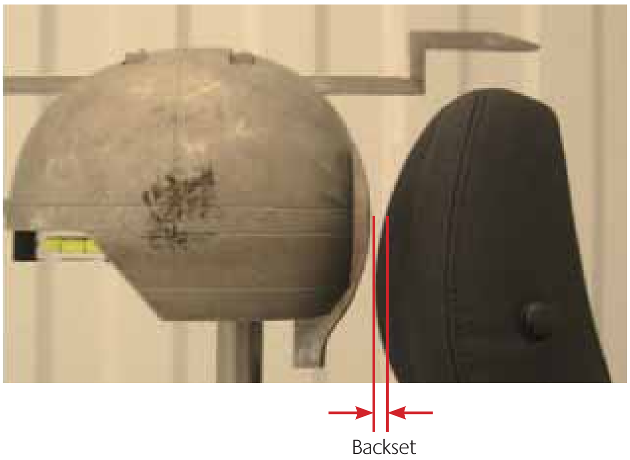

Figure G1 Head restraint backset, ready for measurement with an HRMD

Figure G2 HRMD fitted onto an SAE J826 H-point machine

Figure G3 SAE J826 H-point machine (no HRMD)

Appendix A: UNECE Regulation 17 and Regulation 25 head restraint height measurement error

There are a number of reasons why the Research Council for Automobile Repairs (RCAR) head restraint heights are not the same as those made using the United Nations Economic Commission for Europe (UNECE) Regulation 17 method. Fundamentally, these are potential differences in the locking position of the head restraint that is measured (top-most use position in Regulation 17 and Regulation 25, and mid-locking position in the RCAR procedure) and the definition of the torso angle for the seat back (the manufacturer's design torso angle in Regulation 17 and a fixed angle of 25° in the RCAR procedure).

More subtle differences come about through the measurement strategies themselves. It was found that the measurement of the maximum (adjustable) height of a head restraint using the Regulation 17 method could be misleading as it includes "height", which may not contribute to the protection of the occupant. This error is explained in the following figures.

The text describing the measurement procedure from UNECE Regulation 17 is reproduced below and is shown by the blue lines in Figure A1.

6.5 Determination of the height of the head restraint.

6.5.1 All lines, including the projection of the reference line, shall be drawn in the vertical median plane of the seat or seating position concerned, the intersection of such plane with the seat determining the contour of the head restraint and of the seat back (see Figure 1 of Annex 4 to this Regulation).

6.5.2 The manikin described in Annex 3 to this Regulation shall be placed in a normal position on the seat.

6.5.3 The projection of the reference line of the manikin shown in Annex 3 to this Regulation is then, in the seat concerned, drawn in the plane specified in paragraph 6.4.3.1 above. The tangent S to the top of the head restraint is drawn perpendicular to the reference line.

6.5.4 The distance "h" from the R-point to the tangent S is the height to be taken into consideration in implementing the requirements of paragraph 5.5 above.

The National Highway Traffic Safety Administration (NHTSA), in its final regulatory impact analysis for FMVSS 202 (NHTSA, 2004), published an approximate conversion between the RCAR and Regulation 17 measurement techniques. This was an attempt to convert RCAR height measurements to the Regulation 17 height and is shown in Figure A2. The red triangle shows the RCAR height measurement (vertical distance from the H-point to the top of the head of a 50th percentile male minus the vertical distance between the top of the head and the top of the head restraint, i.e. 755 mm – RCAR height) and the projection of this height on to the torso angle line at 25° to the vertical (dotted red line). Similarly, the green triangle shows the backset component (the horizontal distance between the H-point and the back of the head of a 50th percentile male plus the RCAR backset measurement, i.e. 254 mm + RCAR backset). The dotted green line shows the projection of the backset component on the torso angle line. However, the backset component is actually slightly longer than 254 mm + RCAR backset, as shown in Figure A3. The error that this produces along the torso angle line is shown in Figure A4.

This demonstrates the (typically small) error in converting the RCAR height and backset measurements to an equivalent measurement along the torso angle of the 3-D H-point machine. However, there is an additional (and typically larger) error between this value and the value measured using the Regulation 17 height measurement method, as shown in Figure A5. The pink lines show the difference between the NHTSA estimate (which is an overestimate) of the RCAR-equivalent height and the Regulation 17 height measurement. The difference is due to the fact that the Regulation 17 method measures to the top, backmost corner of the head restraint (unless the top of the head restraint is sloped back at an angle at least equivalent to the torso angle, which is very unusual). This error has been documented previously in HR-02-03e from the GRSP Informal Working Group on Head Restraints.

For the seat shown here, the total error is approximately 48 mm. If the head restraint height was intended to protect 95% of the UK male population, this overestimate of the effective height of the head restraint would mean that only 56% of the UK male population would actually be protected. The error will be greatest for head restraints with large front-to-back depth and high rear edges.

According to the calculations used in the WG20 cost-benefit study, a head restraint height of 800 mm would be expected to protect 55% of the UK male population and 98% of the UK female population. With an error of 48 mm in the height measurement, these proportions become 8% and 64%, respectively.

Fixed head restraints typically have a narrow front-to-back depth (which would reduce the error), but one of these head restraints has an error of approximately 40 mm. The error would be expected to be worse for adjustable head restraints than fixed head restraints due to their typically greater front-to-back depth.

References

NHTSA (2004). *FMVSS no. 202 head restraints for passenger vehicles: final regulatory impact analysis.* Docket no. NHTSA-2004-19807. Washington DC: National Highway Traffic Safety Administration.

Figure A1 UNECE Regulation 17 method for measuring head restraint height

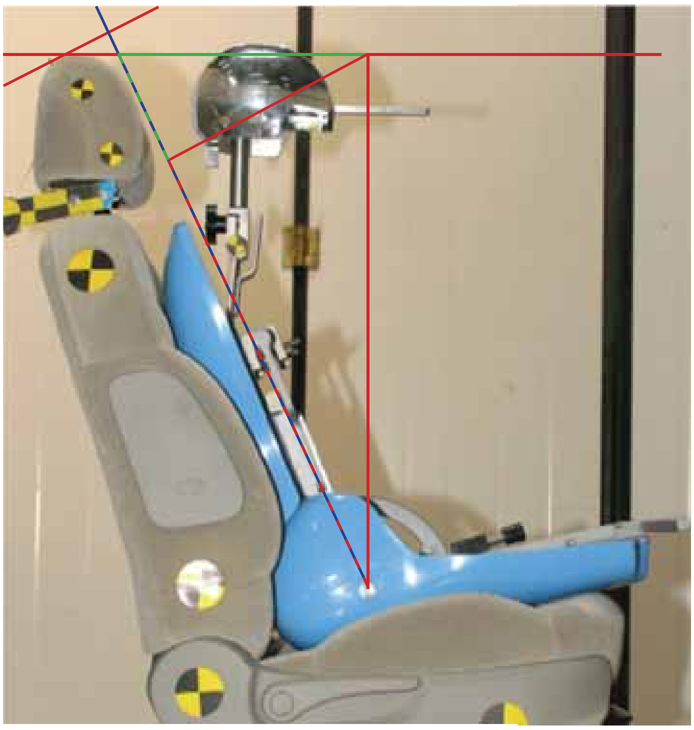

Figure A2 NHTSA conversion between RCAR and UNECE Regulation 17 head restraint height measurement

