Rail Safety & Standards Board

Research Programme

Engineering

Assessment of three-point passenger restraints (seatbelts) fitted to seats on rail vehicles

Assessment of Three-point Passenger Restraints (seatbelts) Fitted to Seats on Rail Vehicles

July 2007

Executive Summary

This report details the work carried out under project T201, Three Point Seatbelt Assessment. It is part of a wider scope of work concerned with improving passenger safety including the prevention of ejections. This report follows on from the assessment of Two Point Seatbelts and the possible fitment of such devices to passenger carrying rail vehicles.

In conducting the research into the possible fitment of "Lap and Diagonal" (colloquially known as 3 point seatbelts) passenger restraint devices to seats in rail vehicles, an existing rail seat was used as a donor seat. This was extensively modified to accept the anchorages and fixtures required. It was found that the seat structure required additional stiffening to accommodate the increased load case of restraining an occupant, whilst also resisting impact from an unrestrained passenger from the rear.

It was found that injury outcomes for passengers choosing to wear restraints were substantially improved. However, there was a slight general worsening of injury outcomes for passengers choosing not to wear restraints as they impacted the modified (stiffened) seat. There was a significant problem when considering unrestrained 5th percentile female passengers (those of small female and adolescent stature) choosing not to wear restraints when impacting the modified seat. Neck injury (Nij) in this group significantly increased to a level outside acceptable limits. It may be possible to reduce this feature if a new seat were designed which took account of this problem, however the difficulties and implications that this represents should not be underestimated.

In an earlier phase of this work, 6 recent significant accidents had been analysed in which it was established that there is a possible negative consequence to the fitment of any passenger restraint device. That is, in those accidents there had been areas of significant vehicle structural intrusion into the passenger compartment, to an extent where passengers' survivability would have been compromised, if they had been restrained in their seat by seatbelts. In the accidents investigated, the unrestrained passengers in these areas were thrown clear of this structural intrusion. Although this phenomenon is not fully understood, its importance and significance should be recognised. This report takes this phenomenon into account in establishing if there is a net benefit to passenger safety to be gained by fitting lap and diagonal restraints to seats on rail vehicles. At this time no net safety benefit can be identified.

Contents

1 Introduction

As part of the Rail Safety and Standard Board's (RSSB) research into improving the safety of passengers on the GB mainline railways DeltaRail (formerly AEATR) had been commissioned to carry out research into the fitment of lap and diagonal, colloquially termed 3-point belts, on seats in passenger carrying rail vehicles.

This report details the work carried out under project T201 Three Point Seatbelt Assessment as part of a wider scope of work concerned with Seats and Tables on passenger carrying rail vehicles.

2 Background

A structured and sequential programme of research designed to improve passenger safety is being undertaken by RSSB. The first phase of this research was to establish the tolerable levels of injury, associated with people, in each individual body region [1]. Development of suitable injury criteria, and the inability of available test devices to measure all of the key criteria, resulted in the need for a device able to measure those criterion.

Modifications to the industry standard Hybrid III Anthropomorphic Test Device (ATD or crash test dummy) were required to enable chest and abdomen criteria to be measured. Suitable instrumentation was added to a standard Hybrid III ATD to measure these criteria. The biofidelity (ability to mimic human response) of the ATD was also improved by modification to the hip and lower spine. These improvements made the ATD more suitable for testing train tables and passenger restraints, and give a more human like response over the longer excursions experienced on trains when compared with those experienced on other transport industries. The modified ATD is known as the Hybrid IIIRS. Other international authorities are now using this test device.

Tests of currently used passenger seats and tables were completed in 2005 [2] using appropriate injury criteria and the Hybrid IIIRS ATD. This provided information regarding the predicted passenger injury levels sustained under various crash scenarios and the results served as a benchmark against which to measure the relative benefits of the restraint devices being investigated.

Following benchmarking the research programme aimed to consider the effect, in terms of injury criteria, of fitting passenger restraint devices and the benefits that could be achieved by introducing crashworthy tables to the UK railway. The work investigating lap belt, or 2-point, passenger restraints has been completed under RSSB research project T201 [3]. This report details the findings of the work undertaken investigating lap and diagonal, or 3-point, passenger restraints.

3 Scope of Work

The work and research summarised in this report was undertaken by AEA Technology Rail on behalf of RSSB. Testing was carried out at the Transport Research Laboratory (TRL) at its establishment at Crowthorne. The rationale and stages of work undertaken in the process of completing this project were designed to determine if there is a safety benefit to passengers from fitment of a 3-point passenger restraint system to seats on rail vehicles.

The stages of work for the project were as follows:

- **Positioning Paper**
  A positioning paper [4] was co-authored by DeltaRail and the Transport Research Laboratory (TRL). This positioning paper formalised the test parameters and protocol. The paper was peer reviewed by technical experts (both from within and external to the rail industry) at a workshop held at TRL. Peer review validated the proposals, the rationale used, the conditions for testing and the proposed boundary cases. The positioning paper was similar in nature to that used for the 2-point passenger restraint work.

- **Computer Modelling**
  Computer modelling was undertaken using MADYMO© 6.5 software. This modelling included detailed Finite Element Analysis of the seat structure to provide information regarding the structural design change requirements necessary to support the loadings resulting from the installation of passenger restraint.

- **Testing**
  A suite of tests as detailed in the positioning paper was carried out. Results of the tests have been analysed with regards to predicted injury levels to passengers. Where appropriate these results have been compared to the levels defined in AV/ST9001, Vehicle Interior Crashworthiness [5] and the previous research.

- **Children**
  The suitability of 3-point passenger restraints when used by children has been discussed. DeltaRail have taken guidance from experts in child occupant safety at TRL when considering this topic.

- **Structural Intrusion**
  The possible effect of structural intrusion on passengers restrained within seats has been discussed. When restrained in a seat, although prevented from being ejected out of the vehicle, a passenger may be at risk from a loss of survival space. A number of recent train accidents had been considered and this phenomenon examined.

- **Train Specific Issues**
  When considering the fitment of 3-point passenger restraints on passenger carrying rail vehicles, a number of factors specific to rail vehicles and rail passengers have been reviewed.

- **Discussion**
  Consideration was also given to other factors, which may have an effect on passenger injury outcomes. Issues such as “out of position passengers” are discussed.

- **Conclusions and Recommendations**
  A summary of the conclusions drawn from the work is detailed along with a set of recommendations.

4 Project Rationale

The rationale used throughout this project considered the factors listed below. It should be noted that in the majority of cases the rationale used in this work follows that detailed in the 2-point passenger restraint project [3]. Where this is the case a detailed description outlining the rationale is not provided and in these cases the key points are covered below. For factors specific to 3-point restraints (and thus requiring further consideration) a more detailed commentary is given.

Factors that needed evaluation and optimisation to conduct the work were:

- **Collision pulse/rate of deceleration:**
  The deceleration pulse as detailed in AV/ST9001 was used for the tests; Figure 1 below. The use of an identical pulse for all related projects was essential in order to permit direct comparison of results for assessment purposes.

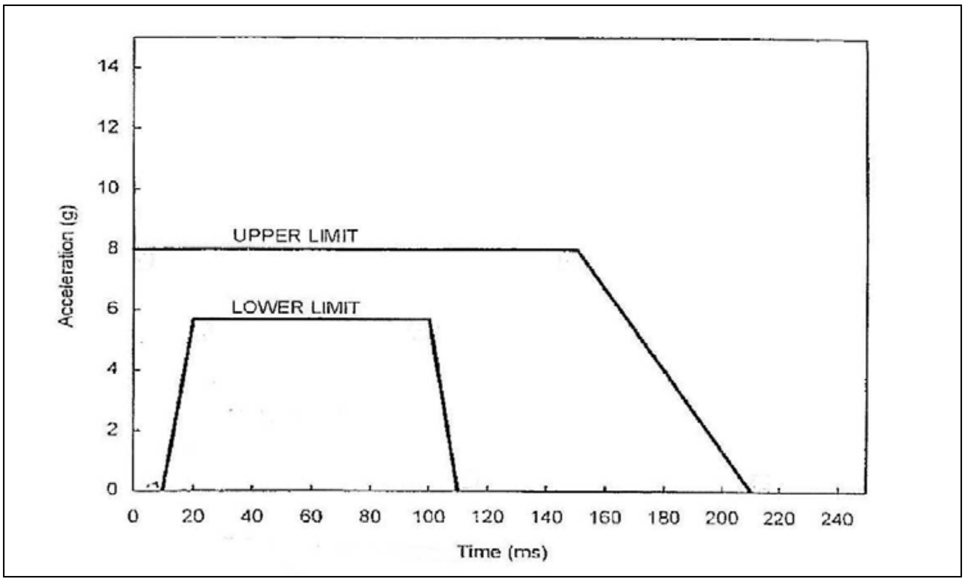


Figure 1 - AV/ST9001 Crash Pulse

- **Vehicle type and structural integrity between seat and vehicle**
  For the purpose of evaluating the effect of fitting 3-point passenger restraints to rail vehicles, the modified seat was rigidly fixed to the test sled thus eliminating the variability to be found between vehicle types and vehicle structures.

