Seatbelt performance in quarry vehicle incidents

Final Report

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RESEARCH REPORT 406
Seatbelt performance in quarry vehicle incidents

Final Report

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Quarrying and open cast coal mining has been recognised as one of the most dangerous work environments in which to be employed, with the fatality rate more than three times that of the construction industry and 20 times that of all industry (Foster, 2003). The most frequent type of accident in quarries is those involving vehicles, accounting for approximately 40% (HSE, 1993). Industry standards have been implemented in the UK with respect to all round visibility from vehicles, edge protection and brake testing to reduce the number of casualties. The effectiveness of restraint systems is considered as the next step to achieving casualty reduction targets.

This research has reviewed current international standards relating to occupant protection and accident data. A range of accident conditions were simulated using multi-body numerical models that were evaluated against data from full scale tests. This information was supplemented by assessing the risk from structures inside the vehicle cab and consideration of practical issues relating to the use of restraints.

Restraint of the torso was shown to provide additional benefits over the current lap belts. Wider implementation of more comprehensive restraint systems should be encouraged. However, a number of issues should be considered before full implementation throughout the industry.

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EXECUTIVE SUMMARY

Quarrying and open cast coal mining has been recognised as one of the most dangerous work environments in which to be employed, with the fatality rate (number of fatalities as a percentage of employees) more than three times that of the construction industry and 20 times that of all industry (Foster, 2003). The Health and Safety Commission (HSC) and the Health and Safety Executive (HSE) are responsible for regulating risks to health and safety in UK work places. Part of the HSC Strategic Aim was to meet the quarry industries Hard Target initiative to reduce accidents by 50% between 2000 and 2005.

The most frequent type of accident in quarries is those involving vehicles, accounting for approximately 40% (HSE, 1993). These types of accident can have a high risk of death, accounting for 60% of fatalities in the RIDDOR (RIDDOR 1995) database for 2000/2001. Accidents where earth-moving machinery is involved in an impact or rollover result in a substantial number of fatal and serious injuries worldwide. Industry standards have been implemented in the UK with respect to all round visibility from vehicles, edge protection and brake testing to reduce the number of casualties. The effectiveness of restraint systems is considered as the next step to achieving casualty reduction targets.

The minimum requirements for restraints in such vehicles are two point lap seatbelts, which some accident investigations suggest may have contributed to the severity or cause of injuries. TRL Ltd were commissioned by the HSE to carry out an investigation of the effectiveness of occupant restraint systems in selected vehicle incidents in the quarrying industry. The objectives of this research were:

- To review current standards and practices in the UK and overseas
- To evaluate the performance of different restraint systems in different vehicle types and incident scenarios
- To make recommendations as to the most effective restraint systems in order to minimise injury over a range of accident situations

The current standards and practices for operator restraints were reviewed for both the UK and overseas. This confirmed that minimum requirements in most countries were to fit two point lap belts and the SAE Information Report J2292 provides technical guidance for upper torso restraints and the use of retractor. The Australian Standard AS 2664 also provides requirements for the anchorage points of a torso restraint (diagonal belt).

The performance of different restraint systems, including lap belts, three-point lap-diagonal belts and harnesses, were assessed by numerical simulation. The numerical simulation was supported by accident analysis to determine the vehicle types and scenarios to be modelled. Four vehicle types were considered, rigid dump truck, articulated dump truck, wheel loader and dozer. All scenarios were simulated with a 50th percentile human body model and some cases were repeated with a 95th percentile human body model. One of the vehicle models was evaluated against data collected during full scale rollover tests. In general, improving the restraint of the torso reduced the risk of injury from contact with other items in the cab, however, a harness type restraint was more effective for both clockwise and anti-clockwise rollovers.

Practical issues relating to the use of the different restraint systems was also considered which included acceptability by the vehicle operators. This included consultation with vehicle operators who had used both lap and harness type restraints. It was found that acceptance of a different type of restraint would be mainly dependent on the type of work being carried out. It is likely that most of these issues can be resolved through improved design of vehicles, seats and restraints but further, more objective, investigation of the issues will be required.
The assessment of the restraint systems was supplemented by a risk assessment of the interior of the cab which allowed items within the cab that could not be included in the models to be assessed. It was found that cab interior design was typically not occupant friendly and that hostile structures (e.g. small radius steel handles) were frequently located in areas that critical body regions such as the head are likely to collide with during a rollover or frontal collision. Improvement in occupant protection could be achieved through improved design (e.g. moving hostile structures or making them softer or less “sharp”) and ideally this would be combined with improved restraint to reduce the size of the envelope into which the head could move during a collision.

This research has identified a potential issue with locking mechanisms used in the retractor on the lap belts tested, where during the slow speed rollover (falling under gravity over period of half a second) they did not lock. This should be further investigated to ensure that current lap belts are working effectively, maybe leading to alternative locking retractor designs.

RestRAINT of the torso, particularly with a harness type restraint, has been shown to provide additional benefits over the current lap belts. It is recommended that wider implementation of more comprehensive restraint systems be encouraged in particular operating conditions. However, before full implementation throughout the industry there are a number of issues that need to be addressed. These include the lack of standards for the design of such systems for quarry vehicles, the potential increased risk of injury during normal operation and the range of movement required by vehicle operators to work efficiently and safely.

It is also recommended that manufacturers should be encouraged to consider occupant protection when designing cab interiors. Measures should include considering positioning of features, materials used and radius of any corners or edges.
1 INTRODUCTION

In the UK, the Health and Safety Executive (HSE) and the Health and Safety Commission (HSC) are responsible for regulating risks to health and safety in the workplace. Quarrying and open cast coal mining has been recognised as one of the most dangerous work environments in which to be employed, with the fatality rate (number of fatalities as a percentage of employees) more than three times that of the construction industry and 20 times that of all industries (Foster, 2003). Part of the HSC Strategic Aim was to meet the quarry industries Hard Target initiative to reduce accidents by 50% during the five year period, starting in 2000. The most frequent type of accident in quarries is those involving vehicles, accounting for approximately 40% (HSE, 1993). These types of accident can have a high risk of death. In 2001 there were three fatalities, accounting for 60% of fatalities for that year, recorded in the RIDDOR database. However, in other years there were no fatalities in these types of accident.

A substantial number of fatal and serious injuries in the international quarrying industry arise from accidents where earth-moving machinery overturns or is involved in a collision. Best practice guidelines published by the HSE have been adopted as industry standards in relation to all round visibility, brake testing and edge protection and ensuring that effective restraint systems are used is seen as the next step to achieving casualty reduction targets. The minimum requirements for restraints in such vehicles are two point lap seatbelts, which some accident investigations suggest may have contributed to the severity or cause of injuries. TRL Ltd were commissioned by the HSE to carry out an investigation of the effectiveness of occupant restraint systems in vehicles used in the quarrying industry.

The principal objectives of this research were:

1. To review current standards and practices in Britain, Europe and overseas (especially Australia and the USA) regarding seatbelt types in quarry vehicles
2. To evaluate the performance of different restraint systems in different vehicle types and incident scenarios
3. To make recommendations as to the most effective restraint systems in order to minimise injury over a range of accident situations

These objectives have been addressed by:

1. Reviewing standards relating to the use of seatbelts and technical specifications
2. Reviewing accident data from the UK and overseas
3. Carrying out a parametric study using numerical simulation
4. Carrying out full scale rollover tests to compare two different restraint systems and to evaluate the numerical models used in the parametric study
5. Performing a risk assessment of vehicle cab interiors to consider potential areas for improvement in cab design
6. Assessing different types of restraint systems based on practical issues such as comfort, maintenance and acceptance by vehicle operators.

This report describes the work that has been carried out for each of the tasks described above. The outcomes of each individual task are discussed to formulate recommendations.
2 REVIEW OF LITERATURE AND STANDARDS

The aim of this review was to determine the current practices relating to operator restraint systems in earth-moving machinery. The information determined was used to identify the types of restraint systems considered in the modelling part of the project. Appendix A contains detailed information from the literature and standards that were reviewed.

In 1996, TRL carried out a project to consider the ergonomics of agricultural vehicle seatbelts (Robinson et al, 1996). The project involved a review of international standards and literature relating to earth-moving machines because operational considerations for such vehicles are similar to those found in agriculture. However, the review was restricted to the requirements of the restraints. The majority of references that were identified were foreign language papers for use by Civil Engineers when selecting machinery and therefore translations were not obtained and reviewed. The key points identified in this previous review have been included in this document.

There have not been any significant changes to regulations since this previous review. This document expands the scope of the previous review to include details of regulations that were not previously considered, such as the Quarries Regulations 1999 and the Supply of Machinery (Safety) Regulations 1992 for the UK. Rollover protection standards were also included in the review because of the relationship between structural integrity and the effectiveness of restraint systems. The most relevant documents identified during the previous review and new literature were analysed and are summarised in this section.

2.1 ANALYSIS OF THE LITERATURE AND STANDARDS

The main objective of this review was to identify the national and international standards applied to the fitment and wearing of seatbelts in quarry vehicles.

The review found that all of the standards for seatbelts that were identified had required a minimum requirement of a two point lap belt. No standards were identified that required a more comprehensive restraint system to be fitted.

ISO 6683 (1990) specified that the seatbelt system “can” contain a retractor, which implied that a static belt would be sufficient to comply with the standard. The ISO standard does not contain any requirements for alternative restraint systems.

The Australian standard specifies a minimum requirement of a lap belt but also provides technical requirements for upper torso restraint if an operator or manufacturer chooses to fit one.

The Quarries Regulation (1999) requires that companies apply their own in-house standards in relation to safety. Examples of such in-house standards were obtained and reviewed by TRL and it was found that all of those examples identified stated that seatbelts must be fitted and worn. However, there was no further specification of the type of seatbelt or the minimum technical standards for construction of the seatbelt.

Codes of practice (CoP) relating to the use of mobile machinery were identified for South Africa and New Zealand. The South African document provides requirements for fitting protective structures, but not seatbelts. In New Zealand, the fitment of seatbelts is related to the risk of rollover or tip-over and if a protective structure is fitted. The CoP states requirements for the seatbelts.

Systems that restrain the upper torso and include inertia reels, like the harness system shown in Figure 60 (Appendix A), are marketed to the quarry industry with some success. It is, therefore, known that some quarry vehicles are fitted with more comprehensive restraint systems and it is possible that some quarry companies individually require such restraints as a minimum standard. However, it should be noted that no published literature was identified that assessed
the effectiveness of such restraints in rollover accidents. The Australian Standard contained technical requirements for the upper anchorage locations. The SAE Information Report J2292 provides technical specifications for braking strength, twisting on anchorage points and positioning of anchorage points. This guidance also recommends that restraints that are only sensitive to webbing feed out should not be used unless the pelvic portion of the belt meets load requirements for Type 1 or 2A assemblies. It should be noted that the initial publication of J2292 (1997) recommended prohibiting restraints that were only sensitive to webbing feed out. However this was amended in 2000 to allow webbing sensitive restraints as long as the belt webbing and anchorages have sufficient strength to meet the load requirements (where the test is carried out with the retractor mechanism locked). It is possible that the change was made to make the guidance consistent with the requirements of SAE J386, which does not specifically prohibit any type of retractor mechanism. It is worth highlighting that the lap belt used in the full scale tests (Section 4) would have met the requirements of the 2000 version of this guidance, but not the 1997 version. In at least one test with this belt, the retractor did not lock. SAE J2292 also stated that emergency locking retractors fitted with a vehicle sensitive locking mechanism should provide adequate locking in rollover conditions as well as adequate comfort in rough riding conditions.

In the literature, Appel et al (1984) identified that in low speed (angular velocity) rollover accidents the seatbelt retractors may not lock at the most appropriate time to restrain the operator in their seat. Where the standards were found to mention the inclusion of retractor in the system there was no specification for their mechanical operation to ensure that they would be effective in rollover situations. TRL agree that there is, therefore, a risk that single sensitivity locking retractor mechanisms may not work during a slow speed rollover. This risk was borne out in the full scale tests described in Section 4.

Wearing a seatbelt has been shown to reduce the risk of ejection from a vehicle (Edwards and Neale, 2000) and it is well known that ejection carries a substantially higher risk of serious injury. This fact combined with the fact that most international, national and in-house standards require the use of at least a static lap belt, means that it is appropriate for the HSE to compare the difference in performance between a standard two-point lap belt and a more comprehensive pelvic and upper torso restraint system.

Once occupant ejection has been prevented by the use of a lap belt, the survivability of an impact will be determined by the movement that the restraint allows within the vehicle, the amount of survival space available to the operator and the aggressiveness of any structures that the operator comes into contact with during the course of the impact. The motion of the operator within the cab has been assessed in the test and simulation work carried out as part of this project (Sections 4 and 5) and an initial assessment of the likely aggressiveness of interior cab structures has also been carried out (Section 1). However, the integrity of the cab structure itself is covered by existing ROPS standards and a comprehensive assessment of ROPS performance did not form part of the test and simulation work and is not discussed in this report.