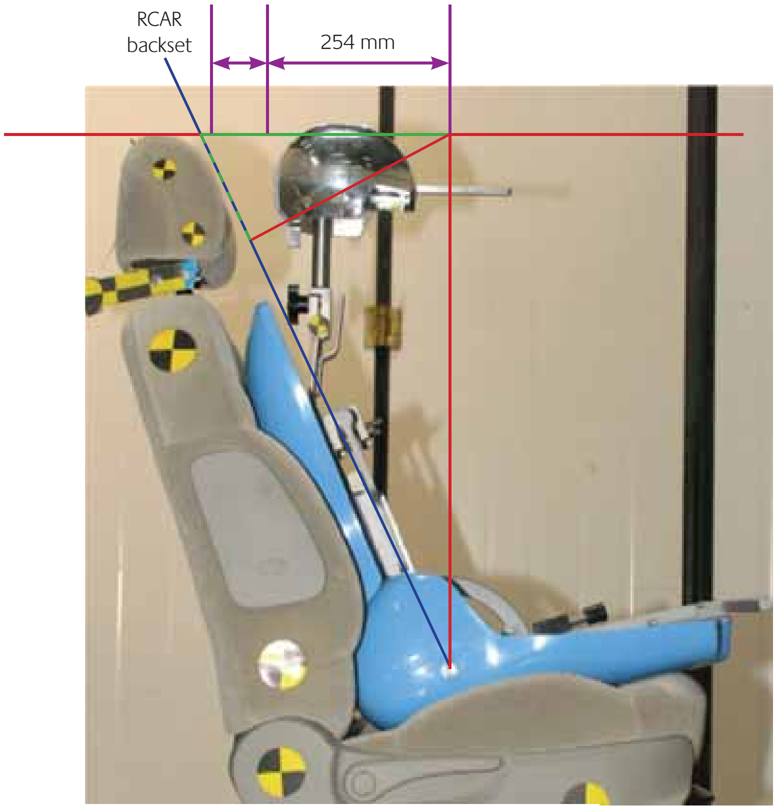

Figure A3 Underestimation error in backset conversion

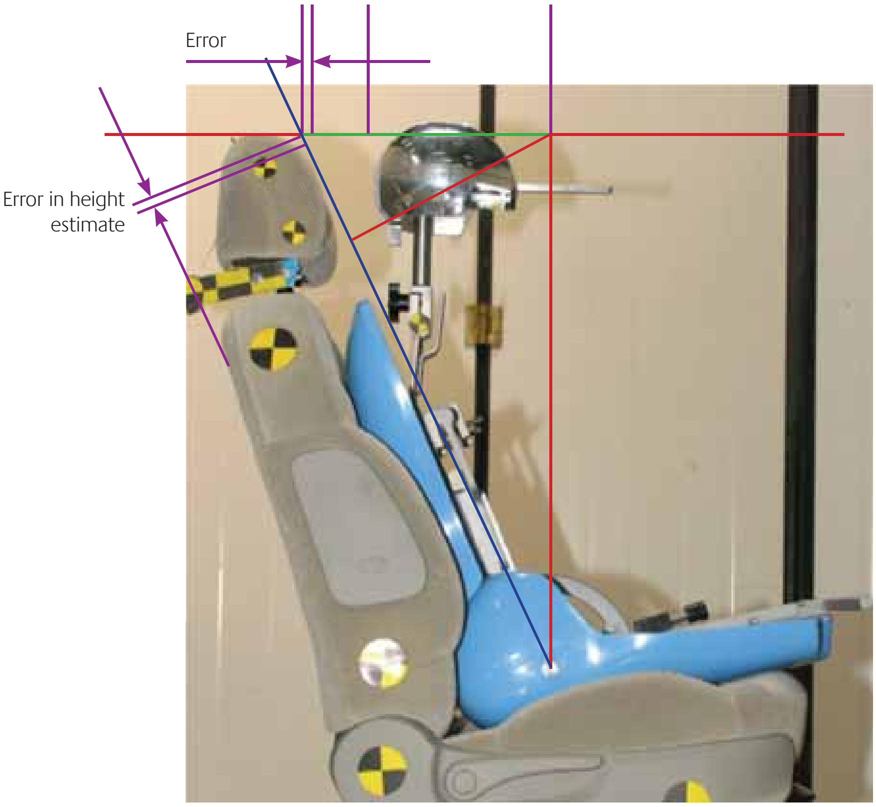

Figure A4 Effect of backset error on height estimation

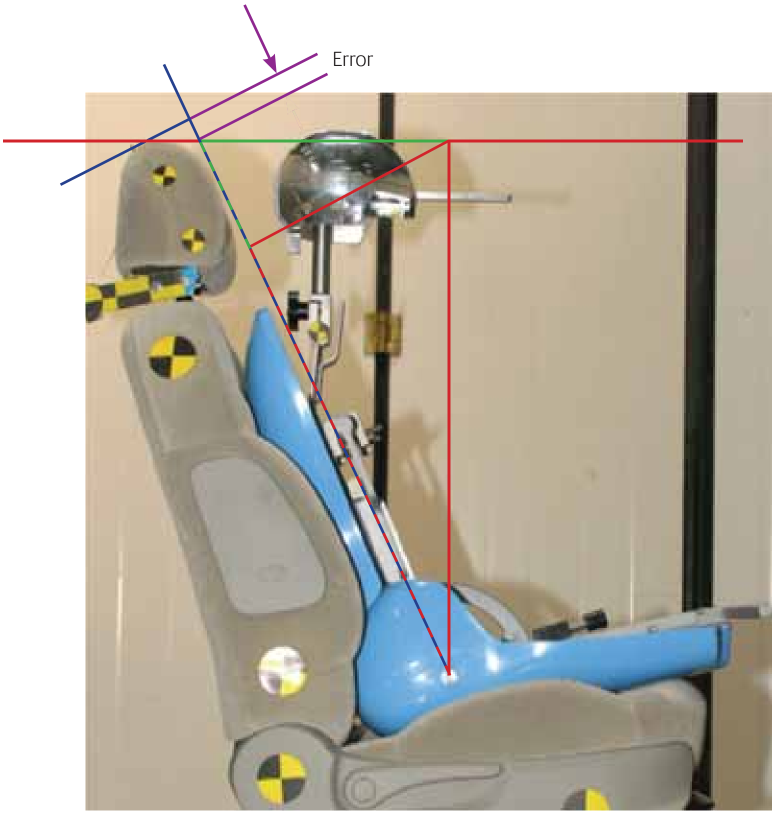

Figure A5 Error arising through inclined line defining the top of the head restraint

Appendix B: Dynamic geometry measurements from film analysis

B.1 Marker tracking for head restraint movement and dynamic backset

To track the position of the relevant points of interest, it was expected that conventional side views of rear impact sled tests could be used. The image needs to show the seat back, in its entirety, as well as the head restraint and (for dummy retraction) the head and neck of the dummy, and these points of interest need to be clearly visible throughout the impact event. Test videos were made available by five Euro NCAP Whiplash Technical Working Group (TWG) laboratories for a preliminary assessment of the dynamic geometry measurement options.

Within the videos analysed to evaluate the different options, a number of different test set-ups were used, regarding on-board and off-board cameras, acceleration and deceleration sleds, and left- and right-sided views. It is important that any measurement criterion should be robust and reproducible despite any differences in the way in which the points of interest are videoed and tracked. Therefore, the camera position differences in the video material provided were thought to be a useful test of the analysis set-up to calculate the parameter being considered for each option.

A typical image used in the video analysis process is shown in Figure B1. This figure shows the points that were used in the analysis: the upper and lower seat back points (used for both options), upper and lower head restraint points (used for the head restraint movement option) and the occipital condyle (OC) and T1 (first thoracic vertebra, at the base of the neck) pins, used for the dynamic backset measurements. These points were tracked using motion analysis software throughout the impact (of approximately 150 ms in duration) to give x and y co-ordinates for each. The x and y co-ordinates were then processed to give the parameters being considered in each case.