- **Age and stature of passenger**
  The Hybrid IIIRS 50th percentile and the 5th, 50th and 95th percentile Hybrid III ATD's were used for the testing. The issue of children and the use of passenger restraints has been reviewed separately within this project; Section 7.

- **Seat type**
  The same seat type as that used in the 2-point passenger restraint research and the benchmarking exercise was used throughout this project. This provides consistency between the research areas and allows comparisons to be drawn where this is appropriate.

- **Seat pitch and orientation**
  Seat pitches in the range used during the 2-point passenger restraint work have been tested in this project. From the workshop referred to in Section 3(see "Positioning Paper") it was considered that three point passenger restraints would be most effective for forward facing, unidirectional seated passengers. This seat orientation has been tested during this project.

- **Choice of passengers in adjacent seats to wear or not wear belts**
  It has always been considered that a passenger seat should be "sacrificial to the benefit of the safety on the passenger". The effect on predicted passenger injury levels of any strengthening of the seat structure, and the consequential increase in stiffness of the seat, has been considered.

- **Availability of modelling techniques.**
  Work conducted under the 2-point restraint project used LSDYNA© and MADYMO© software packages to model the seat and the occupant kinematics respectively. The MADYMO© model was provided to TRL for validation in terms of 3-point passenger restraints.

The factors unique to 3-point passenger restraints are discussed in detail below. As previously noted in section 3, these were peer reviewed at the Workshop.

- **Type of 3-point restraint device fitted**
  In view of the number of different types and configurations of 3-point restraints available it was necessary to review the applicability of each for rail use, and then decide which of these was most appropriate to the objectives of the project. The purpose of the test was to establish the effect of such a restraint on injury levels, not to assess the relative merits of restraint types or configurations.

Three-point passenger restraints can comprise of a number of features, such as:

1. A static belt
2. A retractor belt
    a) Non locking
    b) Manually unlocking
    c) Automatic locking
    d) Emergency locking
    e) Emergency locking with higher threshold
3. Load limiters
4. Pretensioners
5. Advanced seat belts e.g. inflator belts.

A static belt, type 1 above, is relatively easy to fit and can be adjusted by the user. Unlike retractor belts there will be no un-spooling during loading. The webbing, as with all belts, would be expected to stretch when significantly loaded. Belt slack is one factor, which reduces the efficacy of a three-point passenger restraint. The major disadvantage of the static belt is the potential for user misuse leading to incorrect positioning and the introduction of excess slack.

There are a number of retractor belts available. Most commonly used are the Automatically and Emergency Locking Retractors, ALR(s) and ELR(s) respectively. An ALR will allow extraction of the webbing to a required length following which the retractor will spool in any excess. Further extension of the belt is prevented by the ratchet within the retractor, until the belt is fully recoiled. This mechanism prevents occupants from moving in the seat and can become uncomfortable to wear. It is considered that this will ultimately affect the take up rate of passengers choosing to wear such a device.

The locking mechanism in the ELR restraint system can be actuated by the deceleration of the vehicle and/or by the movement of the webbing (it can also be activated automatically). This provides the user with greater freedom of movement due to being able to extract or retract the webbing at all times when the locking mechanism is not actuated. For the ELR system to work effectively it is necessary to understand and mitigate the accelerations that naturally occur during a train journey to ensure that unnecessary actuation is prevented.

It is possible to improve the protection of the occupant by fitting retractors with load limiting devices that spool webbing from the retractor when the webbing force exceeds a pre-determined level. This mechanism acts to reduce the risk of high belt force injury but does permit occupant excursion. These are commonly used in conjunction with an airbag to absorb excess energy and limit displacement.

Pretensioners and advanced restraints have the requirement for an activation method. This activation method can be extremely complex to configure and requires automatic sensing and decision making systems to determine whether to fire or not. It is important that these systems operate at the correct time to provide occupant protection and avoid injuries due to misfiring the device.

The workshop supported the use of static 3-point passenger restraints for this project, with its objective of assessing the benefits in protection against injury compared to unrestrained passengers and those restrained by 2-point restraint devices. This removes un-necessary variables and provides a more stable format for testing. This arrangement will also provide maximum occupant protection when considering passenger lap and diagonal restraint.

- **Location and structural integrity of restraint fixings and structural integrity of seat**
  The juxtaposition between the passenger and restraint device is important. To provide suitable protection and comfort during use, the 3-point passenger restraint must be of an appropriate fit for each occupant considered. The passenger statures considered were the 50th and 95th percentile male and the 5th percentile female occupants. Anthropomorphic data was found in 'Adult Data' – The handbook of adult anthropomorphic data and strength measurements – Data for Design Safety by the Department of Trade and Industry. This information was used to determine the expected sitting heights for the 5th, 50th and 95th percentile occupants.

  The location of the anchorage on the seats should be such as to provide correct belt routing for all statures being tested. The lower anchorage position was set in the 2-point restraint work and was in the same position for the 3-point tests. The upper anchorage is positioned according to the UNECE Regulation 14 for the M2 and M3 (buses and coaches of 8 seats or more).

It was found that the 5th percentile female shoulder height is below the permitted anchorage zone. This was considered not to be of concern as the anchorage position should be above the shoulder to prevent loading vertically towards the spine.

Preliminary modelling was undertaken to allow an initial study of the dynamic response of the seat during loading to be made. The findings of this study indicated that the seat would be strong enough to support a 3-point belt upper anchorage load without catastrophic failure. A structural test run was conducted to prove this result and indicated that although a seat, both being impacted by an unrestrained 95th percentile and restraining a second 95th percentile ATD, did not fail catastrophically, the deflections were unacceptable. A risk of entrapment to the restrained occupant was presented and other risks identified e.g. the angle of the deformed seat forming a slope suitable to launch the unrestrained rear occupant thus losing compartmentalisation (a passive safety system by which passenger excursions are restricted with the use of limiting interior features, such as crashworthy seating, to absorb some of the energy of passenger impact). It was therefore necessary to increase the stiffness of the seat to prevent these scenarios. This stiffened seat type was used for the reminder of the test suite.

5 Testing

In order to ensure that the proposed dynamic test regime depicted a realistic seat pitch and arrangement that could be found on new, refurbished and older rail vehicles, the pitches as defined in the 2-point passenger restraint work were used. These pitches were established from a vehicle survey and ranged from 752mm to 900mm.
Using the information available regarding seat pitch and considering the statures to be tested a test suite was established. The programme was designed to investigate the influence of seat pitch on restrained and unrestrained passengers. It was also considered essential that the influence of passenger stature was tested. ATD's representing the following user population where used:

- 5^{th} percentile female
- 50^{th} percentile male
- 95^{th} percentile male.

The Hybrid III RS was used to provide information regarding injury to the abdomen and chest regions, which a standard Hybrid III cannot provide. Validation of the Hybrid III RS was undertaken during the 2-point restraint work and thus it was deemed appropriate to continue using the Hybrid III RS for the restrained occupant. Due to the increased restraint of the occupants upper body in a 3-point restraint, the increased biofidelity of the Hybrid III RS was not apparent, however, this would be realised over longer excursions.

The photographs below, Figure 2, show the upper and lower anchorage points for the 3-point passenger restraint. The upper anchorage has three location points; the lowest for the 5^{th} percentile, the middle for the 50^{th} percentile and the highest for the 95^{th} percentile. This provides the best routing for the belt and should provide maximum restraining properties.