In general, the greater the survival space that is maintained by the vehicle structure, the lower the risk of penetrative, crush and other types of contact injury. The ROPS standards specify a deflection limiting volume (DLV) into which no part of the ROPS may enter at any time when the test loads are applied. The DLV is a geometric approximation of an arctic clothed large male as illustrated in Figure 66 (Appendix A). In an impact the ROPS is permitted to deform to the limit of the DLV which closely follows the shape of the seated operator with no allowance for movement of the operator during the collision. The DLV also takes no account of the potential for the operator to be out of position before the main impact, which is likely to occur in a slow rollover where the upper body is not restrained. Therefore, regardless of the restraint being worn by the operator there is a high risk of contact between the operator and the deformed cab structure if the ROPS does not perform to a level substantially exceeding the minimum standards specified. This, in turn, leads to a high risk of serious or fatal injury from contact with
the deformed structure. If the structure can be made to deform less, then the fully restrained operator is likely to make contact with the deformed vehicle structure later in the impact at a reduced relative speed. TRL, therefore, believe that the ROPS standards and the DLV may also need to be considered when making recommendations for improvements to the safety of quarry vehicles.

2.2 CONCLUSIONS

- Minimum technical requirements in international standards for seatbelts (SAE J386, ISO 6683) specify two point non-retractable lap belts, although information is supplied in the standard regarding retractor mechanisms, but not discussed here

- The Australian Standard (AS 2664) provided information for torso restraint anchorage points, however these are optional

- The Quarries Regulation (1999) requires operators to specify in-house safety standards. Examples of these standards obtained specified that operators must use seatbelts, but details on the type of seatbelt were not supplied. The specification of the seatbelt is sometimes part of the purchasing requirements for new vehicles

- Once occupant ejection has been prevented by use of a lap belt, injury mitigation becomes related to the survival space and the aggressiveness of the object within the cab. The ROPS standards define this survival space which is based on an arctic-clothed 95th percentile operator that does not move from the seated position, which is unlikely to happen if only a lap belt is being worn
3 ACCIDENT ANALYSIS

The objectives of this accident analysis are:

1. To understand the conditions under which fatal and serious injuries are sustained by quarry vehicle operators and the types of injuries sustained
2. To determine the most common/critical types of accident to focus the modelling investigation
3. To provide information about the deformation of the vehicle structure to assist with development of vehicle models

3.1 METHODS

The objective of the first stage of this accident analysis was to identify data sources. In the UK, accidents in quarries are reported under the “Reporting of Injuries, Diseases and Dangerous Occurrences Regulations” (1995) (RIDDOR). The RIDDOR system requires the reporting of certain work related injuries and for that reason the database contains information about a wide variety of accident types and the data available is not detailed and is limited to specific coded field entries and text descriptions. RIDDOR was used in combination with previous research to provide high-level information about annual statistics. The accident descriptions for 25 cases of all injury severities from RIDDOR were available for review under this project. It was possible to obtain further detailed information on cases recorded by RIDDOR by contacting the inspector responsible for the case. More detailed information was obtained for two of the cases identified in RIDDOR that were particularly relevant to this study.

Summaries of fatal accidents in the USA were available from the Mine Safety and Health Administration (MSHA) website, all of which were reviewed. Additional detailed information about four specific cases was requested, however no further details were available. Data and a summary report from a previous study were also provided by MSHA.

Information about accidents in Australia was available in a report published on the Natural Resource Management (NRM) website. Accident statistics for South Africa were available through data tables and the Chief Inspector of Mines annual reports that were on the Department of Minerals and Energy (DME) website. German Accident data was provided from a study by the University of Clausthal using data from the insurance institute StBG.

The second stage of this analysis was to analyse the data that was available in order to meet the overall objectives of the research, however, the information available was limited. Therefore, the second stage focused on categorising the accidents and case studies rather than a statistical analysis.

3.2 RESULTS

The following sections summarise the data obtained for accidents in the UK, USA, Australia, South Africa and Germany.

3.2.1 UK data

RIDDOR

The injury rate (per 1,000,000 employees) in the quarrying industry is twenty times higher than the injury rate for all industries and more than three times that of the construction industry (Foster 2003). RIDDOR data from 1996/97 to 2003/04 on the number of reportable injuries resulting from serious accidents in the quarrying industry was supplied by the HSE. This data is summarised in Figure 1.
There has been a large reduction in the total number of injuries from 1996/97 to 2003/04, particularly between 2002/03 and 2003/04 where the numbers of minor and major injuries almost halved. The number of fatalities is a small proportion of the total number of injuries and has fluctuated around the same level for the duration of this data. However, as a proportion of the total number of injuries, fatalities have increased from a maximum of 0.97% in the period 1996/97 to 2002/03 to 2.2% in 2003/04 as illustrated in Figure 2.

In addition to the data in Figure 2, data for accidents involving vehicles in quarries was also provided for 1996/97 to 2001/02. The only fatalities in these accidents occurred in 2000/01 when three employees were fatally injured, two in overturned vehicles and one in an accident.
involving collapsed plant. These three vehicle overturn/collapse related accidents accounted for 60% of the fatalities for the year 2000/01.

Summary data from the RIDDOR database was supplied for 25 cases involving vehicles between 1996 and 2003. There were 12 minor injuries (two of the accidents involved road going vehicles), 12 major injuries (two of the accidents involved road going vehicles) and one fatal injury. The accidents involving road going vehicles have been excluded from further analysis. All but two of the machines involved were either rigid or articulated dump trucks in a ratio of approximately 1:2. The other two machines were loaders. The remaining 21 accidents were categorised by type of accident as shown in Table 1. However, there was minimal information about the use of seatbelts to allow their effectiveness to be assessed.

**Table 1 Types of accident recorded on RIDDOR Database**

<table>
<thead>
<tr>
<th>Type</th>
<th>Fatal</th>
<th>Major</th>
<th>Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>No forward motion 90º</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Forward motion 90º</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Forward motion 180º</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Forward motion unknown rotation</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Backwards</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Severe deceleration</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Rollover on flat</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1</strong></td>
<td><strong>10</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

Examples of each accident type are described below:

1. **No forward motion 90º**
   a. Vehicle is tipping and becomes unstable and rolls to the side 90º
   b. Edge (or other type of ground) gives way under stationary vehicle and the vehicle rolls to the side 90º

2. **Forward motion 90º**
   a. Vehicle drives over edge and vehicle rolls 90º downhill
   b. Edge collapses under forward moving vehicle causing vehicle to roll 90º downhill

3. **Forward motion 180º**
   a. As point 2 but vehicle rolls 180º downhill

4. **Forward motion unknown rotation**
   a. As point 2 but not known how many times the vehicle rolled downhill

5. **Backwards**
   a. Vehicle drives backwards over edge causing the vehicle to fall or roll end over end backwards
b. Edge gives way under rear of vehicle causing the vehicle to fall or roll end over end backwards

6. Severe deceleration
   a. Frontal impact with wall
   b. Trailer of articulated dumper collided with roof of tunnel causing the cab to decelerate
   c. Failure of “U” joint caused occupant to be thrown forward in cab

7. Rollover on flat
   a. Vehicle rolls over when travelling round corner on level ground

8. Other
   a. Vehicle rolled backwards up a slight incline and rolled onto its’ side
   b. Vehicle ran into water
   c. Brakes failed – no other details

The only fatality in the sample assessed was caused by a backwards longitudinal rollover. Lateral rollovers with forward motion accounted for 40% of the major and 40% of the minor injuries. There were also two major injuries (20%) caused by severe deceleration of the occupant. There were a number of accidents classified as “other”, however, there were minimal similarities between these cases. This data indicates a need to consider lateral rollover both with and without forward motion, longitudinal (backwards) rollover and accidents involving severe deceleration of the cab.

Lack of, or poor edge protection, contributed to the cause of four of the accidents. In one of the cases where there was no edge protection there was a rule that required vehicles to stay at least 20m from the edge. Five accidents were caused by defects to the vehicle including a jammed tailgate that resulted in two accidents, contaminated brake fluid leading to brake failure, defective steering and failure of the “U” joint. Vehicle defects contributed to the cause of almost 24% of the accidents studied, this is very high proportion when compared with figures for road going Heavy Goods Vehicles involved in fatal accidents, 6% (Knight, 2001).

Previous research

The following section describes accident statistics from a variety of sources. As such, the time periods used are different and therefore not directly comparable.

Published accident data for the quarrying industry showed that there were 81 fatalities in the quarrying and open-cast coal industries in the ten years from 1983 to 1992 (HSE, 1993). The most frequent types of accident were those involving vehicles, which accounted for 33 (41%) of the quarry deaths. The objective of this accident analysis is to identify the types of accident where the restraint systems may have had an effect on injury severity. During the ten year period covered in the previous research (HSE, 1993), the restraint systems may have influenced the injury outcome of accidents caused by:

• Over-edge, eight fatalities – the vehicle ran over the open edge of quarry face, bench or ramp. These accidents may involve rollover about the longitudinal axis of the vehicle
• Overturned, five fatalities – vehicle overturned on quarry floor or road. These are likely to have been dynamic rollover accidents affected by vehicle speed and dynamics
• Other impacts, five fatalities – vehicles ran into each other or crashed into quarry plant...
Data on the cause of 60 fatalities between 1989 and 2000 presented at a QNJAC meeting in 2001 (Foster, 2003) showed an increase in transport related accidents in the quarry industry over the ten year period studied. The accidents associated with vehicles increased to 54%.

3.2.2 USA data

**MSHA fatal accidents**

Figure 3 shows the number of equipment related fatalities per year in the US mining industry (coal, metal and non-metal).

![Figure 3](image)

**Figure 3 Number of equipment related fatalities 1994-2003**

It is clear that there was a sharp increase in fatalities in 1997 and 2002, but overall the number of fatalities appears to be decreasing.

Figure 4 shows the types of equipment that were involved in the fatal accidents. The “other” category is very wide ranging and includes forklifts, shuttle vehicles, scrapers, excavators, locomotives and many more types of equipment.
Excluding the “other” category, haul trucks were the most frequent type of equipment that was involved in fatal mining accidents, accounting for between 15% and 35% of the accidents. Front end loaders were involved in between three percent and 18% of the accidents. Dozers typically accounted for less than 10% of the accidents and load haul dumpers (LHDs) were infrequently involved.

The accidents where the use of seatbelts was an issue, i.e. not being worn or they were insufficient, were identified by Skrabak (2004). Skrabak identified 76 cases where the use of a seatbelt was an issue. A further four cases were added to the analysis by TRL after studying the case summaries.

Figure 5 shows the use of seatbelts in the 80 accidents that were identified.
Thirteen cases (16%) were identified in which the equipment operator was wearing a seatbelt at the time of the accident. The accident mechanisms for these cases are shown in Table 2.

**Table 2.** Types of fatal accidents in USA where operator was wearing a seatbelt

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of fatalities</th>
</tr>
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<tbody>
<tr>
<td>No forward motion 90º</td>
<td>0</td>
</tr>
<tr>
<td>Forward motion 90º</td>
<td>2</td>
</tr>
<tr>
<td>Forward motion 180º</td>
<td>0</td>
</tr>
<tr>
<td>Forward motion unknown rotation</td>
<td>2</td>
</tr>
<tr>
<td>Backwards</td>
<td>3</td>
</tr>
<tr>
<td>Severe deceleration</td>
<td>3</td>
</tr>
<tr>
<td>Rollover on flat</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13</strong></td>
</tr>
</tbody>
</table>

The possibility of reducing the severity of the operators’ injuries to non-fatal was considered based on the information available. If the crush of the cab was a major factor in causing the fatality, improved restraints were considered not to be of benefit.

It is possible to consider the effectiveness of a restraint system as “probably” or “maybe” reducing the severity of injuries to non-fatal, based on the application of basic criteria to the details of the accident. There were two cases where it was considered that the accident would probably have been survivable if a harness was used. There were a further four cases where the accidents may have been survivable if a harness was fitted. A harness combined with ROPS that met with the SAE standard may have reduced the severity of injuries to non-fatal in one of the accidents.

**Table 3.** Types of fatal accidents in USA where an improved restraint system may have reduced severity of injuries

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>No forward motion 90º</td>
<td>0</td>
</tr>
<tr>
<td>Forward motion 90º</td>
<td>1</td>
</tr>
<tr>
<td>Forward motion 180º</td>
<td>0</td>
</tr>
<tr>
<td>Forward motion unknown rotation</td>
<td>1</td>
</tr>
<tr>
<td>Backwards</td>
<td>1</td>
</tr>
<tr>
<td>Severe deceleration</td>
<td>2</td>
</tr>
<tr>
<td>Rollover on flat</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7</strong></td>
</tr>
</tbody>
</table>
Of the remaining six cases, two were considered not to be survivable and three may have been survivable if the ROPS had met the SAE requirements. In the final accident, the seat came away from the machine and would have been survivable if the seat had been firmly fixed to the machine.