In the following discussion, measurements are made relative to a seat back co-ordinate system. Other co-ordinate systems – such as a T1 co-ordinate system formed by the T1 marker wand – were also evaluated, but were found to give less consistent results.

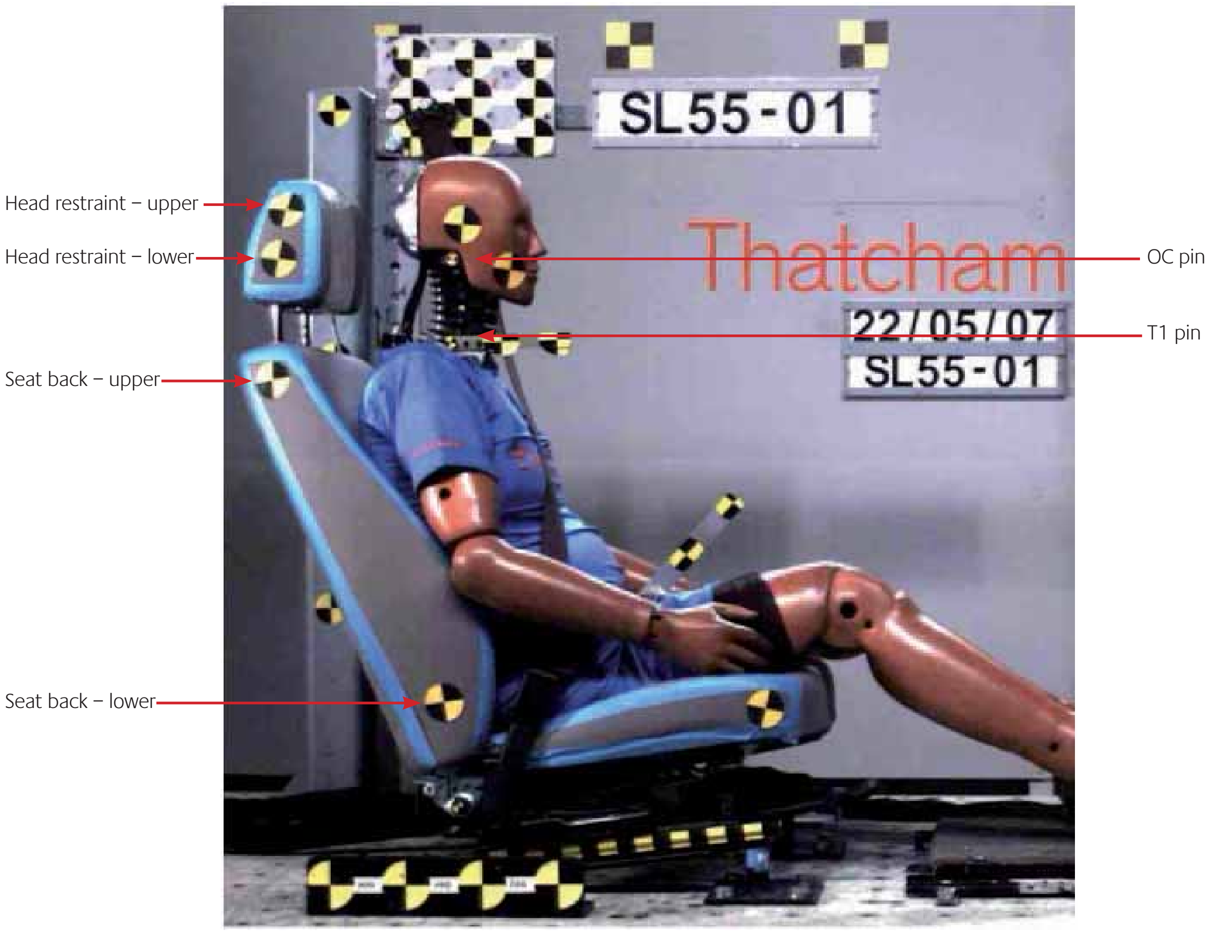

Figure B1 Pre-impact image captured from a Thatcham rear impact test video showing the BioRID II in position, with the dummy and seat points to be tracked circled

The process for the calculation of both the head restraint movement and dynamic backset was similar and is outlined below. The figures show data from an off-board camera view, where the whole seat and dummy move through the field of view of the camera during the impact event.

- Figure B2 shows the initial marker co-ordinates in each frame.
- The lower seat back marker is then translated vertically and horizontally in each frame to its position at T0, and all other markers are translated by the same amount in each frame (Figure B3). This gives all marker co-ordinates relative to the lower seat back marker in a laboratory co-ordinate system and effectively removes the motion of the sled relative to the camera.
- The markers were then rotated by the amount through which the seat back had rotated in each frame, relative to the seat back angle at T0 (Figure B4). This removes seat back rotation from the assessment of head restraint motion or head–T1 relative motion.
- The movement of the head restraint can then be assessed, or the x-axis displacement of the OC neck pin with respect to the T1 pin can be calculated (see Appendix B.2).

The process is also shown in the sequence of frames in Figure B5. Frame A shows the position of the dummy at T0; frame B the position of the dummy at maximum dynamic backset; and frame C superimposes frames A and B to show the movement of the dummy. It is apparent from frame C that the seat back markers have not moved between frames A and B, but the head restraint and dummy (as well as the seat base) have moved relative to the seat back.