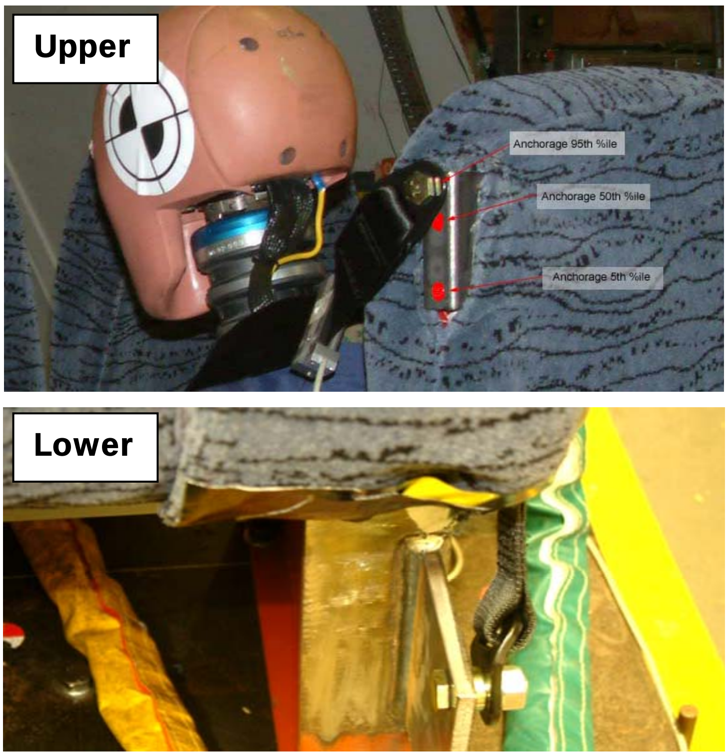
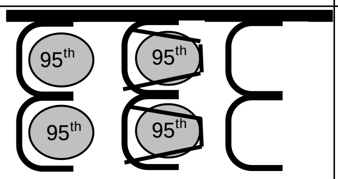
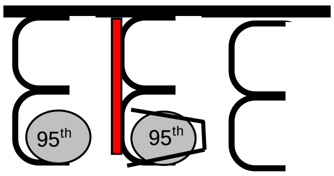
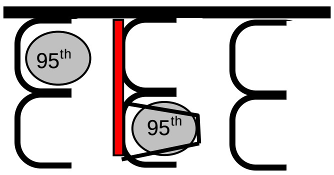
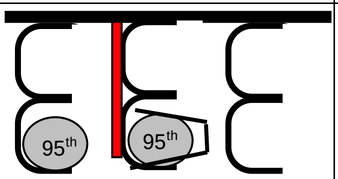
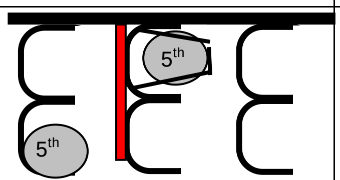
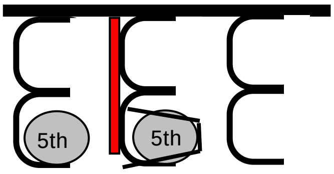
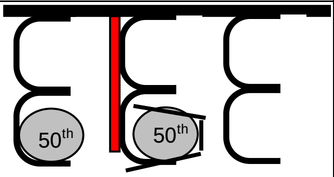
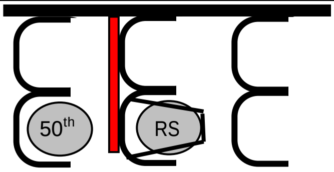
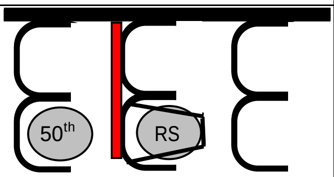
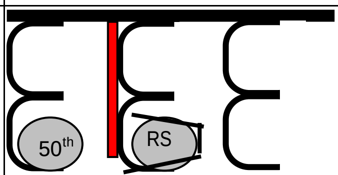
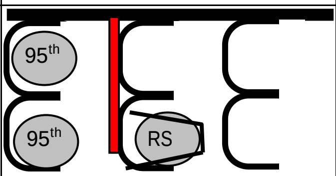
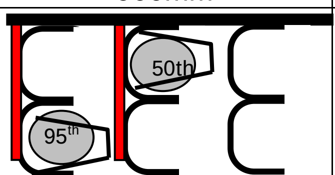


Figure 2 - Anchorage Positions for Testing (Upper and Lower)

The test suite carried out is shown in Table 1. The red lines indicate where the stiffened, modified, seat has been used. Only Test 01 used unmodified seats (as discussed above).

Table 1 - Test Matrix

Test	Configuration	**Description**	**Data acquisition**
	→ **Direction** →		
Case 1:	 900mm	• Unmodified seat • 4x95ths: front 2 restrained, 900mm seat spacing	Instrumented: • Window side 95ths instrumented
Case 2:	 900mm	To Compare effect of strengthening seat • 95th restrained. • 95th unrestrained • 900mm seat spacing	Instrumented: • 95th percentiles • Seatbelt tension
Case 3:	 830mm	To compare effect of seat pitch. • Unrestrained 95th and restrained 95th. • 830mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension
Case 4:	 830mm	To compare effect of unrestrained passenger loading. • 95th restrained and 95th unrestrained • 830mm seat spacing.	Instrumented: • All available instrumentation • Seatbelt tension
Case 5:	 830mm	To understand effect of stature • Unrestrained 5th and restrained 5th. • 830mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension

Test	Configuration	Description	Data acquisition
	→ **Direction** →		
Case 6:	 752mm	To compare seat pitch. • $2x5^{th}$s – restrained and unrestrained. • ATDs in line • 752mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension
Case 7:	 830mm	• Unrestrained and restrained 50^{th} • ATDs in-line • 830mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension
Case 8:	 830mm	To compare stature • Unrestrained 50^{th} and restrained HIII RS (50^{th}). • ATDs in line • 830mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension
Case 9:	 800mm	To compare pitch • Unrestrained 50^{th} and restrained HIIIRS (50^{th}). • ATDs in line • 800mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension
Case 10:	 752mm	• Restrained HIIIRS (50^{th}) and unrestrained 50th. • ATDs in line • 752mm seat spacing.	Instrumented: • All available instrumentation • Seatbelt tension
Case 11:	 900mm	To compare seat stiffness and unrestrained occupant impact • $2x95^{th}$ – unrestrained. HIIIRS (50^{th}) restrained • 900mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension
Case 12:	 900mm	Compare effect of fitting retractor belt • 95^{th} and HIIIRS (50^{th}) restrained with retractor belt. • 900mm seat spacing	Instrumented: • All available instrumentation • Seatbelt tension

5.1 PREDICTED PASSENGER INJURY MEASURES

From the test programme carried out as described in Section 5 a lot of information has been obtained. In total over 1500 channels of information were recorded giving information on different areas of the various ATD's used and of the test conditions themselves. It was beyond the scope of this project to complete a full analysis of all of this data, accordingly this report does not comment on every aspect of the tests themselves. This report represents an initial analysis of that data where predicted passenger injuries pose the greatest threat to life. It would be possible to conduct further analysis for RSSB in the future.

It is sensible to concentrate on those aspects of the test where recorded injuries pose the greatest threat to life, or where there were body region values which exceed those values and norms contained in AV/ST9001, and the previous work in this research stream.

A review of information from the tests showed that the injuries presented to the head and neck were the greatest threat to life and where there were significant exceedances to the accepted criteria in the 2-point passenger restraint work. It was prudent to use the same measures for head and neck injury for the 3-point passenger restraint work for comparability of results. Other measures may be analysed in detail at a later date if required. This rationale has been used internationally in comparable assessments.

The following section of the report, Section 5.2, concentrates on these two areas. The criteria concerning these areas are Head Injury Criteria, or HIC, and Nij, a non-dimensional criteria based on a combination of moments and forces in the ATD's upper neck.

The Head Injury Criteria, or HIC, is the standardised maximum integral value of the head acceleration (deceleration). This provides a measure of the difference in velocities of the skull and the brain. This will cause an impact of the brain against the skull which can lead to concussion and ultimately fatality.

In the research an absolute limit of 500, with a target of 150, has been specified for HIC. This value is lower than that used in the automotive industry by a factor of two (HIC 1000). A lower limit has been specified on the railways for a number of reasons which reflect the difference between the two modes of transport. The accessibility of the rail environment, time to treatment and the desire that passengers remain coherent in the aftermath of an incident have led to this more stringent figure. HIC is extremely sensitive to the local stiffness of the head impact position and position of head strike as it is based on the resultant acceleration of the centre of gravity of the head.

Historically bending moments have been used to predict upper neck injury in extension and flexion; with limits as defined in AV/ST9001 of 190Nm and 57Nm respectively. Recently Neck Injury Criteria, or Nij, has been used as a more accurate representation of human injury levels and although not yet included in the AV/ST9001 standard, is the rail industry standard neck injury measure. Nij takes account of the compression and tension forces on the neck as well as the bending moments. Derived from previous testing, Nij should not exceed a value of 1. The Nij value calculation does not define whether the moments are flexion or extension. It should be noted that Nij provides an indication of the predicted injury levels at the upper neck.

5.2 TEST RESULTS

The test results have been analysed to provide a comparison of the predicted passenger injury levels, in terms of Nij and HIC, for the following situations:

- **Comparison 1** - Occupants restrained in 3-point belts versus unrestrained occupants impacting seats stiffened to cater for 3-point belts
  This compares the injury levels sustained by a passenger wearing a 3-point belt with the injury levels incurred by an unrestrained passenger impacting a seat stiffened for use with a 3-point belt.
- **Comparison 2** - Unrestrained occupants impacting unmodified seats versus unrestrained occupants impacting modified seats
  This compares the injury levels sustained by an unrestrained passenger impacting a seat stiffened to accommodate a 3-point restraint with the injury levels sustained by an unrestrained passenger impacting a current design of crashworthy seat.
- **Comparison 3** - Occupants restrained in 3-point belts versus occupants restrained in 2-point belts.
  This compares the injury levels sustained by a passenger wearing a 3-point belt with the injury levels sustained by a passenger wearing a 2-point belt.
- **Comparison 4** - Occupants restrained in 3-point belts versus unrestrained occupants impacting an unmodified seat.
  This compares the injury levels sustained by a passenger wearing a 3-point belt with the injury levels sustained by an unrestrained passenger impacting a current design of crashworthy seat.

The comparison identifying the differences in performance between static and retractor belts is shown in Section 5.2.5. For each pitch tested a number of data points represent different dummy statures tested at that spacing.

5.2.1 Comparison 1

It has been shown that occupants restrained by a 3-point passenger restraint do not impact the seat in-front. Conversely, an unrestrained occupant will impact the seat in-front and if the impacting seat is made stiffer it is likely that the predicted Nij and HIC injuries will increase for this unrestrained occupant.