The descriptions of injuries sustained were described in four of the accident cases:

- Cranial cerebral injuries
- Brain trauma
- Traumatic injuries
- Asphyxia (partially ejected, preventing ejection may have prevented asphyxia)

The causes of the 13 fatal accidents where seatbelts were worn, which may have been combined, included:

- Brake defects
- Inadequate edge protection (berms)
- Loss of control
- Excess speed
- Driving too close to the edge
- Edge collapse

Ensuring that the vehicles were free from brake defects and that edge protection could not be driven through or over could potentially have prevented five (38%) of these fatalities.

Of the 56 fatalities that were not wearing seatbelts, it was estimated that up to 45 (80%) may have had the severity of their injuries reduced to non-fatal if a lap belt had been worn. If the minimum requirements were a ROPS that meets SAE requirements and a harness, it was estimated that up to 53 (95%) of the operators may have been saved.

**Previous research**

Fesak *et al.* (1996) performed an analysis of surface powered haulage accidents from January 1990 to July 1996. The analysis contained 640 accidents resulting in trauma, 139 of which were fatalities. The major factors that contributed to the accidents were analysed, some examples are:

- 136 accidents (21.3%) caused while dumping at edge of dump, 25 were fatal
- 117 accidents (18.3%) occurred on haul roads with gradients greater than 7%
- 112 accidents (17.5%) involved failure of either brakes, steering or drivetrain

Fesak *et al.* stated that serious injuries were caused when self-propelled mobile equipment overturned or collided with other vehicles or stationary objects and the driver was not wearing a seatbelt. In more than 200 of the accidents in the study, the drivers had not worn their seatbelts.

**3.2.3 Australian data**

A report on high potential incidents (HPI) involving vehicles in Queensland, Australia, between 1st July 1999 and 30th June 2003 was published on the NRM website. The majority of information contained in the document focused on the time, location and cause of incidents. Causal factors included human, equipment, environment and organisational. There was no specific mention of the type of incident or severity. Equipment factors included non-installation of safety devices, six percent of incidents, or failure/breakdown of safety devices, 17% of incidents.
The types of vehicles involved in the incidents are shown in Figure 6 below.

![Figure 6 Quarry vehicle HPIs – major equipment (N=23) (NRM, 2005)](image)

More than half of the vehicles involved in these accidents were dump trucks (including highway vehicles) and front end loaders.

### 3.2.4 South Africa

The annual report by the Chief Inspector of Mines contains information about the accidents that occurred within each year. There are also data tables published on the Department of Minerals and Energy (DME) website. Table 4 summarises the published accident data from South Africa.

| Number of accidents in South Africa resulting in casualties and fatalities |
|-------------------------------------------------|-----|-----|------|
|                                   | 2000 | 2001 | 2002 |
| **Casualty Accidents** |      |      |      |
| Total                          | 1187 | 1150 | 1369 |
| Trackless Machinery           | 115  | 120  | 140  |
| Fatal Accidents               |      |      |      |
| Total                          | 71   | 83   | 97   |
| Trackless Machinery           | 30   | 20   | 30   |

Table 4 shows that the total number of fatal accidents has increased from 2000 to 2002. However, the number of fatalities caused in accidents involving trackless machines has fluctuated between 20.6% and 42.3% of the total number of casualties. The total number of casualty accidents were similar between 2000 and 2001 and has increased between 2001 and 2002. The number of casualty accidents involving trackless machinery as a proportion of all casualty accidents has remained very similar over the three year period.
The types of trackless machines that were involved in fatal accidents are shown in Table 5. The types of fatality are also shown, vehicle occupants or pedestrians.

**Table 5** Trackless machines involved in fatal accidents in South Africa and types of fatality

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dump truck</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Load haul dumper</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Front end loader</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Crane</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Tractor</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pick-ups and 4x4s</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Forklift</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bus</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Drill/Rig</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Scoop</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>30</strong></td>
<td><strong>22</strong></td>
</tr>
</tbody>
</table>

For the two years where data is available, dump trucks were the most frequent type of trackless machinery involved in fatal accidents. Load Haul Dumpers were also frequently involved, however the involvement of front end loaders appears to be inconsistent.

### 3.2.5 German data

Tudeski and Könnecke (2004) presented data on accidents involving earth-moving machinery in Germany from 2001 to 2003 inclusive. The number of accidents per year decreased by 21%, from 418 in 2001 to 332 in 2003. The distribution of vehicle types involved in the accidents is shown in Figure 7.

![Figure 7](image)

**Figure 7** Distribution of vehicle types in accidents involving earth-moving machinery in Germany (Tudeski and Könnecke, 2004)
The majority of vehicles, 52%, were loaders. Excavators were the second most frequent type of machinery involved.

The data was separated into accidents that were caused by vehicle design and those caused by operations. Accidents where an earth-moving vehicle overturns are usually caused by the operation of the vehicle, 33% of the accidents in Germany were operational. The most frequent type of operational accident (51%) was caused by maintenance. Thirteen percent of the operational accidents were classified as “driving” accidents. Driving accidents include those where the speed of the vehicle is not consistent with the condition of the road, driving without seatbelts, collisions with obstacles resulting from carelessness and travelling over edge protection or dump sites. The stability of the vehicle, where unstable ground results in sloping and overturning of the vehicle accounted for five percent of the operational accidents. This is equivalent to approximately five overturning accidents in 2003. The severity of the injuries or use of restraints was not reported.

Some of the accident data used in the study by Tudeski and Könnecke (2004) was supplied, including the descriptions of the accidents. These cases were categorised in the same way as the RIDDOR data for the UK, except there was no indication of the severity of the injuries. There were 37 cases provided, however it is clear that one of these took place on a construction site and so has been excluded. The remaining 36 cases are summarised in Table 6.

Table 6 Types of accidents occurring in Germany

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>No forward motion 90°</td>
<td>8</td>
</tr>
<tr>
<td>Forward motion 90°</td>
<td>7</td>
</tr>
<tr>
<td>Forward motion 180°</td>
<td>1</td>
</tr>
<tr>
<td>Forward motion unknown rotation</td>
<td>3</td>
</tr>
<tr>
<td>Backwards</td>
<td>4</td>
</tr>
<tr>
<td>Severe deceleration</td>
<td>4</td>
</tr>
<tr>
<td>Rollover on flat</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>36</strong></td>
</tr>
</tbody>
</table>

3.3 DISCUSSION OF THE ACCIDENT STATISTICS

In the UK, the total number of accidents has been decreasing, however, the number of fatalities has remained approximately constant. Therefore, as a proportion of all accidents, the number of fatalities is increasing.

From the accident data, it is clear that the vehicle types that are involved in accidents vary between countries and this may be as a result of the types of vehicles used in the different types of operation. In the UK, the vehicles involved in the accidents for which descriptions were obtained, were mostly articulated and rigid dump trucks. There were also two accidents involving front end loaders. The data from the USA, Australia and South Africa also confirmed that these types of vehicle were most frequently involved. In Germany, loaders accounted for over half the machinery involved in accidents. Dozers were generally the least frequently involved type of machinery in the accidents studied from all countries. This indicates that the modelling should be focused on rigid dump trucks, articulated dump trucks and front end loaders. Although dozers are not frequently involved in accidents, this may be because they are
currently not used as much as other vehicle types. The accident data, therefore, supported
modelling of rigid and articulated dumpers and front end loaders but not dozers. The dozer was
retained in the modelling because of the types of sites on which it operates (tips).

The UK accident descriptions were able to be categorised into a number of generic accident
scenarios. When categorised, the data indicated that there is a need to consider the following
scenarios:

- Lateral rollover with forward motion
- Longitudinal (backwards) rollover
- Severe deceleration
- Lateral rollover without forward motion

The accident descriptions from the USA and Germany also indicate that these are frequent
generic accident scenarios.

There was insufficient data for the UK to analyse the effectiveness of seatbelts. The MSHA data
and analysis indicated that up to a maximum of approximately 80% of the unbelted fatalities
may have been prevented by wearing a lap belt. Over half the operators that were wearing lap
belts may have had the severity of their injuries reduced to non-fatal if a harness type restraint
had been fitted and worn.

In the UK vehicle defects and inadequate edge protection contributed to the cause of almost half
of the accidents studied. Brake defects and edge protection were also frequently cited as causes
of accidents in the USA. For both the UK and USA the proportion of accidents where vehicle
defects contributed to the cause were very high, 24% and 17.5% respectively. Analysis of fatal
accidents involving HGVs on the road in the UK showed that vehicle defects contributed to
only six percent of the accidents (Knight, 2001). The analysis of the US accidents involving
belted occupants showed that 38% of the fatalities could have been prevented by ensuring that
edge protection was adequate and that there were no brake defects. It is unlikely that the cause
of accidents with unbelted occupants is significantly different to those where the seatbelt is
being worn, and hence it can be assumed that 38% of all vehicle operators could have been
saved if these issues were addressed. These issues were also seen in the RIDDOR data from the
UK, however this data relates to accidents dating back to 1996. The HSE have published, on
their website (http://www.hse.gov.uk/quarries/hardtarget/), best practice guidance on brake
testing and edge protection and it is possible that this will be effective at reducing the proportion
of accidents caused in this way. This guidance has since become industry standard and may
have been a factor in the overall reduction in UK casualties shown in Figure 1.

Although the detailed data is limited to US accidents where seatbelt wearing rates may be
different to the UK, there are some indications that the greatest safety benefits may be achieved
by ensuring that all operators wear a seatbelt meeting current standards. However, the simple
analysis of accidents does suggest that there are still additional benefits to be gained by fitting
effective harness type restraints, 50% of the belted fatalities may have been prevented.

3.4 CONCLUSIONS

- In the UK the number of fatal accidents as a proportion of all accidents has increased
- Articulated and rigid dump trucks were the most frequently involved vehicle types in
accidents in the UK. Wheel loaders were also involved. This was similar to the types of
vehicles involved in other countries, with the exception of Germany where wheel
loaders accounted for approximately half the vehicles involved
- Four generic accident scenarios could be generated for the accidents that were studied:
- Lateral rollover with forward motion
- Longitudinal (backwards) rollover
- Severe deceleration
- Lateral rollover without forward motion

- There was insufficient data to assess the effectiveness of seatbelts for UK accidents. However, the data from the USA indicated that the greatest benefits may be provided by ensuring that all operators wear a seatbelt but there are still additional benefits to be gained by fitting harness type restraints

- The effectiveness of the restraints has been based on US accident data. However, many of these accidents could have been prevented by regular brake testing or improved edge protection. The UK industry has already adopted standards relating to these subjects
4 PHYSICAL TESTING

The objective of these tests was to compare the effectiveness and demonstrate any safety benefits of a harness and a lap belt when a quarry vehicle is rolled over. The injury predictions from the two tests were compared to illustrate the differences between the two types of restraint system. The data from the tests was also used to evaluate the numerical models of the rollover. The tests provided measured results against which predictions from one of the developed vehicle models could be compared to confirm the setup of the model parameters. Two tests were carried out; one with the dummy restrained by a lap belt only and the repeat test using a more comprehensive restraint system. A third test was carried out in which the lap belt was fitted and the vehicle was rolled in the opposite direction.

4.1 METHODS

4.1.1 Location
All tests were carried out at Luxulyan quarry, which is a dormant quarry in Cornwall. The tests were carried out on a compacted surface.

4.1.2 Vehicles
All tests were carried out on one Heathfield H33 rigid dump truck that was no longer in service. The vehicle was drivable prior to preparation for the tests and is shown in Figure 8.

![Figure 8 Test vehicle](image)

The original seat was replaced with a new seat fitted with an inertia locking retractor lap belt or a three-point inertial locking retractor harness. Details of the restraints are in Appendix B.

4.1.3 Instrumentation and measurements
An inclinometer was fitted to the rear of the vehicle and recorded using the video cameras. This allowed the angle of the vehicle to be measured during the test. Linear string potentiometers were fitted across the suspension to allow the deflection of the suspension to be measured. Outputs from the inclinometers and linear potentiometers were recorded as the vehicle was...
hoisted to allow the pseudo-static movement of the vehicle to be recorded. The accelerometers and rate sensors were then used to record the dynamic part of the overturn with the dummy recording the effect of the subsequent impact on the operator.

\( T_0 \) was defined as the time at which the vehicle started to fall under its own weight. The impact with the ground was recorded by the data logger using an event marker to assist with data analysis. The main criteria to measure were:

**The cab acceleration/deceleration** was measured using accelerometers in the X, Y and Z axes. The accelerometers were mounted on the cab behind the seat, close to the plane of the centre of gravity of the dummy.

**The suspension stiffness** was measured using four string potentiometers with a maximum travel of 500mm. A string potentiometer was used to measure the distance between the axle and the body for both the front and back of the vehicle. This was done for both the struck and non-struck sides of the vehicle. The potentiometers were positioned as close to the wheels as practical. Measurements of the distance from the potentiometer to wheel centre line were also recorded. Static measurements were also taken with the vehicle unladen and laden. This data was used to clarify the setup of the vehicle models.