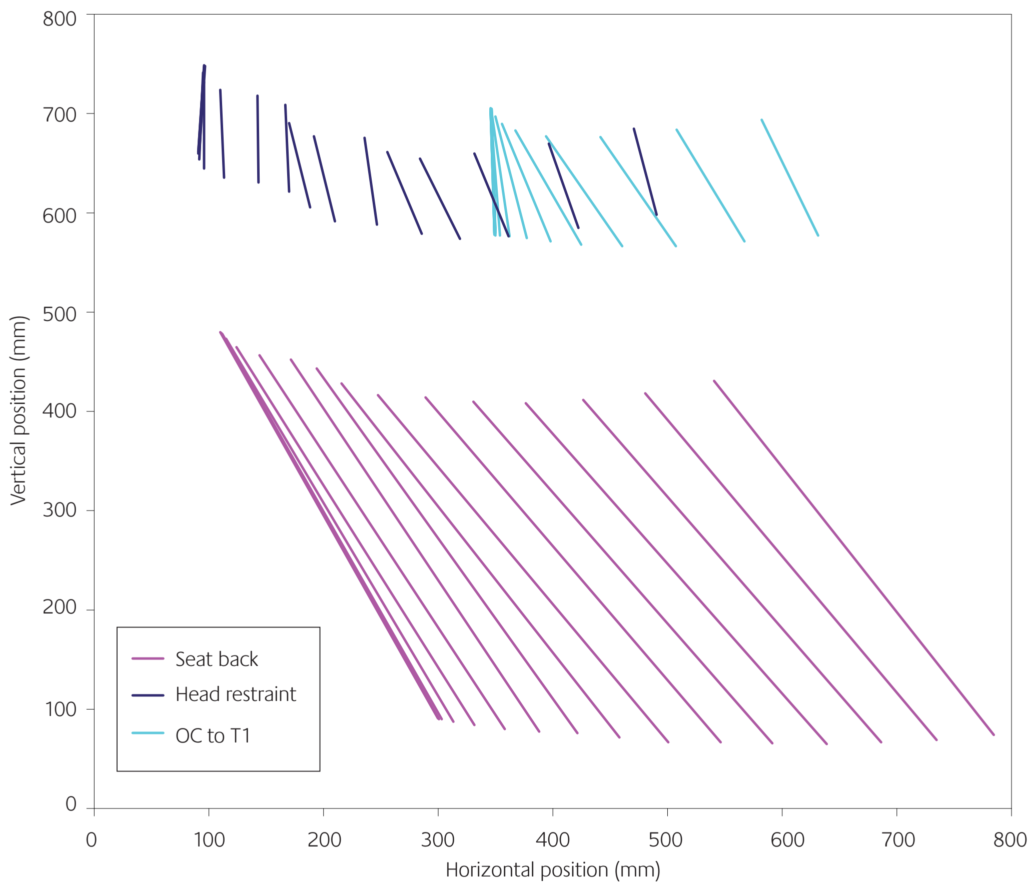

Figure B2 Example raw tracked data points

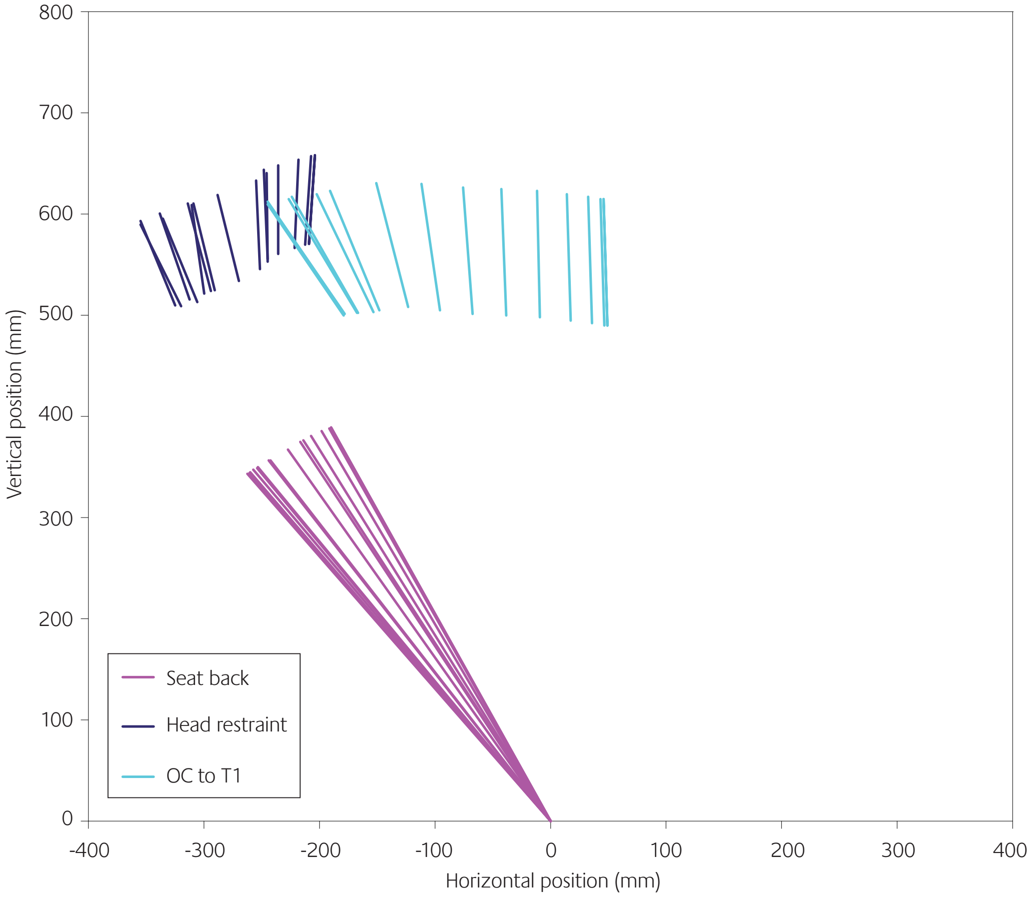

Figure B3 Example data points translated to make the seat back recliner point the origin

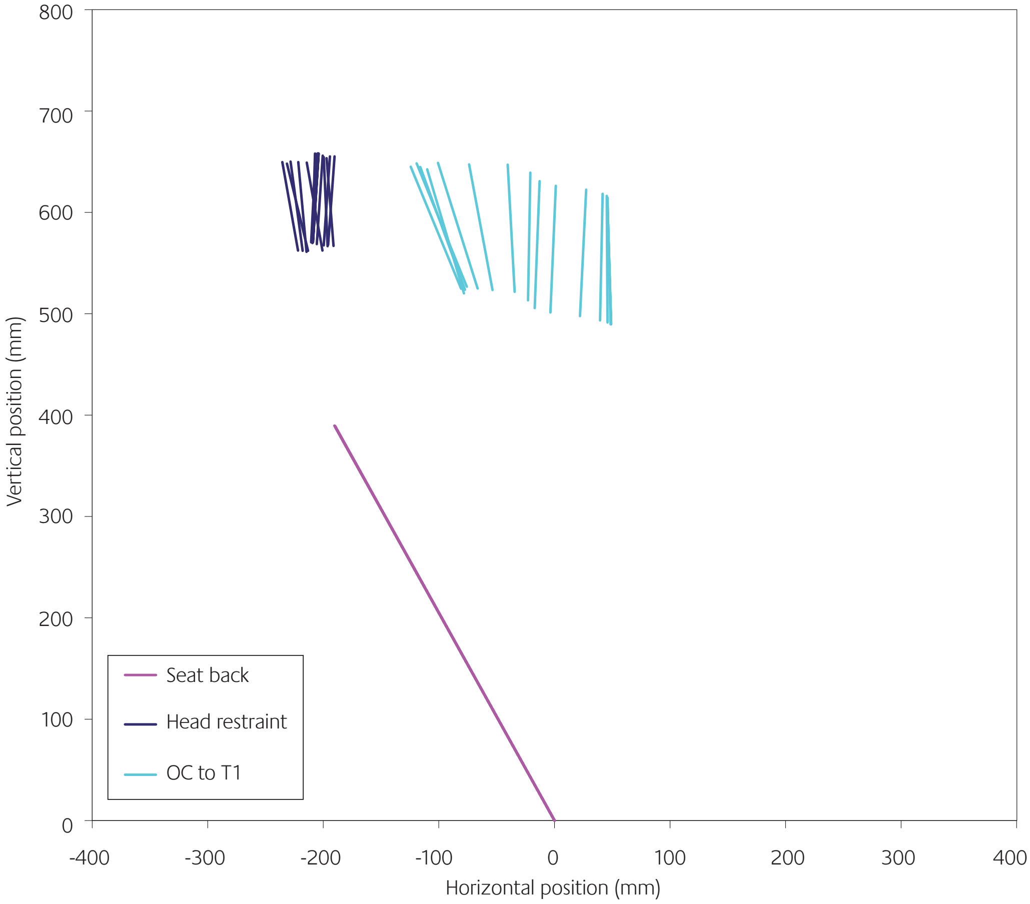

Figure B4 Example data points rotated to keep the seat back angle constant

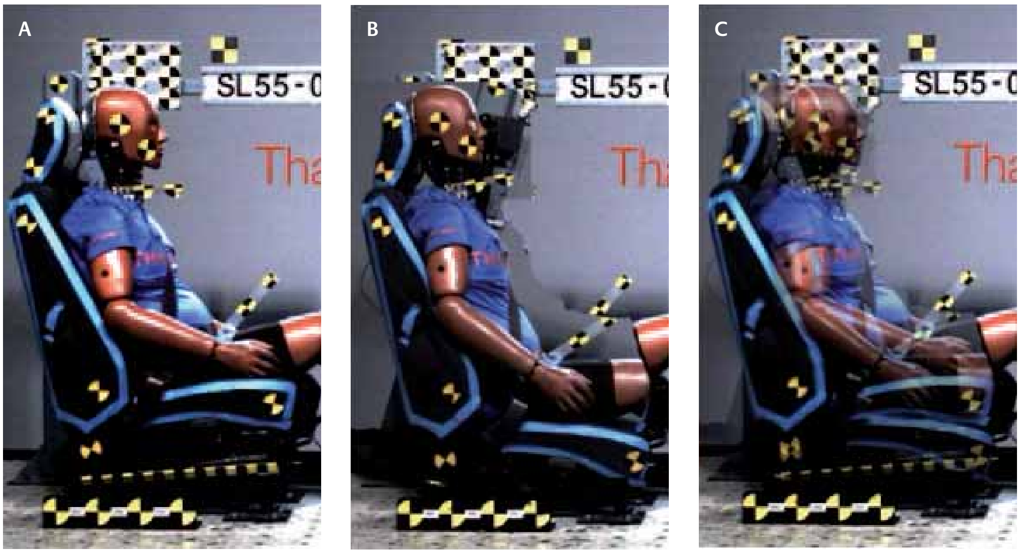

Figure B5 Example of head and head restraint motion relative to the seat back

B.2 Calculation of dynamic backset

Dynamic backset is the difference between the OC x-axis displacement and the T1 x-axis displacement, relative to the seat back angle. That is:

Dynamic backset = OC x-axis displacement − T1 x-axis displacement (Figure B6)

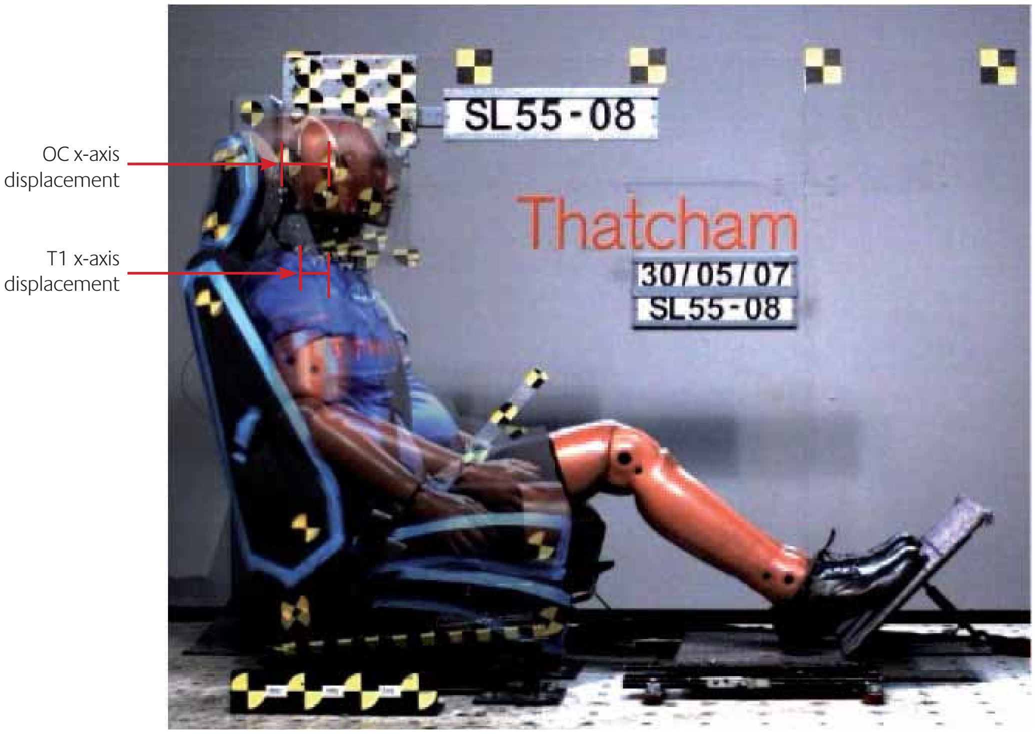

Figure B6 Example of dynamic backset calculation

The steps taken to calculate the dynamic backset measurement are shown in mathematical form in the following equations. The example point used in each case is the OC pin.

Translate all markers with respect to the lower seat back marker. This translation is needed for both the x- and y-axis co-ordinates for each point measured:

$$OC_x trans = OC_x measured - seat\ back\_lower_x\_at\_T0$$

(Equation B.1)

$$OC_y trans = OC_y measured - seat\ back\_lower_y\_at\_T0$$

(Equation B.2)

Determine seat back rotation during the impact (where seat back angle = θ). Care should be taken to ensure that the co-ordinate definition produces a positive angular result between 0° and 90°. Also, the data should be reviewed to make sure that there are no discontinuities due to changes in the quadrant of the angle.

$$\vartheta = \arctan\left(\frac{Seat\ back\_upper_y - seat\ back\_lower_y}{Seat\ back\_upper_x - seat\ back\_lower_x}\right)$$

(Equation B.3)

Then calculate the change in seat back angle at each measurement time:

$$\Delta\vartheta = Seat\ back\_angle - seat\ back\_angle\_at\_T0$$

(Equation B.4)

To calculate the effect of the change in seat back angle for x-axis measurements:

$$OC_x rot = OC_x trans \sin(\Delta\vartheta) + OC_y trans \cos(\Delta\vartheta)$$

(Equation B.5)

By equivalence, the equation to calculate the effect of the change in seat back angle for y-axis measurements is:

$$OC_y rot = OC_x trans \sin(-\Delta\vartheta) + OC_y trans \cos(-\Delta\vartheta)$$

(Equation B.6)

The dynamic backset (DB) measurement is then the x-axis displacement of the OC pin from the T1 pin in the translated and rotated co-ordinate frame:

$$DB = OC_x rot - T1_x rot$$

(Equation B.7)

This needs to be shown with respect to the T0 position:

$$DB = DB_t - DB_{t=0}$$

(Equation B.7)

B.3 Evaluation of head restraint movement relative to initial position

This option seemed to work well in terms of the marker tracking and calculation of the head restraint movement, and could be considered further. If combined with a static backset measurement, the method could give a measure of head restraint dynamic backset for active and reactive head restraints. However, the measurement is dependent on the time at which the measurement is made, which could be at the time of head contact with the head restraint. In this case, it was apparent from the films that many of the head restraints were pushed backwards after initial contact by the inertia of the head. This means that two head restraints with identical dynamic backset (measured in this way) could have very different behaviours after contact of the head with the head restraint, which would be expected to lead to very different risk of injury in the two seats.

Alternatively, the motion of the head restraint could be tracked throughout the impact event, and the most rearward position of the head restraint after head contact could be used. This would give a more realistic assessment of the level of support provided to the head by the head restraint, but the definition of "most rearward position" is not clear, particularly when the head restraint rotates as well as translates due to the loading from the head.

Overall:

- The tracking and calculation method is feasible.
- An equivalent measure to static backset is possible.
- Such a measure is not expected to correlate well with real-world performance (although this was not formally validated).

B.4 Evaluation of dynamic backset

B.4.1 Reproducibility

This option was evaluated using film data kindly made available by five of the Euro NCAP TWG laboratories. The TWG had carried out a round-robin phase of testing around Europe to investigate the potential of a rear impact sled test to be used in the Euro NCAP assessments. The tests were not conducted with the intention of tracking the markers, so although there was a protocol for marker placement it was not too prescriptive and there was some variation in the marker positions between the laboratories (i.e. the lower seat back marker was sometimes on the seat back and sometimes on the recliner), although in all cases the position of the marker was recorded. In addition, the data were from five laboratories, using five different BioRID II dummies, acceleration (HyGE) and deceleration sleds, a combination of on-board and off-board cameras and, in some cases, the film was highly compressed. It was considered that this would be a worst-case scenario for the reproducibility of dynamic backset measurements.