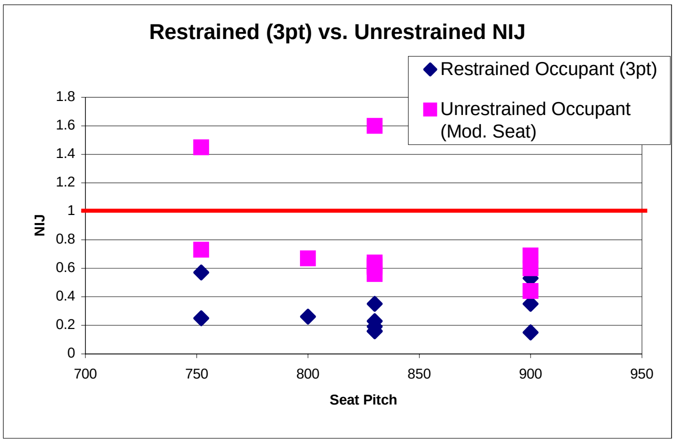


Figure 3 - NIJ comparison for Occupants with Stiff Seats

Figure 3 indicates that in the large majority of cases fitment of a 3-point passenger restraint reduces the Nij, and thus predicted neck injury of passengers when compared to unrestrained occupants impacting a seat that has been modified to withstand the increased forces due to double loading. In 2 cases the unrestrained occupant receives a Nij > 1. There are no cases of Nij > 1 for the restrained passengers. In the majority of situations, the head of the restrained occupant does not strike the seat in-front and thus the Nij value would be expected to be lower than for the unrestrained occupant. This conclusion applies equally to HIC; see below.

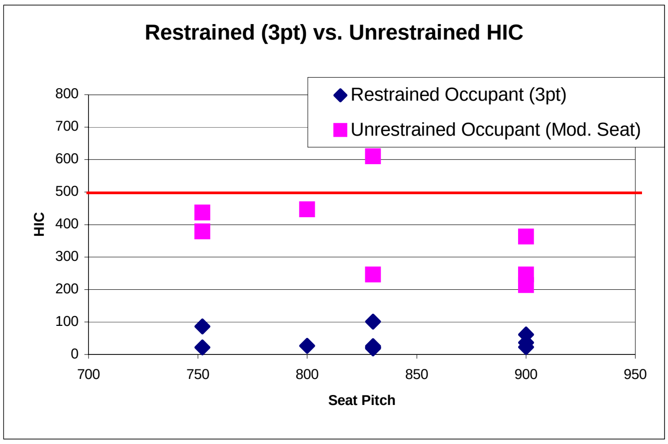


Figure 4 - HIC comparison for Occupants with Stiff Seats

The HIC value, and thus predicted passenger head injury is worse for the unrestrained passenger in all cases tested, see Figure 4. The limit, as defined in AV/ST9001, is 500. The unrestrained occupant exceeds this limit (see above) and is marginally below this value in other situations. The restrained occupant receives a HIC of less that 150 in all cases.

Comparison 1 shows that in the significant majority of cases the predicted injuries, HIC and Nij, for a restrained passenger are lower than for the unrestrained passenger impacting a stiffened seat. This, if considered in isolation, would favour the fitment of 3-point passenger restraints, as it does not consider the effect of stiffening the seat on the unrestrained person.

The photograph below, Figure 5, provides a comparison of the kinematics between an unrestrained and restrained occupant. The restrained occupant is in the front seat and the unrestrained in the rear seat. The unrestrained occupant impacts the seat in-front whilst the restrained occupant does not.

Figure 5 – Photographs from Video of Test 04

5.2.2 Comparison 2

Unrestrained occupants impacting un-modified seats are likely to receive lower predicted injures than those impacting stiffened seats. A comparison has been made between the predicted injury levels of passengers impacting a seat modified to allow the attachment of 3-point restraints versus the previously benchmarked seat. The modifications have increased the stiffness of the seat in the longitudinal direction.

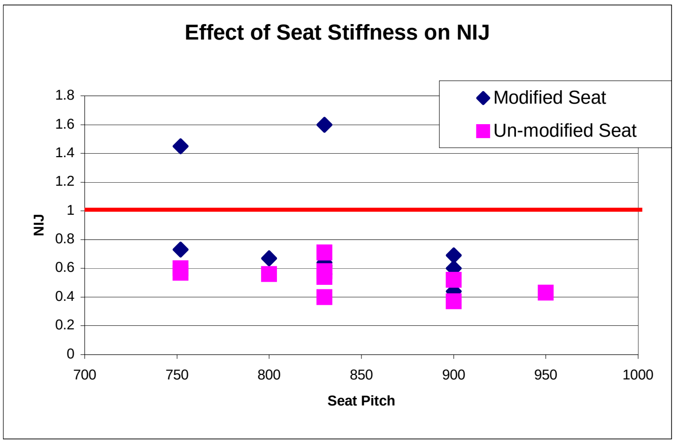


Figure 6 - Effect of Seat Stiffness on NIJ for Unrestrained Occupants

In the majority of cases there is little variation between the Nij values for unrestrained occupants impacting seats with differing stiffness. In two cases the Nij value is above the limit of 1. This occurred when a 5th percentile female occupant impacted the modified, stiffer, seat. It is possible that as the mass of the 5th percentile female ATD is significantly less than the 50th and 95th percentile males, the impact energy is not sufficient to overcome the increased force required to bend the seat, and thus little energy is dispersed in the deformation of the seat.

Head injury for the unrestrained occupants is shown in Figure 7.

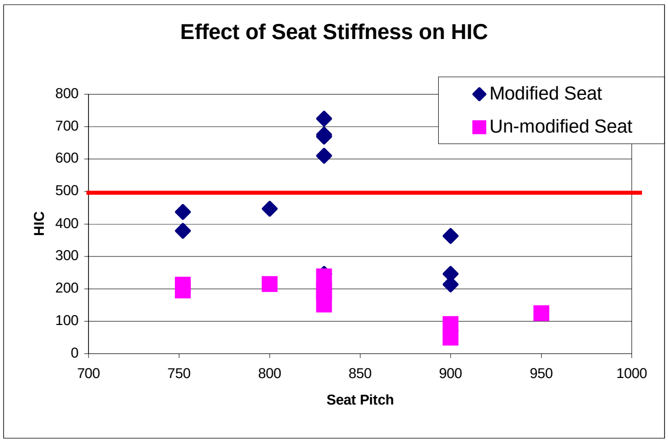


Figure 7- Effect of Seat Stiffness on HIC for Unrestrained Occupant

The head injury criteria is higher in all cases for impact with the stiffened seat. In a number of cases the HIC is above the limit in AV/ST9001 of 500. This is not the case for any of the impacts with the unmodified seat.

5.2.3 Comparison 3

A comparison has been made between 3 point passengers restraints and 2 point passenger restraints in terms of HIC and Nij. The 2-point passenger restraint work concluded that the predicted injuries for passengers choosing to wear the belt would be greater than those who did not.

A comparison of Nij, Figure 8, shows that the predicted injury level is appreciably higher for occupants restrained in a 2-point passenger restraint versus those restrained in a 3-point restraint.

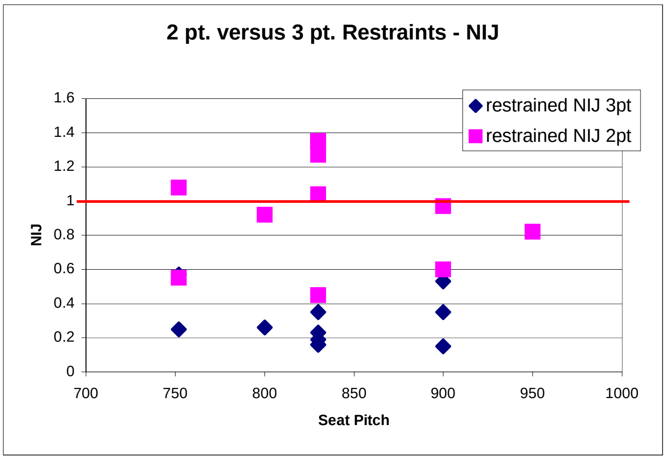


Figure 8 - Comparison of NIJ for 3pt and 2pt Passenger Restraints

Figure 9 shows a comparison between HIC values for occupants restrained in 2-point and 3-point restraints. Similarly to Nij, HIC is shown to be worse for occupants restrained by a 2-point passenger restraint.