**The vehicle roll rate (rotation around the x-axis)** - A roll rate sensor was fitted to the cab behind the seat.

**The seatbelt loads** were measured using seatbelt load gauges. For the first and third tests, only one lap belt load gauge was required. The second test where the harness was fitted required the use of two load gauges, one for the lap section and one for the webbing that feeds into the inertia reel at the top of the seat.

**Occupant injury criteria** for the head, neck, thorax and pelvis were measured for comparison between the two tests. The instrumentation required for the ES-II dummy is listed in Table 7.

### Table 7 ES-II Dummy instrumentation requirements

<table>
<thead>
<tr>
<th>Location</th>
<th>Instrumentation</th>
<th>Parameter</th>
<th>Number of Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Tri-axial accelerometer pack</td>
<td>Ax,Ay,Az</td>
<td>3</td>
</tr>
<tr>
<td>Neck</td>
<td>Shoulder Three axis load cell</td>
<td>Fx,Fy,Fz</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tri-axial accelerometer pack</td>
<td>Ax,Ay,Az</td>
<td>3</td>
</tr>
<tr>
<td>Thorax</td>
<td>3 Rib displacements</td>
<td>Dy</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3 Rib accelerations</td>
<td>Ay</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Four axis torso back plate load</td>
<td>Fx,Fy,My,Mz</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tri-axial accelerometer pack</td>
<td>Ax,Ay,Az</td>
<td>3</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Four axis T12 load cell</td>
<td>Fx,Fy,Mx,My</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3 Abdomen load cells</td>
<td>Fy</td>
<td>3</td>
</tr>
<tr>
<td>Pelvis</td>
<td>Three axis lower lumbar spine</td>
<td>Fy,Fz,Mx</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>load cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pubic symphysis load cell</td>
<td>Fy</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><strong>Total number of channels</strong></td>
<td></td>
<td><strong>33</strong></td>
</tr>
</tbody>
</table>
4.1.4 Test procedure
The original test programme consisted of two rollover tests on the same vehicle. The cab of the vehicle was positioned to one side of the vehicle. The tests were carried out by rolling the vehicle onto the drivers’ side of the vehicle (anti-clockwise) because this was the most likely condition to result in contact with the interior of the cab. The programme was amended on the day of the tests because sufficient time was available to carry out a third test. In this final test, the dummy was restrained using the lap belt and the vehicle was rolled away from the driver’s cab (clockwise).

During the first test, the ES-II dummy was restrained by a lap belt only. In the second test the lap belt was replaced by a retractable harness. The restraints were attached to the seat and so the test seat was replaced between tests. The anchorage points for the seat were reinforced prior to the first test because of the condition of the test vehicle.

The dummy was positioned in the customary manner with the dummy sitting back in the seat and the arms raised towards the steering wheel. Paint was applied to the dummy’s head and shoulders to record the exact location of any contact with the interior of the cab. The position of the dummy with respect to the interior of the cab was recorded as shown in Figure 9 to ensure the dummies were positioned similarly between tests.

The vehicle rollover was performed by gradually hoisting one side with a crane, until the point of rollover was reached and then the vehicle fell under its own weight. The vehicle was loaded to represent an unstable condition under which the vehicle would roll.

![Diagram of dummy in different views](image)

Figure 9 Dummy to cab measurements (not to scale)
Table 8 Key to dimensions in Figure 9

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Back of head to the back of the cab</td>
</tr>
<tr>
<td>b</td>
<td>From the centre of the head to the top of the steering wheel</td>
</tr>
<tr>
<td>c</td>
<td>Top of head to the cab roof</td>
</tr>
<tr>
<td>d</td>
<td>Side of the head to the nearside window</td>
</tr>
<tr>
<td>e</td>
<td>shoulder to the nearside window/door</td>
</tr>
<tr>
<td>f</td>
<td>Pelvis to the nearside door</td>
</tr>
<tr>
<td>g</td>
<td>Side of the head to the offside window</td>
</tr>
<tr>
<td>h</td>
<td>shoulder to the offside window/door</td>
</tr>
<tr>
<td>i</td>
<td>Pelvis to the offside door</td>
</tr>
</tbody>
</table>

Table 9 Dummy to cab measurements for three tests

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Direction of Roll</th>
<th>Restraint Type</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>1</td>
<td>Anti-clockwise</td>
<td>Lap belt</td>
<td>238</td>
</tr>
<tr>
<td>2</td>
<td>Anti-clockwise</td>
<td>Harness</td>
<td>258</td>
</tr>
<tr>
<td>3</td>
<td>Clockwise</td>
<td>Lap belt</td>
<td>198</td>
</tr>
</tbody>
</table>

Initial runs using the numerical models showed that the following approximate test conditions may be expected:

- Angle at which truck begins to rollover is 27 degrees
- Time taken to roll from 27 degrees onto side is 0.3s
- Resultant head impact acceleration = 523.9 ms\(^{-2}\)
- Resultant cab acceleration at impact = 104.8 ms\(^{-2}\)
- Resultant cab velocity before impact = 3ms\(^{-1}\)

The data logger was set up to record over a period of three seconds, therefore the data loggers were triggered when the vehicle was approximately 25° from the ground (approximately 0.3 seconds before impact). The dummy was held in position with an additional restraint strap so that the dummy would be in a typical driving position when the vehicle began to roll under its own weight. The additional straps were released at the same time as the data logger was triggered.

After the first test had been carried out, the vehicle was righted. The vehicle and dummy were checked for damage to ensure that the second test was representative of the first. The second test was carried out by repeating this procedure but with the lap belt replaced by a retractable harness. The seat with the lap belt was re-instated for the third test.
4.1.5 Test matrix
Table 10 summarises the tests that were carried out.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restraint type</td>
<td>Lap belt</td>
<td>Retractable harness</td>
<td>Lap belt</td>
</tr>
<tr>
<td>Occupant</td>
<td>ES-II</td>
<td>ES-II</td>
<td>ES-II</td>
</tr>
<tr>
<td>Direction of roll (from drivers perspective)</td>
<td>Anti-clockwise</td>
<td>Anti-clockwise</td>
<td>Clockwise</td>
</tr>
</tbody>
</table>

4.2 RESULTS
4.2.1 Vehicle motion

A comparison of the lateral and vertical cab accelerations between tests are show in Figure 10 and Figure 11.

![Graph showing vehicle lateral acceleration](image)

**Figure 10** Vehicle lateral acceleration (y-direction)

The data shows that the cab acceleration in test one and test two are very similar, with peaks of similar magnitude occurring at similar times, showing repeatability. In test three, the vehicle was rolled in the opposite direction to tests one and two resulting in the cab being accelerated in the opposite direction. However, the phase and magnitude of the acceleration is similar to that seen in the previous two tests.
Figure 11 also shows that tests one and two had similar acceleration characteristics in the vertical direction. In this direction, test three was also similar to tests one and two. The most significant difference is the negative acceleration for tests one and two that is not present in test three. This may be related to the interaction between the cab and the ground. In tests one and two the cab may have been decelerated in the vertical direction by digging into the ground. In test three the cab did not make contact with the ground and so this deceleration did not occur.

Unfortunately, no data was available from the roll rate sensor or the string potentiometers which were destroyed during the first test. This resulted in fewer parameters being available for the model evaluation, however, the acceleration resulting from the impact with the ground was available and considered to be the most important parameter.

4.2.2 Dummy motion
The following section describes the motion of the dummy during the tests.

Test 1 - Lap belt
Figure 12 shows example stills from the on-board camera footage for test 1. The dummy started to rise up out of the seat and made contact with the roof of the cab. With the top of the head still in contact with the roof, the upper body then moved towards the window flexing the neck. The head then slid across the roof of the cab and was stopped by the roof geometry and the upper body being restrained by the window. This caused the neck to flex further. There was some rebound of the dummy, but the head remained in contact with the roof at all times.

The inertial locking mechanism on the lap belt appeared not to be activated during the test. Unfortunately this cannot be confirmed because of a failure in the seatbelt gauge during this test.
**Test 2 - Inertia reel harness**

Stills from the on-board camera during test 2 are shown in Figure 13. The head of the dummy made contact with roof at the point where the roof meets with the side of the cab. The upper body of dummy moved towards the window recess. The head does not appear to move from where it made initial contact with the roof and the neck started to flex. The upper body then started to re-bound from window recess although head to roof contact was maintained.

The inertia locking mechanism on the harness appeared to be activated and was locked when checked after the test. This was confirmed by the loads in the seatbelt gauges.

**Test 3 - Lap belt**

Figure 14 shows stills from the on-board camera during test 3. The dummy started to rotate relative to the seat, which was later accompanied by an upward motion out of the seat. The head of the dummy appeared to slide across the roof of the cab as the upper body moved towards the window causing the neck to flex. The shoulder of the dummy made contact with the window.
and was loaded by the upper body, again causing the neck to flex as the head remained in contact with the roof.

It was clear that the inertia locking mechanism on the lap belt was not activated because the belt had fully paid out of the reel during the test. There was also no load on the belt until late in the impact, which is most likely to be co-incident with the belt reaching its maximum length.

![Figure 14](image)

**Figure 14** Dummy motion during test 3, head contact with roof (top left), contact with side of cab (top right) and contact with window (bottom)

### 4.2.3 Injury criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Test Number</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Restraint type</strong></td>
<td>1</td>
</tr>
<tr>
<td>Lap belt</td>
<td>Inertia reel harness</td>
</tr>
<tr>
<td>Anti-clockwise</td>
<td>Anti-clockwise</td>
</tr>
<tr>
<td><strong>HIC15</strong></td>
<td>49.9</td>
</tr>
<tr>
<td><strong>HIC36</strong></td>
<td>49.9</td>
</tr>
<tr>
<td><strong>3ms exceedence head acceleration</strong></td>
<td>37.3g</td>
</tr>
<tr>
<td><strong>Peak head acceleration</strong></td>
<td>51.3g</td>
</tr>
<tr>
<td><strong>Rib deflection</strong></td>
<td>3.15mm</td>
</tr>
<tr>
<td><strong>Total abdominal force</strong></td>
<td>0.04kN</td>
</tr>
<tr>
<td><strong>Pubic symphysis Force</strong></td>
<td>0kN</td>
</tr>
<tr>
<td><strong>Lap belt load</strong></td>
<td>.**</td>
</tr>
<tr>
<td><strong>Shoulder belt load</strong></td>
<td>N/A***</td>
</tr>
</tbody>
</table>

*ES-II is set up to measure rib deflection from the side that is struck. The third test was in addition to what had initially been planned and therefore the dummy was not set up to measure chest compression during this test.

** Channel failure

***There was no shoulder belt in these tests.
4.2.4 Analysis

The following are performance limits for acceptable risk used in EuroNCAP and European regulation for the assessment of car impacts, these are related to specific risk of injury or types of injury where possible:

- Resultant 3ms exceedence head acceleration of 88g
- HIC\textsubscript{36} of 1000 also represents a 20% risk of serious injury (AIS\textgreater{}3) such as a fracture to the base of the skull
- Rib deflection (for worst rib) of 42mm represents a 30% risk of serious injury (AIS\textgreater{}3) such as more than three fractured ribs on one side or a tear in the pulmonary artery
- Total abdominal force of 2.5kN
- Pubic Symphysis Force of 6.0kN represents pelvic fracture in young adults

All of the data collected from the tests were substantially below these performance limits, indicating a low risk of serious injury for these impact conditions. For both the head and chest, the measured injury criteria were lower when the dummy was fitted with a harness rather than a lap belt. The direction of roll appeared to have a minimal effect on the measured injury criteria. The belt loads recorded were lower than the 15kN test load specified in SAE J386. The kinematics of the occupant were different between the clockwise and anti-clockwise test, however there were no clear trends in the injury criteria data.

These tests represent a low severity “ideal” rollover impact where the trajectory of the occupant was well controlled. However, the accident analysis showed that there are a number of variables that may increase the severity of the rollover. The vehicle may have forward motion and so the occupant may be decelerated at the same time as being rolled. The vehicle may also rollover the edge of a road which may cause the vehicle to roll more than 90º. The vehicle may also roll onto an uneven surface, which may result in rocks penetrating the cab causing additional injury to the operator.

The tests also identified a potential issue relating to the effectiveness of the locking mechanisms on the seatbelts used in the tests. In the two tests with the lap belts, the locking mechanism was not activated and the webbing was able to spool out without giving the occupant any belt based protection. The cause of the failure was because of the fact that this lap belt only had one sensitivity; feed out of the webbing. In passenger cars inertial locking retractor belts are dual sensitive. They will either lock when the motion of the vehicle exceeds a set parameter or when the webbing is pulled out at a high rate. On examination, the vehicle based mechanism was not present in this belt, possibly to prevent the belt locking during day to day operations of the vehicle. The secondary mechanism, belt sensitivity, would only lock if the pelvis was accelerated out of the seat quickly enough to activate the mechanism (0.8g) which would have been higher than seen in the simple rollover test. The harness was fitted with a dual sensitive inertial locking mechanism and would have been locked by the vehicle sensitive mechanism.