Figure B7 shows the calculated dynamic backset for one particular vehicle seat. The videos came from the five test laboratories involved in the testing, two of which used deceleration sleds and the other three HyGE sleds, and two of which had on-board cameras and three off-board. The figure shows the characteristic kinematics expected with the dynamic backset (the following description is based on a HyGE test, but an equivalent process will occur with a deceleration sled). Firstly, the dummy torso loads the seat back forcing it to rotate rearwards. At this time, the head of the dummy stays in approximately a constant position due to its inertia. This gives the impression of a forward head motion relative to the seat back. Subsequently, the rearward torso movement slows and the head begins to retract, moving past the starting orientation and continuing rearwards with respect to the torso. This is shown by the negative peak in the response. It is thought that the amount through which the head can retract with respect to the torso will be related, in some way, to the potential for the impact to be injurious.

The seat used for this testing has a very good real-world performance, based on insurance claims data. Therefore, it is not surprising to see that the peak dynamic backset measurement is less than 20 mm. Indeed, the analyses of the data from the different laboratories show the retraction to be between about 13 mm and 20 mm. The form of the response is similar in all five cases, which indicates good reproducibility.

In the evaluation of this option, a further two seats from the Euro NCAP TWG rear impact testing were also analysed. The dynamic backset retraction graphs for these two seats are shown in the following two figures, Figure B8 and Figure B9. These seats demonstrated a larger dynamic backset peak value than the seat shown in Figure B7. Such a difference in dynamic backset measurement was expected based on subjective consideration of the video footage.

From figures B7 to B9, it can be seen that the reproducibility of the dynamic backset measurements was good (within about 5–15 mm). While this may not be ideal for a displacement criterion, for the reasons mentioned above this analysis was expected to be a worst-case test of the criterion. It would be expected that if the specification concerning the means of recording and analysing the video footage were more tightly controlled, then the reproducibility would be improved. However, this would need to be demonstrated as part of the validation of the dynamic backset. It should also be noted that the marker tracking was undertaken using simple 2-D marker tracking software, with no correction for the parallax errors resulting from the markers being different distances from the focal plane of the camera. Again, this correction would be expected to improve the reproducibility of the criterion. As part of further work on this criterion by the European Enhanced Vehicle-safety Committee (EEVC) Working Group 20 (Rear Impact), some of the films have been re-tracked using depth correction by the laboratories that undertook the original tests. However, to date not enough tests have been re-tracked to be able to comment on the effect of depth correction on the reproducibility.

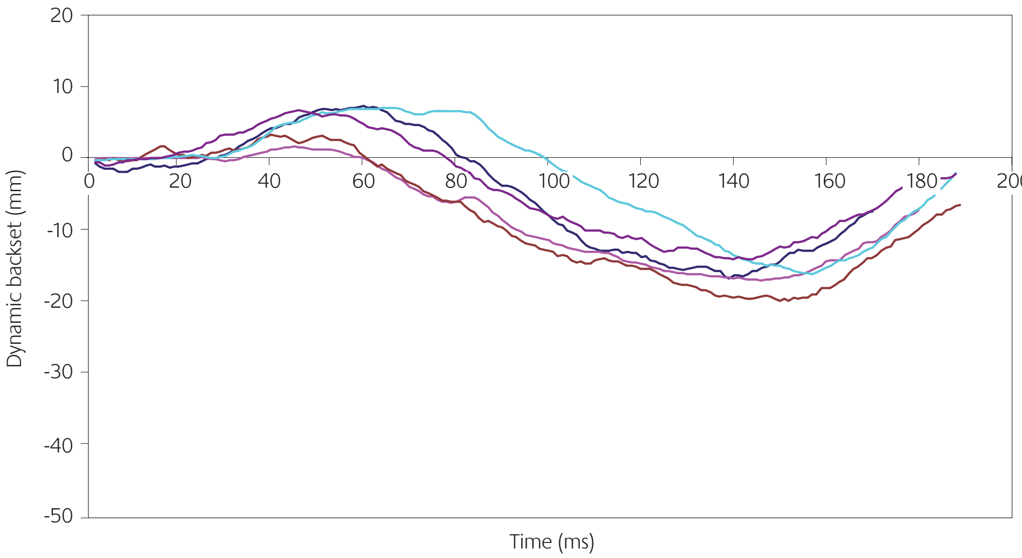

Figure B7 Initial dynamic backset analysis of Euro NCAP TWG videos, S3 seats
Five laboratories and BioRID IIs: two deceleration sleds, three HyGe (two on-board cameras, three off-board cameras)

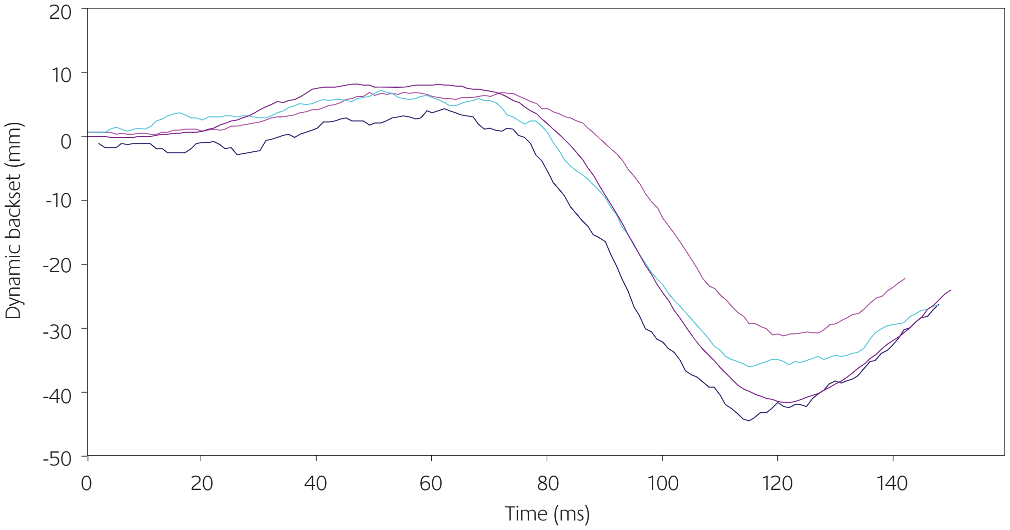

Figure B8 Initial dynamic backset analysis of Euro NCAP TWG videos, S4 seats
Four laboratories and BioRID IIs: two deceleration sleds, two HyGe (one on-board camera, three off-board cameras)

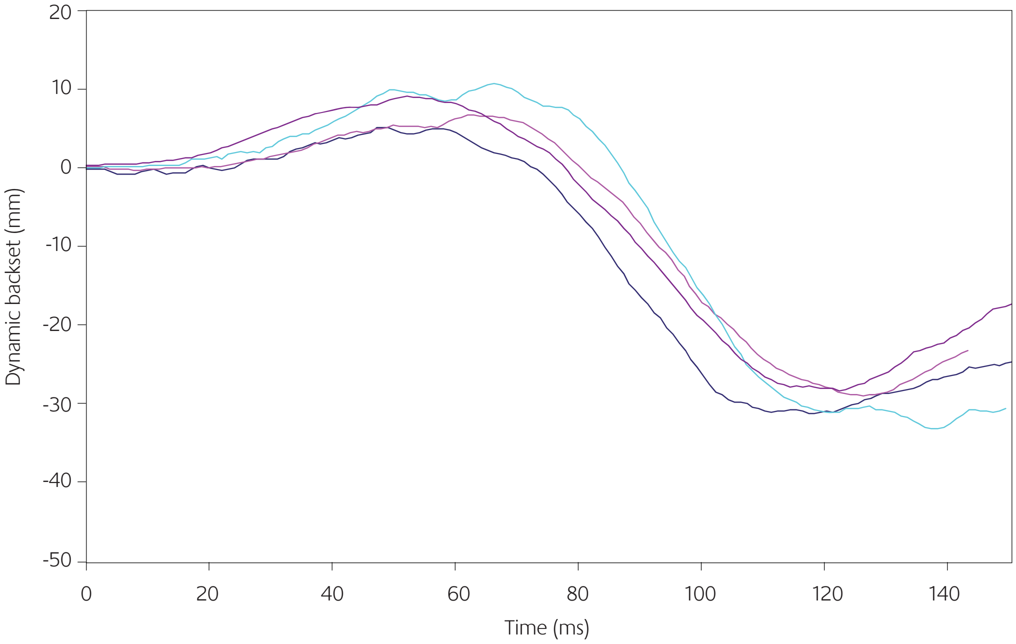

Figure B9 Initial dynamic backset analysis of Euro NCAP TWG videos, S5 seats
Four laboratories and BioRID IIs: two deceleration sleds, two HyGe (one on-board camera, three off-board cameras)