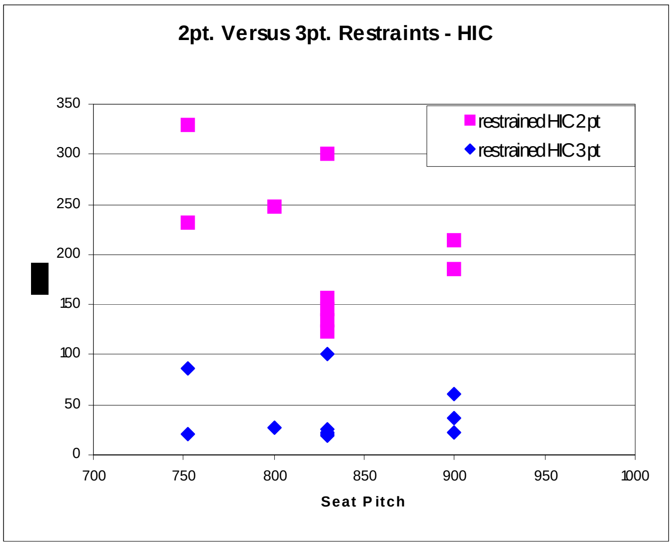


Figure 9 - Comparison of HIC for 3pt and 2pt Passenger Restraints

5.2.4 Comparison 4

A comparison has been made between 3 point passenger restraints and unrestrained occupants impacting un-modified (benchmarked as crashworthy) seats in terms of HIC and Nij.

A comparison of Nij, Figure 10, shows that the results for both the unrestrained and 3pt restrained occupant receive predicted injury levels less than 1 for NIJ. The restrained occupant receives lower predicted injuries than the unrestrained occupant although both are within tolerable limits.

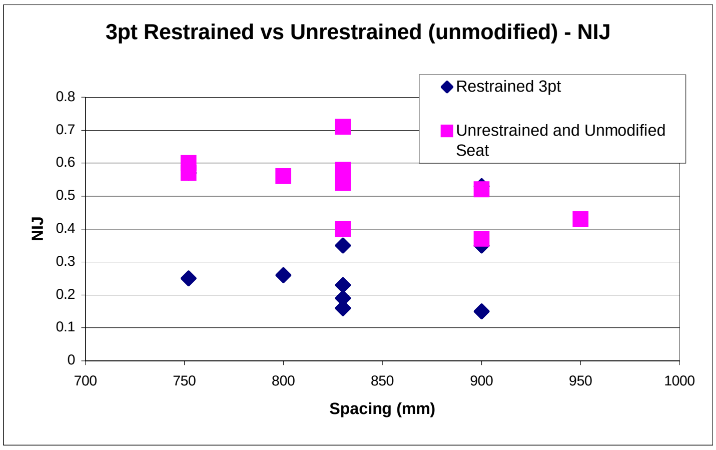


Figure 10 – Comparison of NIJ for 3pt passenger restraint and unrestrained (unmodified seat)

Figure 11 shows a comparison between HIC values for occupants restrained in 3-point restraints and unrestrained passengers in unmodified seats. Similarly to Nij, HIC is shown the be lower for the restrained occupant. The HIC results for both the restrained and unrestrained occupants are low when compared to the tolerable values as defined in AV/ST9001.

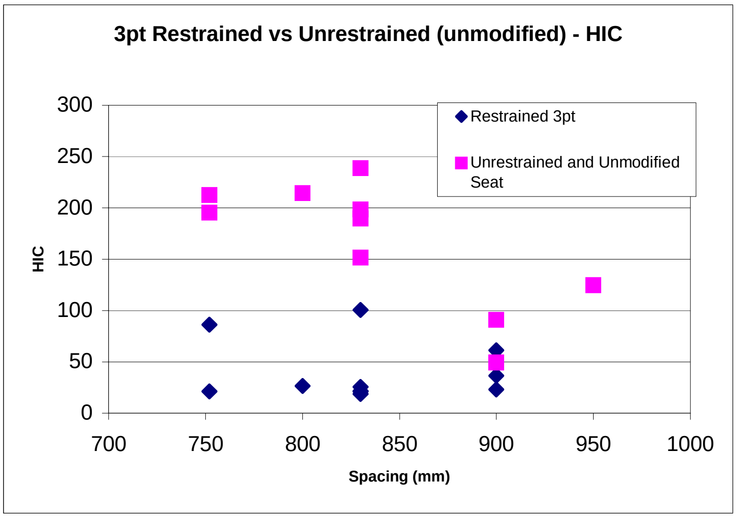


Figure 11 - Comparison of HIC for 3pt passenger restraint and unrestrained (unmodified seat)

5.2.5 Static versus retractor belt

When considering the net effect of 3-point passenger restraints, static belts, if worn correctly, provide the maximum passenger containment. In service however, the use of static belts could lead to mis-use, vandalism and tripping hazards. A test has been conducted to allow a comparison to be made between the use of static and retractor belts in terms of injury criteria. A static belt will only allow occupant excursion due to webbing stretch. Retractor belts, on top of this stretch, will allow an amount of belt to un-spool from the reel as the webbing tightens. This allows a greater occupant excursion.

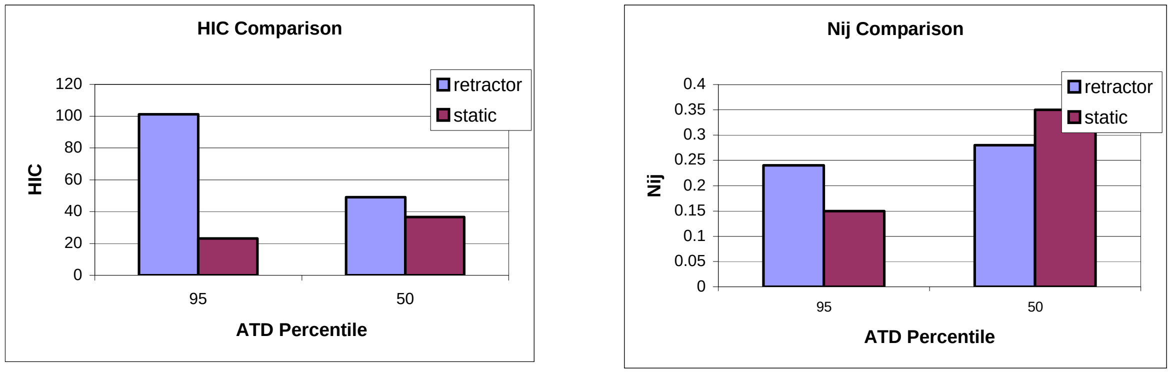
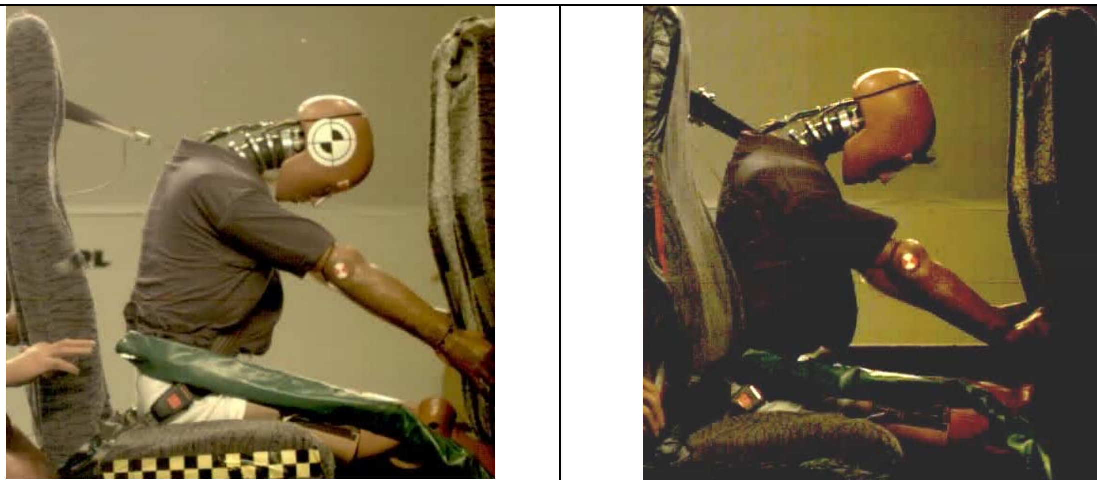


Figure 12 - Predicted Passenger Injury Static vs. Retractor Belt

The testing indicated that for a seat spacing of 900mm using 95th and 50th percentile male ATD there is no significant difference between injury criteria for static or retractor belts, Figure 12. It is possible that the large pitch for this test has negated the effect of the extra excursion, Figure 13 and Figure 14.



Retractor Belt	Static Belt

Figure 13 - Comparison of Excursion for 50th Percentile

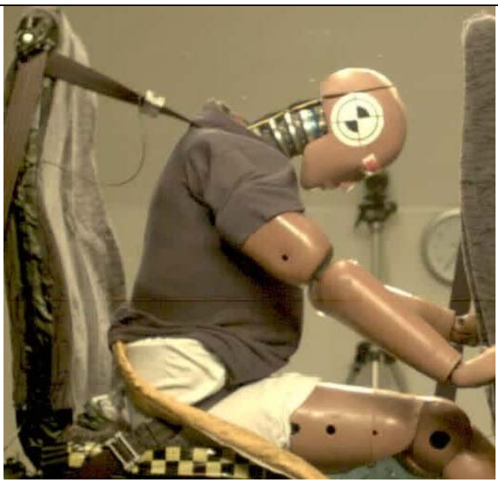
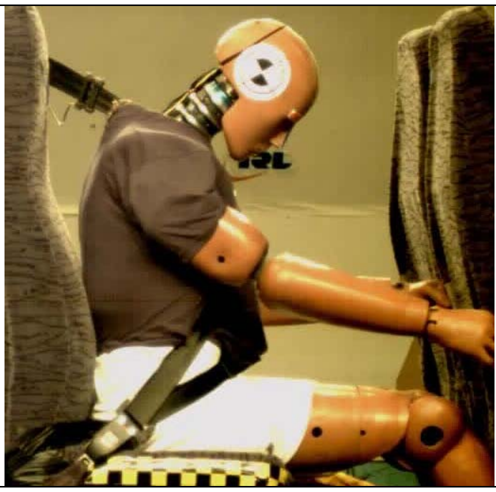
	
Retractor Belt	Static Belt

Figure 14 - Comparison of Excursion for 95th Percentile

5.2.6 Unrestrained Occupant Knee Intrusion

As noted in the 2-point passenger restraint work knee intrusion from the unrestrained occupant into the rear of the restrained occupant is a cause for concern. Hybrid III ATDs, including the Hybrid IIIRS, do not have a mechanism to measure impact into the lower back from behind and thus a prediction of injury cannot be made. The amount of deformation occurring, especially for the 95th percentile male ATD's is extensive and may be injurious to the restrained passenger, Figure 15. .