The data collected during the tests has been used to evaluate the numerical models. This evaluation is described in Appendix C.

4.3 CONCLUSIONS

- All data from the tests were substantially below recognised injury threshold limits for the dummy used in these tests
- The injury criteria for both the head and chest were lower when the occupant was fitted with the harness than when the lap belt was used
• The tests identified potential issues with the effectiveness of inertial locking retractor mechanisms in slow rollover events
5 NUMERICAL SIMULATION

Numerical simulation was used to reconstruct a series of generic quarry vehicle accidents in order to assess the effectiveness of a variety of different restraint system designs in protecting quarry vehicle operators. The numerical simulation approach was taken because this provided the most cost effective and practically achievable means of assessing the performance of a number of restraint systems under a variety of impact conditions. The work involved the creation of four generic MADYMO quarry vehicle models. Within these vehicle models, occupant models were fitted and restrained by a number of representative restraint system designs to provide predictions of injury risk for a variety of simulated accident conditions. Predictions from one of the developed vehicle models were evaluated against comparable physical measures from the full scale 90° rollover tests described in Section 4. This evaluation allowed the credibility of the predictions from all the developed models to be ensured.

5.1 METHODOLOGY

5.1.1 MADYMO
MADYMO is a proprietary software package which analyses the dynamic response of systems undergoing large displacements by idealising the structure into a number of rigid and/or flexible bodies connected by joints. Surfaces can be attached to these bodies and these are used to simulate contact interactions. The program generates the equations of motion which are solved by numerical techniques enabling interaction forces to be calculated by reference to user supplied force/deflection characteristics. MADYMO is recognised internationally as a “State of the art” simulation package and is widely used and recognised throughout the automotive industry to simulate occupant kinematics.

5.1.2 Parametric investigation
A matrix of model runs was constructed to investigate how the following impact variables influence occupant injury risk:
- Vehicle type (rigid dumper, etc)
- Occupant size
- Restraint system design
- Accident conditions

These variables are described in the following sections.

The generic quarry vehicle models
The four generic MADYMO vehicle models were developed and run under version 6.2 of the MADYMO code. The models were developed to represent the generic external structure and internal cab confines of a rigid dump truck, an articulated dump truck, a wheel loader and a bulldozer. Images of the four models are presented in Figure 15. The intention was that the models would provide a representative cross section of vehicle types involved in rollover accidents, in UK quarries.
The basic dimensions and total mass of the modelled vehicles were obtained from published marketing material provided by vehicle manufacturers and distributors. For each vehicle type a broad cross section of dimensions and total masses were obtained. These basic measures were averaged for each vehicle type and the averages used as the basis for the development of the generic vehicle models. Information on the typical mass distribution of each quarry vehicle was generally limited to the mass of the vehicle’s bucket where applicable. Hence, in this instance engineering judgement was used to estimate the mass and inertias of many of the quarry vehicle features, such as wheels, engines, etc, based on their basic dimensions and material properties. The accuracy of this approach was tested by checking that the static load on the front and rear axles of the models was comparable to values presented in the marketing material and through the evaluation of the prediction provided by the models, as described in Appendix C. Where applicable the models were developed with generic suspension and joint characteristics in order to better approximate the dynamics of the vehicles in a rollover event. However, due to the chaotic nature of the rollover conditions, assumptions were made that the steering remained fixed and that buckets remained in a fixed position relative to the overall structure of the vehicle models.

The rigid dump truck, articulated dump truck and wheel loader were modelled carrying a full payload in order to represent a less stable condition with a high likelihood of rollover. The payload was simulated by attaching a separate payload mass to the bucket in each model. The typical size of these masses was derived from the marketing information described previously. During simulated rollovers with these models the payload was released at an appropriate interval in the simulation approximating the ejection of the payload from the vehicle. It was accepted that the approach for modelling the ejection of the payload simplified the actual process of ejection, but it was considered that this was adequate for approximating the change in the inertial characteristics of the vehicles during rollover conditions. Table 12 details the vehicle mass and payload for each model.
Table 12 Basic details of the quarry vehicle models

<table>
<thead>
<tr>
<th></th>
<th>Vehicle mass (kg)</th>
<th>Payload (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid dump truck</td>
<td>34,723</td>
<td>40,000</td>
</tr>
<tr>
<td>Articulated dump truck</td>
<td>30,600</td>
<td>30,250</td>
</tr>
<tr>
<td>Wheel loader</td>
<td>19,511</td>
<td>5,000</td>
</tr>
<tr>
<td>Bulldozer</td>
<td>40,000</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The generic confines of the cabs in each vehicle model were averaged from measurements made directly on comparable vehicles during visits to quarries and quarry vehicle distribution centres. The basic confines of each modelled cab are presented in Table 13.

Table 13 Generic confines of the cabs in each vehicle model

<table>
<thead>
<tr>
<th></th>
<th>Cab height (m)</th>
<th>Cab width (m)</th>
<th>Cab length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid dump truck</td>
<td>1.50</td>
<td>1.22</td>
<td>1.12</td>
</tr>
<tr>
<td>Articulated dump truck</td>
<td>1.49</td>
<td>1.40</td>
<td>1.57</td>
</tr>
<tr>
<td>Wheel loader</td>
<td>1.54</td>
<td>1.40</td>
<td>1.24</td>
</tr>
<tr>
<td>Bulldozer</td>
<td>1.41</td>
<td>1.21</td>
<td>2.03</td>
</tr>
</tbody>
</table>

Additional features represented in each cab model included the driver’s seat, the pillars around the windows and doors, the steering column and wheel and the front console. For the bulldozer model the steering wheel and column was omitted in order to match the actual setup of the vehicle. Figure 16 provides an example of the detail represented in the cabs of the quarry vehicle models.

![Rigid dump truck interior](image1)
![Bulldozer interior](image2)

**Figure 16** Example of the details represented in the modelled cabs

During inspections of quarry vehicle cabs, numerous additional features were identified as being potentially hazardous to the driver in a rollover situation. These included levers, grab handles for doors and metal frames around the windows. The incidence of these features varied considerably between each cab design and this presented difficulties in generalising these structures within the confines of the modelled cabs. Furthermore, the small size of some of these
features presented difficulties in adequately representing these features within the MADYMO software. Consequently, it was decided to omit these more specific details from the modelled cab interiors and address the potential hazards of these structures in the risk assessment of the cabs (Section 6).

**Occupant size and type**

All the parametric model runs were completed using either the 50\textsuperscript{th} percentile or 95\textsuperscript{th} percentile human body model (MADYMO version 4.2 release). The human body models provide an omnidirectional, biofidelic response so it was considered that they would provide good capability for assessing occupant injury risk in quarry vehicle rollover accident conditions. The motion of the occupant model was locked to the motion of the vehicle and released approximately 700 ms prior to the impact with the ground.

The standing height and mass of each occupant model were 1.74m and 75.7kg and 1.91m and 101kg for the 50\textsuperscript{th} percentile human model and the 95\textsuperscript{th} percentile human models respectively. The majority of the parametric model runs were completed with the 50\textsuperscript{th} percentile human model. Selected runs were completed with the larger human model to investigate accident conditions where it was considered that the injury risk to a larger occupant model may be greater compared with that previously identified for the 50\textsuperscript{th} percentile human body model.

**Restraint system designs**

Five designs of restraint system were investigated in the parametric model runs consisting of:

i. No restraint (NR)

ii. Lap belt (LB)

iii. Three point belt (3P)

iv. Reversed three point belt (R3P)

v. Three point harness (3PH) (similar to a four-point harness but shoulder straps feed into a single piece of webbing)

Figure 17 provides images of the four restraint systems investigated in the parametric study as fitted around the 50\textsuperscript{th} percentile human body model. The belt systems were modelled with finite elements (FE) to more accurately simulate the interaction between belt and human occupant model. Multi-body belt segments were used to tether the FE belt systems to the modelled seat.

**Accident conditions**

Based on analysis of the accident data (Section 2) and a general understanding of the working environments and roles of the modelled quarry vehicles, a total of five accident conditions were identified for the parametric investigation.

**90\degree static rollover**

This accident condition matched the impact conditions of the rollover tests completed as part of this research, involving a stationary vehicle being rotated laterally 90\degree. This involved the stationary vehicle being allowed to fall under gravity onto its side as in the full scale tests. See Section 4 for more details of the testing.
Figure 17 Configuration of the restraint systems fitted to the 50th percentile human model

90° dynamic rollover

This accident condition introduced a longitudinal acceleration that was not present in the static 90° rollover conditions. This mechanism represents accidents where an edge collapses as a vehicle drives along it. In these simulations the vehicle models had an initial forward velocity of 8.93 m/s (20 mile/h). During the simulation the ground gives way under one half of the vehicle, which causes the vehicle to roll down a simulated slope set at between 30° and 55° to the horizontal depending on the vehicle type. This type of slope would represent an unconsolidated slope in a quarry. Near vertical excavation edges were not considered because the occupant protection in this accident type would be dominated by the ROPS rather than the restraint system. The quarry vehicle model comes to rest on its side. Images from one of the 90° model runs completed with the articulated dump truck vehicle model are presented in Figure 18 as an example of the behaviour of the vehicle models during these model runs.
One variation in the setup of these impact conditions was defined for the bulldozer model because of the different vehicle operating conditions. Bulldozers often work on sloping surfaces and tend to operate at very low speed, therefore the model was set-up to represent the vehicle starting to slide down a slope with no forward motion. For the 90° dynamic rollover of the bulldozer model, the model was initially set on a 45° slope and had a defined initial translational velocity of 3.5 m/s approximating the behaviour of the model sliding down the slope. The vehicle then strikes an obstruction on the slope causing it to flip over before coming to rest on its side.

**270° dynamic rollover**

This accident condition was intended to introduce a wider range of vehicle accelerations and to expose the occupant to a potentially wider range of motion than the 90° dynamic rollover condition. The setup of the model for these simulations closely matched that for the 90° dynamic rollover condition with the quarry vehicle having an initial forward velocity of 8.93 m/s (20 mile/h). However, in order for a 270° rollover to occur, the slope that the vehicle rolled down needed to be steeper and longer than the one that was used to produce the 90° rollover.
Images from one of the 270° dynamic rollover simulations completed with the rigid dump truck vehicle model are presented in Figure 19 as an example of the behaviour of the vehicle models during these model runs.

The set-up arrangement of the 270° dynamic rollover conditions was generally the same for all the quarry vehicle models with the exception of the bulldozer model for the reasons explained earlier. The method used was similar to that described for the 90° dynamic rollover.

Figure 19 Frames from the 270° dynamic rollover completed with the rigid dump truck vehicle
**End tipping**

This accident condition was designed to subject the occupant to a greater vertical acceleration than the sideways rollover. The setup of the model runs attempted to approximate the situation in which a quarry vehicle is operating at the top of an unconsolidated slope. With the vehicle facing away from the slope, the ground collapses under the rear wheels and the vehicle flips over landing on its roof. Figure 20 provides animation frames from one of the end tipping simulations completed with the articulated dump truck vehicle model as an example of the behaviour of the vehicle in these model runs.

![Animation frames from the end tipping simulations completed with the articulated dump truck vehicle](image)

**Figure 20** Frames from the end tipping simulations completed with the articulated dump truck vehicle

**Frontal impact**

The frontal impact condition was simulated by applying a deceleration time history to the cab of the wheel loader. The crash pulse applied to the wheel loader cab was derived using engineering judgement, based on TRL’s experience of frontal impact testing, to estimate the severity of frontal collisions likely to occur. A pre-impact velocity of 8.93 m/s (20 mile/h) was selected as a representative high velocity for a wheel loader during normal operations. Deformation was estimated to take place over 20cm which could occur in the vehicle or the struck object. To simulate a worst case situation it was assumed that all of the deformation occurred over a very short time period, resulting in a maximum vehicle deceleration of 20g.
Model evaluation

Before conducting the parametric study the model was evaluated against the 90° static rollover tests to ensure the credibility of the model’s predictions. This evaluation was performed with the ES-II dummy model to replicate the tests. Full details of the dummy and the evaluation are given in Appendix C.

Comparison of vehicle and dummy accelerations between the tests and the models showed a good correlation of peak magnitudes and general shape. The model was able to reflect the higher injury predictions for the lap belt found in the tests, demonstrating that the model could be used for evaluation of different restraint systems.

Simulation matrix

A total of 62 model runs were completed and are summarised in Table 14. The setup of each model run is described above. In order to adequately cover the largest amount of issues with the model runs and obtain the greatest value from the modelling work, the choice of model runs to complete was reviewed during the numerical simulation work.

The allocation of the model runs within the matrix were determined based on accident analysis, evaluation of the vehicle model against the full scale tests and results obtained from completed model runs. The modelling was divided into three phases.

The initial phase of modelling concentrated on the rigid dump truck that had been evaluated using data from the full scale tests and the ES-II model (Appendix C). Repeating the 90° static rollover with the human body model provided a baseline measure of the human model predictions against those predicted and measured on the ES-II model and dummy. These simulations were carried out without armrests because this was the set up during the full scale test.