Table B1 Comparison of Hybrid III head angle and IIWPG rating (from Voo *et al*., 2007)

Seat	*Peak head-to-torso rotation (degrees)*	*IIWPG rating*
Saab 9-3	4.1	Good
Honda Civic	7.7	Good
Subaru Outback	4.1	Good
Nissan Altima	17.9	Acceptable

B.4.2 Comparison with NHTSA Federal Motor Vehicle Safety Standard 202a validation data

Further to the reproducibility evaluation undertaken above, TRL performed a study to compare the dynamic backset measurement described above with the Hybrid III head angle requirement used in FMVSS 202a (US Department of Transportation, 2004). Drivers' seats from four passenger cars were evaluated by Voo *et al*. (Voo *et al*., 2007) using the Insurance Institute for Highway Safety (IIHS) and International Insurance Whiplash Prevention Group (IIWPG) procedure. Voo *et al*. also assessed the performance of the seats in dynamic tests carried out in accordance with the requirements of FMVSS 202a. The comparative results from the IIWPG rating and the peak posterior head-to-torso relative rotation for each of the four seats are shown in Table B1, based on Voo *et al*.

IIHS (via Thatcham) provided IIWPG test data on the same four seats using the BioRID II dummy and these films were analysed by TRL to provide estimates of dynamic backset (using 2-D marker tracking with no depth correction). The results are shown in Figure B10. From this figure, it can be seen that the Nissan Altima seat allowed the largest peak retraction of almost 60 mm. This is the seat that was rated "Acceptable" by Voo *et al*.'s IIWPG assessment and allowed a peak Hybrid III head-to-torso rotation of 17.9°. The other three seats, all rated "Good" in the IIWPG assessment, had smaller dynamic backset values, of less than 20 mm.

Based on the dynamic backset results and the published IIWPG ratings for these seats, it is possible to say that the dynamic backset distinguishes between the four seats used in the National Highway Traffic Safety Administration (NHTSA) study in the same way that the IIWPG criteria do. This implies that the dynamic backset is, based on this sample of four seats, broadly equivalent to the IIWPG ratings. This is encouraging for the use of the dynamic backset as the IIWPG ratings have been shown to correlate with real-world effectiveness of seats in rear impacts (Boström and Kullgren, 2007).

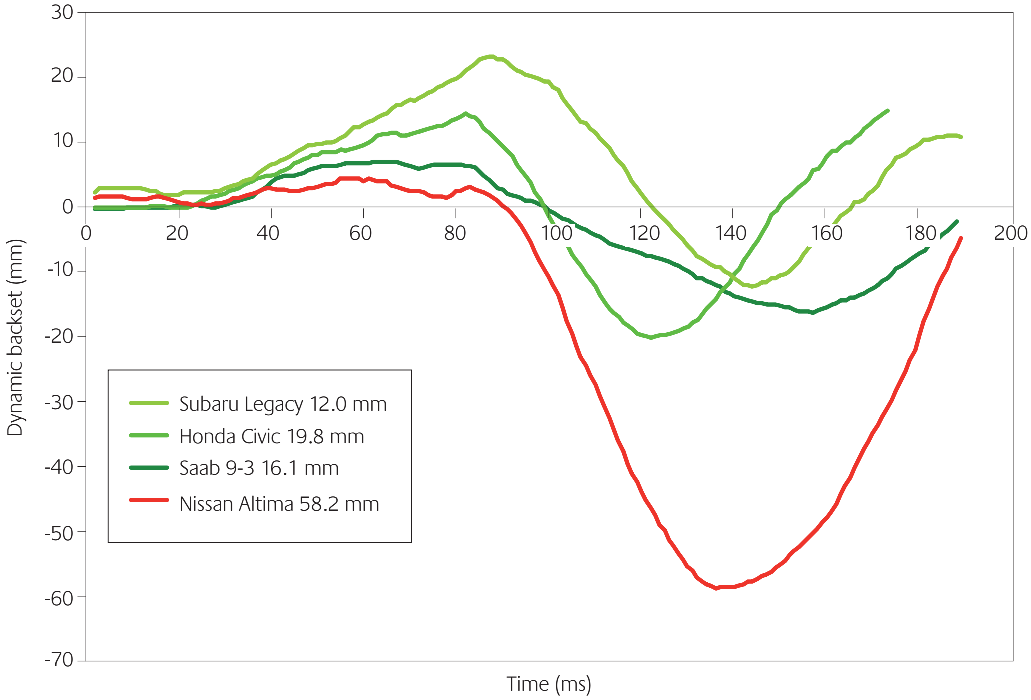

Figure B10 BioRID II dynamic backset for the seats evaluated by Voo *et al*. (2007)

B.4.3 Comparison of seats with and without whiplash mitigation technologies

Within WG20, Autoliv Research calculated dynamic backset for four seats, two with specific whiplash mitigation technologies (Volvo V70 with WHIPS and Saab 9-3 mark 1) and two earlier seats with less well developed whiplash protection (Volvo V70 without WHIPS and Saab 900). The results are shown in Figure B11. In both cases, the more recent, anti-whiplash version of the seat has a lower dynamic backset, which indicates that dynamic backset is sensitive

B.4.4 Autoliv sensitivity analysis

To estimate the effects of parallax errors in the video analysis, Autoliv Research re-analysed a couple of tests using a variety of levels of accuracy in the depth correction they used.

For a test of the Volvo V70 seat without WHIPS, Autoliv Research obtained a dynamic backset value of 69 mm using all the depth of field information that was available in their documentation for this test. This information is as follows:

- Camera to reference plane for image scaling (points 5 and 6) = 2,810 mm.
- Z-axis distance between points 5 and 6 = 802 mm (for pixel conversion).
- Camera to seat markers (points 3 and 4) = 2,280 mm.
- Camera to OC and T1 positions (points 1 and 2) = 2,500 mm.

The points tracked in the Autoliv Research study into the sensitivity of the dynamic backset measurements to depth correction are shown in Figure B12.