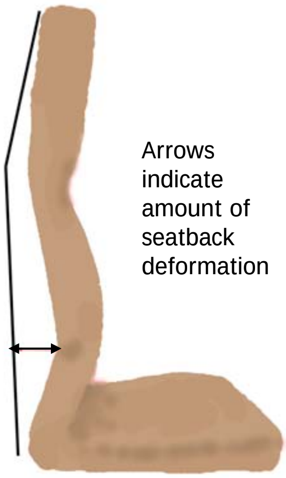


Figure 15 - Knee Intrusion 95th Percentile

Post testing it was found that this knee intrusion was sufficient to permanently deform the seat and thus increase the risk of entrapment and lower back injury to passengers choosing to wear restraints. The restraint was also found to be extremely tight around the occupant following the test with approximately 1kN of force remaining in the belt. The effect this has on predicted injury and egress ability is not understood, however, it is an important and significant factor requiring further consideration.

5.3 DISCUSSION OF TEST RESULTS

The Injury Criteria used to evaluate the performance of lap and diagonal restraints are those criteria developed from earlier research and used during the two-point restraint work. These criteria (forces and accelerations appropriate to individual body regions) are similar to criteria used internationally and throughout other transport industries. Those developed for Rail are generally more stringent than others. The neck injury criteria (Nij) has been used as the best indicator for the performance of the human neck in national and international studies similar to the research undertaken in this report. Whilst using this measure, as it represents the best available recognised and validated measure, we should recognise that detailed analysis for this report has cast some doubt about the sole use of Nij (which is only measured at the upper neck position) to evaluate some (particularly lower) neck injury. This however does not undermine the use of Nij to predict injury to the upper neck.

The following assumptions must be applied to make the conclusions regarding testing valid:

a) The injury levels reviewed are HIC and Nij
b) The restraint is correctly fitted to the occupant and seat
c) A longitudinal forward facing pulse conforming to that in AV/ST9001 is applied (as specified in Section 4 of this report and as used in the two-point restraint work)

Tests have shown that in the large majority of cases occupants restrained by 3-point passenger restraints receive less severe predicted injuries than unrestrained occupants. This case remains true when predicted injuries for 3-point restrained occupants are compared to unrestrained occupants impacting both an un-modified and modified (stiffer) seat. However when comparing unrestrained occupants impacting unmodified seats and 3-point restrained occupants both receive predicted HIC and NIJ values below the tolerable levels of 500 and 1 respectively. In this comparison the levels of HIC and Nij are much closer.

Unrestrained occupants impacting the modified seat receive predicted injuries larger than those impacting the un-modified seat. HIC for the unrestrained occupants does not exceed the limit of 500 for the un-modified seat. Unrestrained occupants impacting the modified seat do, in some cases, exceed a HIC of 500. Neck injury for unrestrained occupants impacting both the modified and un-modified seat are less than 0.8 for all cases except for the 5th percentile female as noted in Comparison 2 above. This phenomenon is important and may have consequences for passengers with smaller statures such as small females or children. Section 7 discusses the use of 3-point passenger restraints with children in further detail.

In terms of the injury criteria used in this report the predicted level of passenger injury will be as follows, from minimum to maximum predicted injury:

- Occupants restrained in a 3- point passenger restraint receive the lowest predicted injuries.
- Unrestrained occupants impacting un-modified seats receive the second lowest injuries.
- Unrestrained occupants impacting modified (stiffer) seats receive predicted injuries worse than occupants impacting an un-modified seat.
- Occupants restrained in a 2-point passenger restraint receive the worse predicted injuries. In some cases the predicted injuries are significantly worse than the other tested configurations.

6 Computer Modelling

The physical testing carried out for this project was designed to examine the most likely scenarios in detail, with boundary conditions as recommended by the positioning paper. Use of a 50th percentile male ATD in a range of appropriate pitches covers most possibilities on the UK railway. To conduct full scale tests for all possible combinations of variables would require significant resources and extended timescales. Validated computer models have the ability to provide results for a large number of test configurations at lower costs and with shorter timescales. It may also be possible to model situations that it is not feasible to physically test.

As part of the 2-point passenger restraint work AEAT created a validated model using the finite element software package MADYMO©. MADYMO© was chosen as the preferred software due to its pre-eminence and position in the rail and automotive industries in occupant modelling. The 2-point restraint model was supplied to TRL for validation of passengers restrained by 3-point belts, Figure 16. The original model as used for the 2-point work was modified to accept a 3-point belt. A physical test was conducted and the model modified by TRL to represent the physical testing. The modified model in Figure 16 shows good agreement with the physical testing as shown, for example, by the head contact with the seat at 200ms.

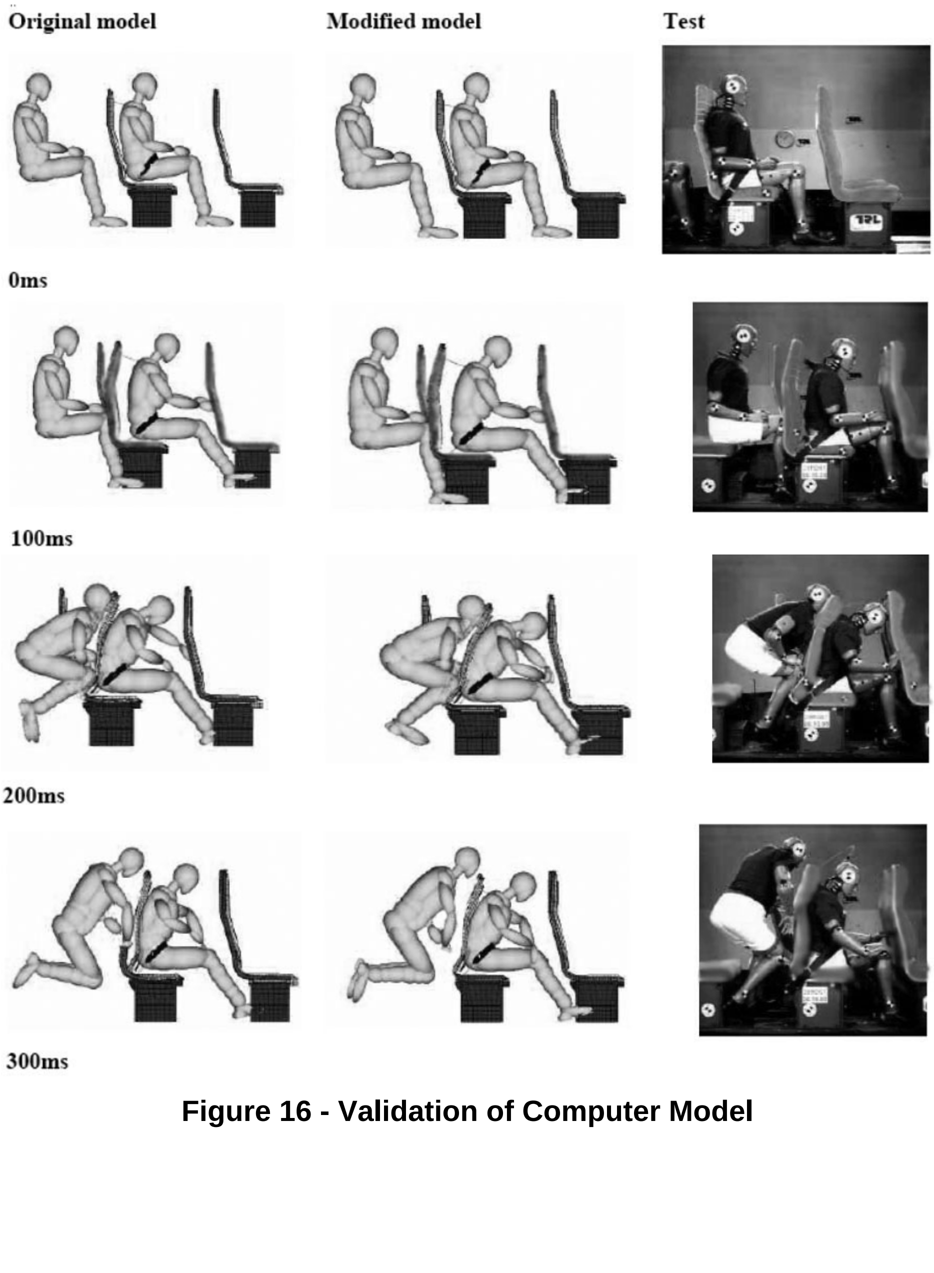


Figure 16 - Validation of Computer Model

Parametric model runs were carried out with the validated model to identify worse case impact conditions for occupants wearing 3-point passenger restraints on rail vehicles. The model predicted that the injury criteria (Nij and HIC) would be below tolerable values. Stiffening of the seat increases the predicted injuries for unrestrained occupants, as found during testing.