In comparison to all other vehicle classes modelled, the cab of the rigid truck model is positioned on the left hand side of the vehicle. As observed in the full scale tests, the direction in which this type of vehicle rolls over has a considerable influence on the kinematics and the injury risk to the vehicle operator. As such 90° static rollover model runs with this model were completed with this model rolled over in both directions without the armrests.

It was decided that many seats are fitted with armrests and so the effect of their use should be investigated. The 90° static anti-clockwise rollover was repeated with the armrests in position. The remaining accident scenarios, dynamic rollovers and end tipping, were then completed with the armrests in place. The 90° dynamic rollover was also simulated without armrests to investigate the difference when a forward acceleration was applied to the occupant.

The second phase of modelling considered three other types of vehicle. These were assessed with lap belt and harness. Additional runs were included to assess the three-point belt in the articulated truck and the unrestrained occupant and three-point belt in the frontal impact for the loader.

The assessment of the dozer considered all restraint conditions except the reversed three-point belt and focused on the dynamic rollovers because these were considered to be the most likely conditions in which the vehicle would roll. End tipping simulations were completed with the rigid dump truck and articulated dump trucks only, because of their frequent involvement in operations and accidents on unconsolidated slopes.
For the simulated frontal impact, a crash pulse was applied to the cab of the wheel loader model only. This decision was based on the likelihood of this class of vehicle experiencing a frontal impact from the accident study. Furthermore it was considered that the results using this cab model would be similar to those that could be obtained for the other cab models because of the close similarities of the cabs in each vehicle model. The exception to this was the bulldozer model which does not have a steering wheel. However the speed of this vehicle model is limited and as such the severity of a crash pulses is likely to be lower for this class of vehicle.

The final phase of the modelling was the simulations using the 95th percentile human body model. These scenarios were selected after analysis of the animations from the completed simulations. In these scenarios, the 50th percentile occupant came close to making contact, or there was a glancing contact, with a surface. In such circumstances it was expected that the 95th percentile human body model with armrests would come close to making contact with the surface. The results using this cabin model would be similar to those that could be obtained for the other cabin models because of the close similarities of the cabs in each vehicle model. However the speed of this vehicle model is limited and as such the severity of a crash pulse is likely to be lower for this class of vehicle.

---

**Table 14 Parametric model runs**

<table>
<thead>
<tr>
<th>Occupant and seat details</th>
<th>Vehicle type</th>
<th>Accident condition</th>
<th>Restraint system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No Restraint</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lap Belt</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Three Point</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reverse Three Point</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Three Point Harness</td>
</tr>
<tr>
<td>50th percentile human body model with armrests</td>
<td>Rigid dump truck</td>
<td>Clockwise 90° static rollover</td>
<td>X X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° dynamic rollover</td>
<td>X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° dynamic rollover</td>
<td>X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>End tipping</td>
<td>X X X X</td>
</tr>
<tr>
<td>Articulated dump truck</td>
<td>90° dynamic rollover</td>
<td>X X X X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° dynamic rollover</td>
<td>X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>End tipping</td>
<td>X X</td>
</tr>
<tr>
<td>Wheel loader</td>
<td>Anti-clockwise 90° static rollover</td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° dynamic rollover</td>
<td>X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° dynamic rollover</td>
<td>X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frontal</td>
<td>X X X X</td>
</tr>
<tr>
<td>Bulldozer</td>
<td>90° dynamic rollover</td>
<td>X X X X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° dynamic rollover</td>
<td>X X X X</td>
</tr>
<tr>
<td>50th percentile human body model without armrests</td>
<td>Rigid dump truck</td>
<td>Anti-clockwise 90° static rollover</td>
<td>X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clockwise 90° static rollover</td>
<td>X X X X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° dynamic rollover</td>
<td>X X X X</td>
</tr>
<tr>
<td>95th percentile with armrests</td>
<td>Rigid dump truck</td>
<td>90° dynamic rollover</td>
<td>X X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° dynamic rollover</td>
<td>X X</td>
</tr>
<tr>
<td>Wheel loader</td>
<td>90° dynamic rollover</td>
<td>X X</td>
<td></td>
</tr>
</tbody>
</table>

---
percentile was at higher risk because of their additional height and mass causing greater excursion which could lead to contact, or more severe contact than for the 50th percentile model.

**Assessment parameters**

It was anticipated that the main injury concerns to a vehicle operator in a rollover event would be to the upper body. A number of injury criteria are applied in the automotive industry for assessing the injury risk to the head, neck and chest in the event of an impact, as detailed in Table 15.

<table>
<thead>
<tr>
<th>Body region</th>
<th>Injury criteria</th>
<th>Lower performance limit</th>
<th>Upper performance limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>HIC 36</td>
<td>1000 (20% risk AIS =3)</td>
<td>650 (5% risk AIS =3)</td>
</tr>
<tr>
<td></td>
<td>Head 3ms exceedence</td>
<td>88</td>
<td>72</td>
</tr>
<tr>
<td>Upper neck</td>
<td>Shear (kN)</td>
<td>3.1</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Tension (kN)</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Extension (N.m)</td>
<td>57</td>
<td>42</td>
</tr>
<tr>
<td>Chest</td>
<td>Compression (mm)</td>
<td>50</td>
<td>22</td>
</tr>
</tbody>
</table>

Furthermore, loads in the belt systems were used to provide additional predictions against which to assess the relative injury potential, despite there being no defined injury criteria for these measures. Loads in the belt system were also used to provide an indication of the structural integrity needed to support the belt loads in the event of an accident. Analysis of all the model animations was completed to identify additional hazards that were not highlighted by the direct predictions from the human body models.

It should be noted that most of the injury criteria used for assessing occupant injury risk, with the exception of those associated with the head, are based on the behaviour of test dummies and not the human body model. There is, therefore, a risk that applying such criteria to the predictions from the human body model may not be as accurate, in absolute terms, as when they are applied to test dummy readings. However, any effect on the results were expected to be equal for all model runs so relative comparisons between different model runs are, therefore, expected to be valid.

### 5.2 RESULTS/DISCUSSION

Detailed tables of predicted injuries from the models are presented in Appendix D. Six key areas were identified for reporting and discussion:

- Comparison of different restraint systems under the various accident conditions
- Difference between the modelled vehicle types
- Directional issues with a three-point diagonal lap belt
- Influence of armrest fitment
- Effect of occupant size
- Modelling considerations
5.2.1 Comparison of different restraint systems

90° static rollover

In general injury risk predictions (Table 18 in Appendix D) were well below upper performance limits, which was consistent with the low severity impact conditions.

When the vehicle rolled anti-clockwise the occupant model was supported by the cab wall irrespective of which belt system the human body model was fitted with. The unbelted occupant slid out of the seat and slumped against the side wall but even this was a relatively benign condition.

In contrast rolling the vehicle clockwise was a more severe condition, as shown in Figure 21. When unbelted, the occupant made contact with the opposite side wall and rolled up to the roof level, although the low rate of rollover meant that injury predictions remained low. When wearing the lap belt, there was a large amount of head excursion although contact with the side wall was narrowly avoided. Rolling clockwise, the three-point belt system and harness provided a more constrained response for the head than when the lap belt was worn. However the effectiveness of the three-point belt in these impact conditions was dependent on the direction that the vehicle rolled and on the direction of the diagonal section as discussed further later in this section. The harness restraint was able to limit the excursion of the body greatly and ensured that the occupant remained distant from any features which could cause injury.

![Figure 21](image-url) Response of the human body model fitted with different restraint systems under the 90° clockwise static rollover with arm-rests
90° dynamic rollover

Figure 22 provides a series of images from the 90° dynamic rollover model runs. With no restraint it was found that the human body model slid out of the seat and struck the right hand corner and windscreen of the cab. Similarly, when wearing the lap belt, the upper torso and head of the occupant flailed towards the right internal corner of the cab. The head of the model extended far enough for the head to strike the side wall and the front fascia of the vehicle. In contrast, when wearing the three-point belt system and the harness, the upper torso was better restrained and the likelihood of the head striking internal features of the cab, with the exception of the seat, was considerably reduced. However, it was noticed that the diagonal belt of the three-point belt system tended to wrap around and load the neck. This appeared to be less of a problem with the harness because the belt system still passed over the chest and abdomen of the model and the support on the alternative shoulder appeared to limit this problem.

Predictions from the model runs (as provided in Table 19, Appendix D) implied that only the head accelerations for the unbelted model runs presented any obvious injury risk. For these model runs the predicted head 3ms exceedence was within 8% of the lower performance limit. Furthermore the neck tensions for these models runs were over 3.5 times greater than those predicted under any other impact conditions, although the predicted values were still only 66% of the upper performance limit for this measure. Furthermore, despite the observed problem of the three-point belt apparently wrapping around the neck of the occupant, this potential hazard was not reflected in the injury predictions because there is currently no injury criteria relating to soft tissue damage.

![Figure 22 Images from the 90° dynamic rollover model runs with armrests](image-url)
**270° dynamic rollover**

With no restraint, the human body model struck and rolled around the top right hand corner of the cab, as shown in Figure 23. Wearing the lap belt, the upper torso and head extended low enough to strike features of the cab at knee level and forward enough to strike the steering wheel and column and fascia. Again, better restraint of the human body models was provided by the three-point belt system and harness which prevented excessive excursion of the head within the cab. However, as shown in Figure 23 the diagonal belt of the three-point belt system slipped off the shoulder during the simulation.

Overall and as shown in Table 20 (Appendix D) injury risk predictions for this set of model runs were below the upper performance limits (Table 15). Head injury risk predictions of HIC$_{36}$ and 3ms exceedence were greatest for the harness model runs, but these were still respectively 38% and 72% of the upper performance limits for these measures.

**End tipping**

The heads of the unbelted and lap belted human models struck the roof of the cab as shown in Figure 24. This resulted in predictions indicative of serious to fatal head injury for these two model runs. As shown in Table 21 (Appendix D) the predicted HIC$_{36}$ for the unbelted model run was 82% of the lower performance limit while the head 3ms exceedence was 127% of the lower performance limit (Table 15). In the lap belted case, these increased to 108% and 133% of the HIC$_{36}$ and 3ms exceedence lower limits respectively. Neck injury risk predictions suggest that serious injuries would be likely to occur in this region of the body, especially in the unbelted case where neck extension was 177% of the lower performance limit. A further concern for these impact conditions was that following the head impact with the roof, the human body models struck the front features of the cab interior increasing the likelihood of
serious injuries. For instance, Figure 25 shows that following the impact with the roof the head of the human body model wearing the lap belt struck the steering wheel.

**Figure 24** Images from the end tipping model runs with the rigid truck

**Figure 25** Head strike with the steering wheel in the end tipping simulation with the human body model wearing the lap belt
As shown in Figure 24 the three-point belt system and harness prevented the head from striking the roof of the cab in the end tipping simulations. Overall both these belt systems limited the amount of head and upper torso excursions within the cab. However, because of the greater extension of the diagonal belt and deformation of the restrained shoulder the head of the human body model wearing the three-point belt system came closer to striking the roof of the cab than the model fitted with the harness.

As shown in Table 21 (Appendix D) head injury predictions for three-point belt and harness model runs were at least half the magnitude of those predicted for the unbelted and lap belt model runs and neck injury predictions were at least 7% below the upper performance limits for these measures. However, chest injury predictions implied the possibility of increased loading to the chest when wearing a three-point belt or harness, with predicted viscous criterion (VC) being between 70% and 86% of the upper performance limit and predicted chest compression being within 3% of the lower performance limit for this measurement.

**Frontal impact**

The frontal impact was conducted with the wheel loader because it was considered to be the vehicle type most at risk of such types of accident. In the frontal impact with the unbelted and lap belted occupant, there was abdominal contact with the steering wheel rim as shown in Figure 26. It was evident that this would present a significant risk of serious injury although there were no injury criteria to quantify the magnitude of risk. In both cases, this was followed by rotation of the upper body over the top of the wheel and contact between the head and windscreen, resulting in a substantial risk of head injury (Table 23, Appendix D). With the three-point belt and harness restraints the abdominal contact was eliminated, however with the three-point belt there was contact between the head and the steering wheel, which caused a high HIC\(_{36}\) and head 3ms exceedance. An issue identified for all restraint systems in this impact was high levels of chest compression. The harness was the only restraint which kept the compression below the lower performance limit.

![Images from the frontal impact of the wheel loader](image)
Summary of comparison between restraint systems

It was implied from the models’ predictions of the parametric investigation that the design of restraint system had a considerable influence on the injury risk to quarry vehicle operators in the event of an accident. Wearing no restraint, the vehicle operator was free to roll around the internal confines of the compartment impacting hazardous structures within the cab such as the steering wheel, levers and grab handles. There also existed the potential for the cab glazing to break or for the doors to open with the possible ejection of the vehicle operator from the cab and the risk of receiving serious or fatal crush injuries, although this was not included in the modelling. The wearing of a lap belt appeared to offer greater occupant protection and restrained the occupant in the vehicle seat. However, with the lap belt there still existed a large amount of head excursion and the potential for the head to impact hazardous structures within the confines of the cab. This is discussed further in the injury risk study part of this report (Section 6). There was also substantial loading through the lap belt in some of the accident conditions which could present a risk of abdominal injuries, however there were no injury measures available to quantify these risks. With the lap belt in the frontal impact condition there was significant contact between the steering wheel and abdomen presenting a risk of injury.