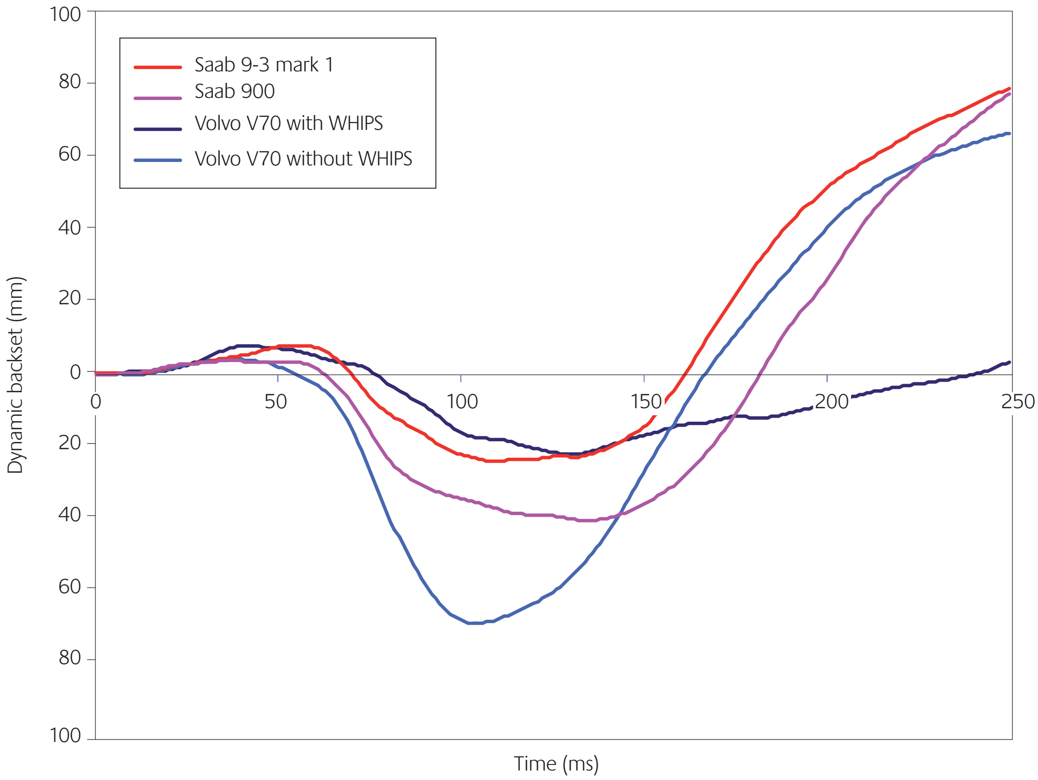

Figure B11 Comparison of dynamic backset for seats with and without whiplash mitigation strategies (data courtesy of Autoliv Research, Sweden)

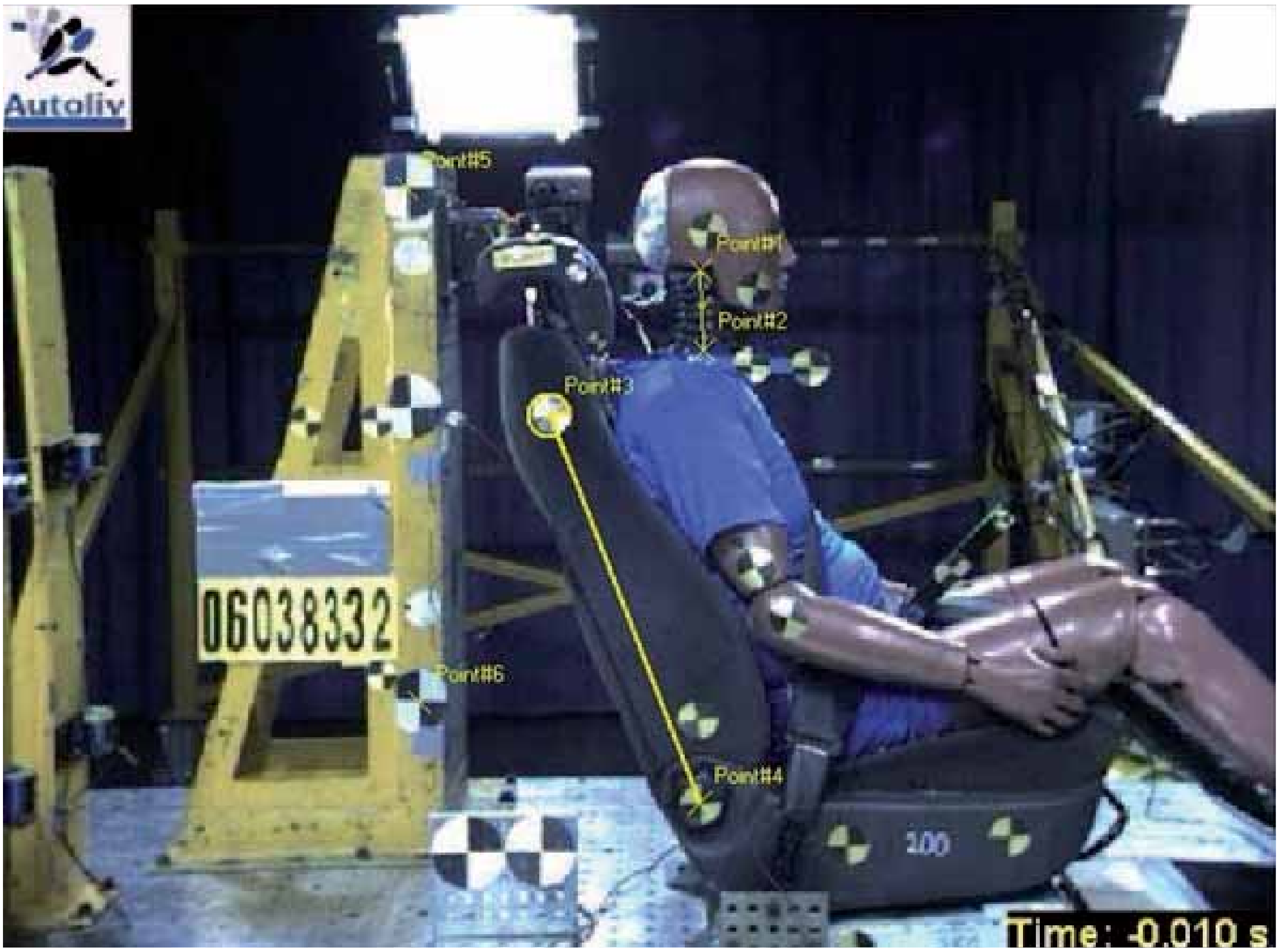

Figure B12 Points tracked in the Autoliv Research depth correction sensitivity analysis (image courtesy of Autoliv Research, Sweden)

The distances were measured with a tape measure, so in the worst case would have an accuracy of about ± 10 mm. Setting the camera distance at 2,810 mm and checking a known 100 mm distance located at the dummy centreline depth plus 10 mm versus the same measurement with the dummy centreline depth minus 10 mm is known to produce about 1% difference in the measurement.

Without any depth correction, i.e. "flat" settings, Autoliv Research obtained a dynamic backset value of 77 mm from this test. In this case, the camera was assumed to be 10 m away from the points being tracked.

With a "rough estimation" of the settings, Autoliv Research obtained an dynamic backset value of 66 mm. The settings used in this case were:

- Camera to reference plane for image scaling (points 5 and 6) = 2,800 mm.
- Z-axis distance between points 5 and 6 = 802 mm (for pixel conversion).
- Camera to seat markers (points 3 and 4) = 2,400 mm.
- Camera to OC and T1 positions (points 1 and 2) = 2,400 mm.

This exercise was completed again for another test. Table B2 shows a summary of the dynamic backset measurements in each case.

Table B2 Autoliv Research analysis of dynamic backset sensitivity to depth correction

Test no.	*Flat depth settings – dynamic backset (mm)*	*Approximate depth settings – dynamic backset (mm)*	*Most accurate depth measurements – dynamic backset (mm)*
1	77	66	69
2	75	64	67

It is clear from this analysis that depth correction should be used to ensure accurate marker tracking data and dynamic backset measurements. Autoliv Research also made the following recommendations:

- The tracked data should be filtered at CFC_30 (SAE J211-1: December 2003).
- The dummy head should always be marked with two target points so that the OC can be tracked virtually if it is obscured or the film quality is bad.
- The OC and T1 points should be painted with a white correction fluid or something similar to facilitate the identification and tracking of these points.

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