7 Children

Consideration of the anatomy, growth and development of children is crucial to the design of effective impact protection. In this sense, children are not small adults and their needs change as they grow. As an example, it is recommended that in cars children should use an appropriately designed restraint system until they are 1.5m in height. There are a number of key requirements for the restraint of infants and children. The restraint forces must be uniformly distributed as widely as possible over the strongest parts of the body. Until reaching puberty the pelvis is not developed sufficiently to withstand the forces of a lap or lap and diagonal restraint. Although, for cars, with the spatial constraints, geometry and orientation that this imposes, it is safer for children to be restrained than unrestrained, even if the restraint is poorly fitted. This is not necessarily the case for children travelling in railway vehicles.

Information provided by TRL contained within the positioning paper, indicates that measurements and observations of 167 children aged 1 through to 11 showed that only those with a sitting shoulder height greater than 420 mm could achieve a good fit from the three point seat belt in a selection of minibus and coach seats. Poor fit of the diagonal belt increases the likelihood of misuse. Observation studies show children sometimes place the belt behind their back or under their arm. Both types of misuse reduce the performance of the seat belt significantly [6]. When the belt is placed behind the back, the fit of the lap part of the belt is not the same as a lap only belt and will very likely sit too high on the abdomen. When the diagonal part of the belt is placed under the arm, the belt forces on the side of the chest are known to result in serious internal injuries in a crash.

A loose or poor fitting shoulder belt offers reduced protection for the child. Due to their larger head size and higher centre of gravity, young children in seat belts tend to rotate out of the restraint. In a study of children aged 2 to 5 years, children in seat belts were at particular risk of significant head injuries when compared with children in child restraints. Slightly older children have a lower centre of gravity and may predominantly load the lap part of the belt. The risk of lumbar spine fractures is greatly reduced because the torso is restrained. However, the risk of abdominal injuries due either to misplacement of the lap part of the belt or the act of sliding under the belt (submarining) is increased. An analysis of UK accident data performed by TRL confirmed that children travelling in a seat belt were more likely to be injured than those using a dedicated child restraint system.

In this project for the Rail Industry there is sufficient evidence to demonstrate that if lap and diagonal restraints were required to be fitted to trains, then corresponding and appropriate special provision would need to be made for children.

8 Structural Intrusion

It is clear that not all accidents have a purely longitudinal pulse. In addition there are other considerations that must be noted. For example structural intrusion has played a significant part in a number of recent accidents.

In work carried out under project T424, six recent accidents have been analysed to understand the actual behaviour of the affected vehicles.[1] An assessment has also been made of the number of seats that have been affected by structural intrusion, a crushing of the vehicle structure to a level where it impinges on passenger survival space when they are in a seat location. The accidents investigated are listed in Table 2.

Accident	Summary	Total Passenger Fatalities
Ufton Nervet – 06/11/04	10 vehicle MKIII HST derailed after striking a car on a level crossing.	5
Potters Bar – 10/05/02	4 vehicle EMU derailed after passing over faulty points	6
Great Heck[2] – 28/02/01	11 vehicle MK4 Train derailed after striking a vehicle located across track	6
Hatfield – 17/10/00	11 vehicle MK4 Train derailed due to fracture of rail	4
Southall – 19/09/97	9 vehicle MKIII HST collided with freight train	7
Watford – 08/08/96	4 vehicle EMU collided with empty passenger train	1

Table 2 - Accidents Reviewed

In these accidents, the number of passengers ejected from the vehicle has been assessed. The number of instances where these ejections have been fatal has also been identified. These are given in Table 3.

Accident	Number of Ejections	Fatalities Due to Ejections
Ufton Nervet	9	4
Potters Bar	6	4
Great Heck	0	0
Hatfield	0	0
Southall	2	2
Watford	2	1
Total	**19**	**11**

Table 3 - Fatalities by Ejection

[1] The data contained in this section is based on the most up-to-date information at the time of reporting. This may differ from that contained in report AEATR-ES-2005-116 – Review of Two-Point Passenger Restraints however this does not affect the conclusions previously made.
[2] There were ten fatalities at Great Heck. Four of these were railway staff and have not therefore been included as the outcome would not have been altered had seatbelts been fitted to passenger seats.

At Great Heck and Ufton Nervet there were very significant instances of structural intrusion into passenger survival space. Some passenger fatalities were found outside vehicles, but this has been put down to structural intrusion and consequential loss of containment in the above tables, not to ejection.

Figure 17 - Structural Intrusion at Ufton Nervet

By making the following assumptions it is possible to compare the effect of restraints on passengers subject to ejection or structural intrusion:

- **A restrained passenger would not be ejected**. This assumption favours restraints as it is possible that a restrained passenger can be partially ejected.

- **Any ejections would be fatal.** This assumption favours restraints as Table 3 shows that only approximately 50% of ejections are fatal.

- **A restrained passenger will not been thrown clear of structural intrusion and would therefore receive fatal injuries.** This is based upon the structural intrusion encroaching within a passenger's survival space; Figure 17. This assumption favours not having restraints.

An assessment has been made of the number of seats that have been affected by structural intrusion causing loss of survival space. Passengers were seated in these areas prior to the impact, and it has therefore been concluded that passengers in this situation have been thrown or pushed clear during the incident, suffering some injury but surviving in the majority of cases. Over the six accidents reviewed a total of 14 fatalities are attributed to structural intrusion. Table 4 gives details of the number of seats that have lost survival space.

Accident	Number of Ejections	Number of Seats with Loss of Survival Space
Ufton Nervet	9	42
Potters Bar	6	0
Great Heck	0	62
Hatfield	0	26
Southall	2	46
Watford	2	44
Total	**19**	**220**

Table 4 - Ejections Versus Loss of Survival Space

These are not comparable numbers, as the number of ejections relates to passengers and the loss of survival space to seats affected rather than passengers affected. The approximate number of passengers in each train is known and therefore the occupancy in those areas suffering loss of survival space has been factored down (or normalised) in proportion to this passenger loading. In the absence of detailed information it has been assumed that passengers were uniformly spread, thus enabling a comparison to be made. This is given in Table 5.

Accident	Number of ejected persons possibly saved by a passenger restraint		Number of Passenger Fatalities due to loss of survival space	Number of passengers affected by loss of survival space. (Hence possible fatality if restrained)
	Total	**Fatalities**		
Ufton Nervet	9	4	0	16
Potters Bar	6	4	0	0
Great Heck	0	0	5	11
Hatfield	0	0	4	8
Southall	2	2	5	25
Watford	2	1	0	28
Totals	**19**	**11**	**14**	**88**

Table 5 - Comparison of Ejected Persons and Loss of Survival Space

The analysis shows that for the six accidents reviewed, approximately 8 times as many passengers (11 vs. 88) would have been affected by loss of survival space, if restrained, as would be saved from fatal ejection. The number of predicted fatalities due to loss of survival space is over 6 times larger (14 vs. 88) than has been found during the accidents reviewed.

Analysis suggests that restraining passengers in seats, whilst reducing the likelihood of ejection, may have other more serious consequences and create significant numbers of additional casualties (or fatalities) as a result of loss of survival space.

9 Train Specific Issues

There are a number of issues specific to the fitment of 3-point passenger restraints on UK mainline passenger carrying rail vehicles. The following topics are discussed:

- Loading of seats restraining passengers and load path to vehicle
- Modification of seats to allow fitment of 3-point passenger restraints
- Out of position occupants
- Configuration and type of restraint
- Other research into preventing ejections

For a 3-point passenger restraint to offer protection to an occupant, the seat to which it is fitted must be strong enough to withstand the loads seen during an accident scenario. In current circumstances it is also foreseeable that an unrestrained passenger could impact this loaded seat; in effect, double loading the seat. A seat, used in conjunction with a 3-point passenger restraint, must be capable of withstanding this double loading, tested by a 95th percentile male impacting the rear of a seat in which a second 95th percentile male is being restrained, without deforming beyond acceptable limits. The limit used for this report, as also used in the bus and coach industry, is that the seat top must not deform past the h-point (an imaginary point on a seat approximately where the hip of a seated occupant would be when viewed from the side).

The loading regime described above should be considered in multiple where such seats, and restraint systems, occur within rail vehicles. In these conditions the loads and complexity of the load path to the vehicle structure is considerably increased. Current vehicle structure (seat rails and their fixings) and the interface to the seat are not designed to accept the loads imparted by restraining an occupant within their seat. The vehicle structure would require considerable re-design and modification to withstand the loads required.