The three-point belt system appeared to provide improved protection for a vehicle operator compared with a lap belt. Additional concerns were that the diagonal belt was sometimes found to wrap around the neck when the human body model rolled in the direction of the shoulder anchorage for the belt system. Predictions from the model did not suggest that there were any particular hazards with this response. However, the injury predictions for the neck were specific to the loads in the spine and were potentially unrelated to the types of soft tissue injury that might occur by having a belt pressed around the neck such as crushing of the trachea. As such only subjective assessments of the injuries that might be caused by the belt wrapping around the neck could be made at this time.

The wrapping of the belt around the neck did not appear to be a problem associated with the harness. Inspection of the model animations suggested that the shoulder elements of the harness tended to lie more vertically down the chest with the load directed more through the torso of the human body model than through the neck. Overall, the harness tended to provide the best restraint for the upper torso and reduced the subjective injury risks identified for the head when the human body model was fitted with a lap belt. Based on the findings of the numerical simulation, the recommendation would be for quarry vehicle operators to wear a harness in order to provide improved protection in the event of the vehicle accidents studied.

5.2.2 Differences between vehicle types

The cabs in the rigid dump truck, articulated dump truck and wheel loader vehicle models were broadly similar, with the exception that the rigid truck had a narrower cab. However, as the seat in the rigid truck was set to one side, rather than centrally, the distance from the wall is actually slightly greater than in the other vehicles when rolled to the right. The most extreme position reached by the occupant during the 90° dynamic rollover with the lap belt and harness in each vehicle type are shown in Figure 27 and Figure 28 respectively. No significant differences were found in the occupant behaviour between these vehicles.
The bulldozer was subjected to slightly different impact conditions to the other vehicles (no initial forward velocity was applied) because of the nature of the work it performs. The vehicle cab was also substantially different to the other vehicles because it was narrower and there was no steering wheel or front fascia. However, the motion of the occupant remained broadly the same as in the other vehicles with contact occurring between the head and side wall when the lap belt was fitted. One difference that was found, was because of the narrow cab. The head was close to hitting the side wall when the harness restraint was fitted, whereas in other vehicles the head was kept at some distance from the walls (shown in Figure 28, note: bulldozer was rolled in opposite direction to other vehicles). The absence of the steering wheel and fascia allowed the legs to swing up unimpeded which could present an increased risk of injury either from or to the flailing limbs.

5.2.3 Directional issues with three-point lap-diagonal belt

When fitting a three-point lap-diagonal belt, the upper anchorage can be mounted on either the left or right side of the seat. The models indicated that the performance of the three-point diagonal belt system was dependent on the position of this anchorage in combination with the direction of roll and severity of the impact.

In the 90° static rollover the effectiveness of the three-point was found to be highly dependent on the direction that the vehicle rolled and on whether the belt system was or was not reversed. As shown in Figure 29, with the lap-diagonal belt reversed and the rigid truck rolling to the right the human body model slipped out of the diagonal part of the belt system. Better restraint of the upper torso was provided by the regular three-point belt system.
By way of contrast, the more severe 270° dynamic rollover with the articulated dump truck is shown in Figure 30. The reverse three-point belt provided better restraint than the standard three-point because in this accident scenario the occupant did not slide out of the diagonal section of the belt, probably because of the vertical component pushing the occupant into the belt. Restraint of the left shoulder by the reverse belt resulted in the occupant being well contained in the seat. With the standard three-point belt the left side of the upper torso rotated over the diagonal belt and the head struck the side wall.

The performance of the three-point belt is therefore clearly dependent on the direction and type of the rollover, making it a less predictable restraint option than the harness. One concern with the vehicle rolling in the direction of the diagonal belt upper anchorage was that the belt showed a tendency to wrap around the occupant’s neck. This behaviour was found to be highly dependent on the initial position of the belt on the occupant, however it was a trend not found with the harness because the belt system tended to still pass down, rather than across the front of the chest. Although it was not obvious from the neck injury predictions it was expected that this loading on the neck could cause additional hazards not considered by the neck injury predictions.

5.2.4 Influence of armrest fitment

The rigid truck in the static and 90° dynamic rollover conditions was assessed with and without armrests fitted to the seat to determine the influence on occupant kinematics and injury risk.

General observation of the results indicated that the presence of the armrests tended to reduce the head and neck injury risk. For example, when wearing a lap belt the armrest reduced the excursion of the head in the right rollover impact conditions to the point where it prevented the head from striking the opposite wall of the cab, as shown in Figure 31. The head impact with
the lap belt but no armrests was only a glancing blow and explained why the head and neck injury predictions for the two model runs (with and without armrests) were very similar and were at least 50% below the upper performance limits defined for the head and neck injury criteria. For equivalent impact conditions with armrests the neck tension was 77% lower than the predicted response without armrests. Armrests also tended to reduce the load in the belt system with loads being between 16 to 65% lower than equivalent predictions without armrests. When three-point or harness restraints were fitted, the armrests had a reduced influence on the occupant excursion.

![Figure 31 Differences in the head excursion with and without armrests](image)

The presence of armrests in the simulations reduced the excursion and the impact velocity of the body with internal structures of the cab. Figure 32 shows the difference in head excursion for the lap belted case. It is clear that the excursion was greater without armrests and in this case excursion was only limited because the occupant’s head hit the side wall. It was not certain how the additional loading from the armrests on the body influences injury risk. It was hypothesised that the armrests would off load the belt system leading to lower belt loads for the model runs in which the armrests were simulated. The predictions in Table 19 (Appendix D) show that this was clearly the case when a lap belt is fitted, however the trend is less clear with the three-point and harness restraints.

![Figure 32 Head excursion during 90° dynamic rollover, with and without armrests](image)
5.2.5 Effect of occupant size

Six model runs, selected based on the results from the 50th percentile occupant, were performed with the 95th percentile occupant. The principal criterion for selecting scenarios was that the 50th percentile either contacted or came into close proximity to structures that the additional height and mass of the 95th percentile may have caused it to hit. Scenarios where the 50th percentile had recorded high injury risk predictions were not considered as it was expected that such results would be similar for the 95th percentile.

The 90° dynamic rollover with the 95th percentile is shown in Figure 33. The equivalent case with the 50th percentile is shown in Figure 22. When restrained by the lap belt, the 50th percentile had a glancing blow against the side wall, whereas the 95th percentile struck the wall more severely. After this impact the head then moved down towards the fascia area. The head injury levels (Table 19, Appendix D) remained considerably lower than the performance limits (HIC36 of 960 for 95th percentile), however the injuries to the 95th percentile are higher than those of the 50th percentile, including a substantial increase in HIC36. When fitted with the harness restraint, the occupant was contained in the seat and the head was kept well away from any structure and the injury risk was no greater than for the 50th percentile.

Under the 270° dynamic impact condition the same behaviour was observed, however the 95th percentile fitted with the harness came close to sustaining head contact with the side wall, which was a risk not seen with the 50th percentile.

Overall, the 95th percentile occupant was found to behave in a similar manner to the 50th percentile, however the increased mass and height meant that the occupant reached structures that the 50th percentile did not. The predicted injury risks for the 95th percentile were similar to the 50th percentile, but when considering the more subjective measures the 95th percentile occupant was found to be at greater risk of interaction with internal features that were not modelled.

![Images from the 90° dynamic rollover with the 95th percentile occupant in the rigid dump truck](image-url)

**Figure 33** Images from the 90° dynamic rollover with the 95th percentile occupant in the rigid dump truck
5.2.6 Modelling considerations

It is important to remember that the results of the simulation work are based on a selective number of accident conditions and variations in the results presented here could be expected by virtue of deviations in actual crash conditions from those simulated here. For instance, deviations in the width and height of the cab and the height and mass of the driver are obvious variables that are likely to influence the severity and types of internal features of the cab that the head will strike. In the model, assumptions have also been made on how the vehicle operator would respond in the event of an accident. In the model the human body model is locked to the motion of the vehicle approximating the restraining response of the driver. Just prior to impact the human model is unlocked from the motion of the cab and then interacts flaccidly with the internal confines of the cab as if the vehicle operator were unconscious. Alternatively, it could be expected that the vehicle operator may well be able to better restrain themselves within the cab and because of the typical long duration (approximately one second) of the impacts would have adequate time to protect potential impacts of their head with their hands and arms. This could potentially reduce the injury risk identified by the modelling in this work, which assumes a worse case condition.

Overall, the model assumes that the belt systems are fitted and operating correctly to provide optimum protection to the wearer. However as found in the rollover tests with the rigid truck, belt functions such as locking retractors may not be activated in all accident conditions, as occurred in the tests. Under such circumstances, injury risks could potentially be greater than those predicted in this study. The model has also not considered the influence that cab intrusion (which is constrained by the ROPS standards) will have on occupant injury risk. With limited cab intrusion, reducing the excursion of the head, as was achieved when wearing the harness, would provide the greatest benefits in protecting the head from impacting intruding features of the cab. However, with excessive cab intrusion, the benefits of a belt system are likely to be irrelevant because the survival space is removed.

5.3 CONCLUSIONS

Generic numerical models of a rigid truck, an articulated dump truck, a wheel loader and a bulldozer were developed. Predictions from the models have been evaluated against test results from three static rollover tests on a rigid truck. Having established that the developed models are suitable for assessing the injury risk to quarry vehicle operators under specific accident conditions, these were then applied to assess the protective benefits of different restraint systems under a wide variety of impact conditions. The main conclusions that can be implied from the models predictions in this work are as follows:

- Unbelted occupants are thrown around the cab, increasing the likelihood of the operator being ejected from the cab if the cab glazing should fail or the doors should burst open. There then exists the potential for the operator to receive serious or fatal crush injuries, however, this was not part of the study.

- In general head impacts are less severe for belted occupants. Furthermore, wearing a harness or three-point belt system can reduce the head excursion within the cab reducing the likelihood of the head striking hazardous features of the cab interior such as levers, grab handles and steering wheels and columns.

- The same general trends of behaviour were observed over all four vehicle types modelled. Although there were different cab geometries and impact dynamics, benefits from fitting three-point belts and harness systems were seen in all cases.

- In a rollover impact, the effectiveness of a three-point belt system was highly dependent on the direction in which the vehicle rolled and the side (left or right) that the shoulder anchorage was mounted. When rolling away from the shoulder anchorage there existed
the possibility of the occupant sliding out of the diagonal belt reducing the effectiveness of the three-point belt system to that of a lap belt. Furthermore, when rolling towards the shoulder anchorage the diagonal belt tended to wrap around and load the neck resulting in possible serious soft tissue injury. This same problem was not observed with the harness

- Armrests tended to reduce the amount of head excursion and the severity of the head impact with the internal features of the cab. Loads on the belt system were also reduced when armrests were used because load was shared between the belt system and the armrests. However, the effect of this redistribution of load on occupant injury risk was uncertain

- Model injury predictions suggested that the injury risk for the 95th percentile was a similar level to the 50th percentile. However, the head and upper torso excursion for the 95th percentile was greater, increasing the likelihood of interaction with hazardous features. This elevated risk for the 95th percentile was present with the harness but was much greater when only a lap belt was fitted

- Overall the harness tended to provide the best restraint for the upper torso and substantially reduced the subjective injury risks identified for the head when the human body model was fitted with a lap belt

Based on the findings of the numerical simulation the recommendation would be for quarry vehicle operators to wear a harness in order to provide improved protection in the event of vehicle accidents.
6 OCCUPANT PROTECTION

There are three main objectives to consider in terms of occupant protection in the type of rollover accident considered by this project:

- Maintaining a survival space within the cab without causing excessive vehicle accelerations
- Restraining the occupant within the survival space and limiting the chance of contact with the vehicle structure
- Designing the elements of the cab interior and structure that might potentially still come into contact with the occupant in a way that will minimise injury (e.g. soft structures not hard, well rounded and not pointed)

The first objective is controlled by the ROPS standards, which are described in Appendix A, and has not been considered in any detail during this research. The main focus of the project has been on the second objective, identifying the standards applicable for restraints (e.g. ISO, SAE etc) and assessing the ability of different types of restraint to minimise movement of the occupant and the forces applied to the occupant during the impact. The third objective is regulated to some extent for cars, for example Federal Motor Vehicle Safety Standard (FMVSS) 201 in the USA that requires interior head form testing of cars, but is completely uncontrolled for quarry vehicles. This section of the report will describe a preliminary risk analysis intended to identify whether there are elements of typical cab design that could still cause serious injury to an occupant even when restrained to the levels simulated in section 5.