The donor seat used for testing required substantial modification to meet the structural requirements as identified by preliminary testing and finite element analysis. The modifications considered the load path from the seat top to the seat pedestal whilst raising concerns as to the possibility of asymmetric loading, which may pose a trapping risk to passengers. Based on Deltarail's extensive knowledge of rail seat design and the appraisal of seats from the benchmarking phase of this work, it is considered that it would not be possible to modify many existing rail vehicle seats to the extent required to accept 3-point passenger restraints.

Recent accident investigations have indicated that generally passengers were unaware of any impending crash and initially did not amend their position or try to brace themselves. The greater space envelope and lack of restrictions to position when compared with road vehicles may result in passengers being 'out of position' in relation to the idealised juxtaposition between passenger and restraint and seat. It is foreseeable that a restraint acting on an 'out of position' passenger has the potential to worsen injury. [6]

During the workshop, discussions were held postulating the best method and configuration of attaching the restraint to the seat in order to maximise benefit during a vehicle rollover. It was suggested, for example, that by having the diagonal of the belt always on the aisle side of the seat such that during a roll there would be less potential for passengers on the high side escaping the restraint. In terms of testing a longitudinal pulse, in a symmetrical seat configuration, the orientation of the diagonal belt would not affect injury outcomes, however it is necessary to record this issue for future investigation if appropriate.

10 Discussion

When considering the net safety benefit or dis-benefit of fitting 3-point passenger restraints a number of factors, including some already discussed, require consideration. The net effect of the fitment of 3-point passenger restraints depends largely on the propensity of passengers to wear the restraints and the suitability of the restraint when used with a large range of passenger statures. The suitability of 3-point restraints for children travelling in trains has not been tested.

It has been shown that, for the situations tested, 3-point passenger restraints reduce predicted injury levels for adults if they choose to wear them. For those passengers who choose to not wear the restraint there is a negative effect on injury levels when impacting the strengthened seat. In order for a seat to withstand the forces imparted by double loading, strengthening of the seat and seat structure was required. This increased the stiffness of the seat and thus worsened the predicted injury levels for the unrestrained occupant. It may be possible, through a complete redesign, to lower the effect the seat stiffening has on the unrestrained occupant's predicted injuries. This however, is un-feasible and prohibitive when considering retro-fitment of 3-point passenger restraints to existing seats. Equally, it is reasonably foreseeable that modifying an existing railway seat to be capable of accepting a lap and diagonal restraint device could be conducted in such a way as to prejudice the safety of the wearer and those in the immediate vicinity, in collision conditions.

If a passenger is involved in an accident whilst wearing a 3-point belt the effect of vehicle structural intrusion requires consideration. It has been noted that the number of fatalities due to structural intrusion is lower than expected given the post accident condition of the vehicle and passenger loading. From analysis of the data it has been concluded that passengers were thrown away from the site of impact and subsequent intrusion, receiving only minor to moderate injuries. This phenomenon has also anecdotally been seen during crash investigations in the USA. If a passenger is restrained in a seat this phenomenon will not occur and it is likely that the number of fatalities due to structural intrusion will outweigh the number of fatalities saved by preventing passenger ejections by passenger restraints (see table 5).

If ejections can be prevented by improving the containment properties of windows then the benefit of fitting 3-point passenger restraints for preventing ejection is negated. If 3-point restraints are installed and the number of passengers choosing not to wear restraints outweighs those choosing to wear them, then the level of overall injury in the event of an accident will increase due to the increased seat stiffness. Conversely, if worn by all passengers the level of injury will be reduced. The level of injury for unrestrained passengers impacting un-modified crashworthy seats is within the tolerable injury levels established by research, however occupants choosing to wear 3-point restraints receive comparable but lower predicted injuries. It is also possible that the level of injury to children is increased by mis-using poorly fitting restraints or by impacting stiffer seats.

Experts in the field of occupant protection expressed concerns with scenario's whereby restrained passengers may be impacted by a passenger from the rear who has chosen not to wear a restraint, this phenomenon is sometimes know as phasing. This is a common injury mechanism in automotive accidents where passenger movements are out of phase such that the front occupant is moving rearward as the rear occupant moves forward. This can lead to head contact between the two occupants. Contrary to these expectations, discernable phasing did not occur at any seat pitch or with any occupant size in the tests that were carried out.

The problem of knee intrusion from the unrestrained occupant into the rear of the restrained occupant has become evident during the testing. Although there are no injury measures for the impact into the lower back the seat deformation indicates that this may be of concern. It is important that if 3-point restraints are fitted, and not worn by all passengers, the effect of knee intrusion must be understood. It may be possible to develop a seat that reduces the knee intrusion whilst keeping femur loads and knee displacement within the criteria defined in AV/ST9001 however this was outside the scope of this report.

11 Conclusions

1 The extensive evaluation has shown that the effectiveness of the various methods of retaining passengers may be ranked as follows:
   a) Passengers choosing to be restrained by 3-point belts are likely to sustain the lowest injury levels and these are within the current levels of acceptance.
   b) Unrestrained passengers in current types of crashworthy passenger seats are likely to sustain slightly more severe injuries, but these also remain well within limits of acceptability.
   c) Unrestrained passengers in seats stiffened for installation of 3-point seat belts are likely to sustain more severe injuries which in some cases are outside limits of acceptability. In the case of 5th percentile female ATD these were significantly outside acceptable limits.
   d) Passengers restrained by 2-point seat belts are likely to sustain the most serious injury levels, a significant proportion of which are outside, or bordering on, limits of acceptability.

2 3-point seat belts, fixed to seats using adult configurations, are not suitable for infants or children under 1.5 metres in stature (approximately 12 years of age or under).

3 Structural intrusion is a significant problem in accidents. Accident data indicates that injuries and fatalities due to retaining passengers in their seats in areas where survival space is lost are likely to increase dis-proportionately to the fatalities due to ejection that may be prevented by the restraints.

4 The fitting of 3-point seat belts to current seats not specifically designed to accept them is likely to result in excessive and injurious deformation in accident situations.

5 Installation of 3-point seat belts would necessitate extensive modification to the seat and the vehicle fixing arrangements which would be extensive and costly. A significant proportion of current seat and rail vehicle designs would not be capable of achieving the necessary modifications cost effectively.

6 Knee intrusion from unrestrained passengers becomes a significant problem for restrained passengers, due to significant deformation of the seat back under the knee impact. Such intrusion is likely to inflict injuries to the lower back of the restrained passenger and result in large constrictive residual loads in the belt across the thigh region. Whilst it has not be possible to quantify the likely injuries to the lower back and constrictive injuries across the thigh, it is considered that these would not be insignificant.

7 There is a difference, in terms of restraining properties, between static and retractor belts. Retractor belts allow a greater occupant excursion which is beneficial in reducing the peak loads (on the passenger), but is disadvantageous in making contact with the seat in front more likely. From the perspective of injury reduction, the static belt may be most advantageous but there are potential operational difficulties such as vandalism and tripping, which would need to be resolved.

8 Out of position occupants were not investigated during the testing although they were discussed extensively during the workshop. It was recognised that the performance of a 3-point seat belt could be seriously prejudiced by out-of-position postures.

9 It has been shown that there is no net safety benefit for passengers who choose to wear 3-point restraints on passenger carrying rail vehicles. Generally passengers who choose not to wear restraints in a vehicle modified to accept 3-point restraints receive marginally more severe injuries. In specific cases injuries to some unrestrained passengers are above those tolerable levels identified by research.

12 Recommendations

1. 3-point passenger restraints should not be fitted for the following reasons:
   a) The benefit would only be marginal relative to a crashworthy seat designed to meet the current requirements of AV/ST9001.
   b) They are not suitable for infants or children under 1.5 metres.
   c) Passengers restrained in areas of structural intrusion are likely to be more severely injured than unrestrained passengers who, accident data indicates, are usually thrown clear as the intrusion progresses.
   d) Current seat designs and installations would not be suitable to carry the loads imposed by a restrained occupant, together with an unrestrained occupant impacting the seat, without sustaining significant and injurious deformation. The seat and mounting would therefore require significant modification (not possible with all types of design).
   e) There would be an increase in the levels of injury inflicted on those passengers choosing not to wear the restraint device due to impacting a stiffened seat.
   f) Restraining passengers would render them more vulnerable to knee intrusion resulting from unrestrained passengers impacting the rear of the seat.

2. Seats should continue to meet the requirements of AV/ST9001 in order to provide an effective means of absorbing passenger energy in an impact and as a contributory means of containing passengers within the vehicle.

3. This work should be considered in conjunction with the outcome of RSSB research project T424 which considers windows as an effective means of reducing the risk of ejection without the consequential risks identified in this project.

4. In the event of this analysis becoming less representative of the railway situation, due to a significant change in the types of accidents and the associated risks, a further review of the potential benefits of 3-point seat belts must take into account the issues identified above in these recommendations and elsewhere in the body of this report. Such a review should include a consideration of the effect of ‘out-of-position’ on the retention ability of the restraint device.

13 References

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