It is appreciated that there may be many different cab sizes and features such that an exhaustive study is not possible. However, the aim of this part of the research was to study a small but representative range of cab interiors and identify any potential hazards to the occupant and any features that were found to be particularly common across the different makes, for example:

- Grab handles
- Fire extinguishers
- Levers

6.1 METHOD

The risk assessment was carried out in two phases. The first was to make visits to manufacturers and collect as much information as possible into the different cab designs and the potential hazards. The second phase was to take the head trajectory output from the modelling and then investigate what features were most likely to be hit and, therefore, what causes the most risk to the operator.

The project examined a number of different vehicle types and not all types were studied on each visit. Visits were made to manufacturers where a number of different vehicles were inspected and measured. The manufacturers visited were:

- **JCB Earthmovers** – articulated dump truck, wheel loader
- **Komatsu** - Articulated dump truck, wheel loader, rigid dump truck and bulldozers

Although these visits did not rigorously investigate all manufacturers and models, they allowed general trends regarding the types and location of items within the cab to be identified. Visits to actual working quarries exposed researchers to a greater range of manufacturers and models but did not result in any additional hazards being identified. However, it is possible that not all
structures within the cab for all vehicle types have been identified and considered. The method described here for assessing the cab interior could be applied by manufacturers on a vehicle by vehicle basis.

Some information has also been obtained from an internet search, although this data tended to be limited to more general weights, dimensions and specifications, which were not sufficiently detailed for the risk assessment.

On each visit to the manufacturers, measurements and photographs were taken for each vehicle type. The data collected varied because different vehicles demanded more or less measurements, depending on their layout and the number of potential risks identified within the cab interior.

The risk assessment was carried out by firstly looking for major structures within the cab that could cause major head injuries in a rollover impact. The structure and the area surrounding it were examined to see if it would provide any protection for the vehicle operator. Once the major structures had been identified, the smaller features such as levers, handles, rivets etc. that could potentially cause an injury were recorded.

During the research program four visits were made to working quarries and this gave an opportunity to look at other vehicles and identify any common features in the context of their daily operation, thus providing a greater understanding of any potential risks.

The relevant head trajectories for a lap belted occupant from the modelling were taken for different impact scenarios. These were compared to the location of potentially hostile structures within the cab to identify the features which were most likely to be impacted. The modelling results were also used in order to provide an indication of the severity of the impact based on criteria such as head velocity at relevant stages of excursion.

### 6.2 VEHICLE INSPECTION OBSERVATIONS

The four main vehicle types (wheel loader, rigid truck, articulated truck and bulldozer) were all studied during this risk assessment. Two manufacturers were visited during this study which allowed a number of common features to be identified. The visits to the quarries allowed other vehicle types to be inspected (although to a lesser level of detail). No additional features that were considered as a risk to the occupant were identified. However, it is possible that some vehicle designs may contain features that have not been identified in this research. Each vehicle considered in detail is discussed below, and the main risks are identified:

- JCB 426 wheel loader
- JCB 714 articulated dump truck
- Komatsu HD405 rigid dump truck
- Komatsu WA470 wheel loader
- Komatsu 65EX bulldozer
- Moxy MT31 and MT40B articulated dump trucks

#### 6.2.1 JCB 426 wheel loader

This was the first vehicle inspected and a number of measurements were made to ensure that all the data was collected and these are shown in Figure 34.

Figure 34 shows that the driver’s head is very close to the rear of the cab and as a result is also close to the B-pillars of the cab. The vehicle cab was relatively wide with at least 400 mm head clearance on either side, however when sitting in the seat it was found that the head could strike the B-pillars with relative ease. The A-pillars of the cab were also identified as a risk to the operator because the head could strike them in an accident where the driver would be thrown...
forwards as well as side ways. Measurements were taken of the approximate distance from the front of the head of someone sitting in the seat to the A-pillar with the seat in the forward most and rear most seating positions. It was found that this distance ranged from 440 mm to 580 mm, which with the varying statures of the operator will be within striking distance if no belt or a lap belt is worn. In the cases where a harness is worn then the A-pillar will not pose any risk to the operator unless the retractor does not lock on impact. On inspection of the A and B-pillars it was found that there was very little padding covering the metal cab structure, so there was no protection offered to the driver in the event of a head strike. The trim is there for aesthetics reasons only because there is no requirement for occupant head protection. However it is an easy task to add some energy absorbing material around the pillars.

![Cab dimensions for the JCB 426 wheel loader](NOT TO SCALE and all dimensions in millimetres)

**Figure 34** Cab dimensions for the JCB 426 wheel loader

![Interior of the 426 wheel loader cab](Figure 35 Interior of the 426 wheel loader cab)
Figure 35 shows the interior of the cab and the A- and B-pillars and their proximity to the seat as discussed above. Figure 35 also shows the window edge that was identified as a potential risk because the head could strike it. The edge of the window could cause a severe cut if struck during an impact. It is important that the driver is able to open the window, however the design could be altered to reduce the risk of injury.

**Figure 36** Fire Extinguisher attached to the B-pillar

Another feature identified as a serious risk was the location of the fire extinguisher, which is mounted to the B-pillar as shown in Figure 36. As already mentioned the B-pillars are close to the driver and by mounting the fire extinguisher here, it has increased the risk of the driver being hit during an impact. However, because it is not an integral part of the cab it could be easily moved to a safer location, possibly lower down the B-pillar.

Access to this vehicle was quite difficult, with steep steps up into the cab. To aid the operator there were a number of grab handles positioned to provide adequate hand holds. However, one grab handle was placed in such a position that it may be struck by the driver in an accident. The grab handle was positioned on the inside of the cab as shown in Figure 37 below. On inspection of the handle it was found to be constructed from steel tube, which if struck by the head in an impact could cause severe injuries. The risk of impact was quite high as the driver does not have to move very far (approximately 300mm) to achieve head contact.

**Figure 37** Photograph of grab handle inside the cab
Smaller vehicles were also inspected on this visit but the conclusions remained the same because the cabs for all of the JCB wheel loaders were similar.

6.2.2 JCB 714 articulated dump truck

![Figure 38 The JCB 714 Articulated dump truck](image)

The cab of the articulated vehicle is very similar to that of an agricultural tractor and the access to the cab is very different to a wheel loader, as shown in Figure 38. On this vehicle there is a series of steps and a platform on which the operator can stand before they open the cab door. As a result it means that there does not have to be as many grab handles within the vehicle, resulting in a clear occupant space.

Few significant hazards were found within the cab of this vehicle and it should present a lower risk of injury to an occupant in a rollover accident. The cab of this vehicle was bigger than that of the wheel loader, allowing more space in which the occupant could move. This may be beneficial if, in an impact, the occupant did not hit any parts of the vehicle. If head strikes did occur there is the potential that they could be more severe due to the head having more energy. In this vehicle the driver had at least 300mm clearance to the back of the cab and over 525mm from the side of their head to the sides of the cab as shown in Figure 39.

The two main hazards identified in this vehicle were the B-pillars and the roof. The B-pillars were very similar to those in the wheel loader, having very little padding covering the metal cab structure.
The fact that the head has further to travel before colliding with the B-pillars for this vehicle means that the risk of impact is reduced, however it does not mean that it can be ignored. The roof profile was a feature not seen in the wheel loader. The stereo system was mounted into the header rail above the steering wheel and to the right of this was a storage unit. The storage unit projects downwards from the roof, as shown in Figure 40, and the corner is only approximately 550mm from the drivers’ head (depending on driver size). On inspection it was found to be a reasonably solid structure that could potentially cause a serious head injury. However, because this was probably a plastic moulding it should buckle under impact leaving the operator with cuts and bruises at most. If this was a metal structure then severe head injuries could be expected.

Figure 39 Dimensions of the 714 articulated dump truck cab

Figure 40 Photograph of the overhead storage unit.
Because this feature is on the ceiling of the cab it is unlikely that a head strike will occur unless the vehicle is involved in a more severe rollover, such as the end tipping or multiple dynamic rollover, which moves the driver upwards as well as sideways.

6.2.3 Komatsu HD405 rigid dump truck

The first impression of the interior of this vehicle was how different it was to the other wheeled vehicles inspected because it was very similar to that of a car, as shown in Figure 41.

![Figure 41 Interior of the rigid dump truck](image)

There were a number of risks identified for this vehicle as listed below:

- B-pillar and localised rivets
- Dashboard
- Roof rivets

The vehicle inspected had no internal covering over the cab bodywork. This would mean that in an impact there is no added protection to the occupant, the only protection is offered by yielding of the metallic structure. In addition to this, there were two rivets at head height in the B-pillar making a localised hard spot. If the head was to strike this location in a rollover accident then it is highly likely that severe injuries would be sustained. The purpose of these rivets was to mount an external grab-handle, but this could be eliminated if the vehicle was fitted with staircase access as proposed by the HSE (HSE, 2005), moved lower or mounted in a different manner in order to reduce the risk to the driver. Due to the cab having two seats head strikes on the bodywork are only likely where the operator is seated on the struck side. The measurements for this vehicle are shown in Figure 42 below and it shows that there is only 420mm from the seat centre to the B-pillar on the driver's side, meaning that head strikes are a relatively likely. There is also the possibility that in a severe frontal impact that the driver's head may impact the A-pillar, which again offers no protection for the driver.
Figure 42 Cab dimensions for the Komatsu HD405 rigid dump truck

Figure 42 shows that from the seat cushion to the ceiling there is only 1080 mm, which leaves very little clearance from the top of the head. This would not normally pose a risk to the driver however in this vehicle there were a series of rivets in the roof that could cause an injury. These would only be an issue in a severe rollover when a hard head strike with the ceiling is most likely, but the consequences of the head strike could be severe.

The distance between the driver’s knees and the dashboard in this rigid truck were found to be a cause for concern in heavy frontal crashes. Figure 43 shows that for the normal seating position the knee clearance is no more than 100mm, which means that knee impacts are likely in the event of an accident. The potential injuries from these impacts, (including fractured patella and tendon damage), although low severity, can result in long term degeneration of the knee and reduced mobility.

Figure 43 Knee to dashboard spacing in a rigid truck.
Figure 43 also shows that there is an additional risk posed by the location of the key and the possibility of striking it with the knee. This is potentially injurious to the driver and could be easily solved by moving the ignition. Leg injuries are unlikely to be the main risk in a rollover but they may prevent the occupant from getting clear of the vehicle after the accident.

6.2.4 Komatsu WA470 wheel loader

As with the other wheel loader analysed, the main hazard identified was the solid B-pillars. All vehicles have to pass the ROPS test and as the vehicles get larger so does the structure of the cab. In this vehicle the pillars were quite substantial, and covered with foam like material approximately 5mm thick. However, it was considered that this covering material would offer little protection if hit. In this vehicle there were also 3 large rivets in the exact area where head strikes are most likely, as shown in Figure 44. As in the rigid truck these are localised hard areas which if struck by the head could cause a serious injury.

The distance of the centre of the seat from the B-pillars was 565mm which would mean that a collision between the head and the B-pillar would be relatively likely in a rollover accident, similar to the other vehicle studied.

The other risk identified for this vehicle was again similar to the first vehicle described in this report and that is the window join. In this vehicle it is situated in an area where a head strike is most likely to occur as shown in Figure 45 below. The difference in this vehicle is that there is a sharp plastic trim over the edge of the glass providing an edge on which an injury could occur.
On the larger wheel loaders in the same ‘family’ there was increased support on the door and as a result they were equipped with a large handle on the inside to allow the operator to pull the door shut. These handles may not get impacted directly, but could still cause injury if struck during a rollover impact. The solution to this issue is to design a handle that is recessed into the door, or one that would shear off under a set load.

Overall these wheel loaders posed only a moderate number of risks to the operators, however, consideration of occupant interaction with the cab interior in the design process could remove these risks relatively easily.

6.2.5 Komatsu 65EX bulldozer

The bulldozer cab was the smallest of all those inspected and the major hazards were similar to those already identified for the other vehicle types. The width of the cab was only 1020mm between the cab structure and 1215mm from window to window. The close proximity of the cab structure means that there is an increased risk of a head strike on most parts of the vehicle structure around the seat. The main features seen in Figure 46 that pose a risk to the operator are:

- **B-pillar** – there was no protection around the steel structure just an extra plastic coating that did not appear to offer energy absorption potential

- **Grab handle** – this could potentially be injurious, however this one was plastic so has more chance of yielding under impact

- **Window join** – the window had the plastic edge as in the wheel loaders, which could cause injury if impacted
There was some concern over the risk of leg injury on the instrument panel and the protruding switches. However, if the occupant was restrained then it is very unlikely that a substantial leg strike would occur.

6.2.6 MOXY MT 31 and MT40B articulated dump trucks

These two vehicles were older models and had a significantly different design. It was important to see these vehicles so that this assessment considers older styles as well as new ones. The first observation for these vehicles was that the cab was a great deal more spacious than the newer vehicles. This significantly reduced the risk of the cab structure causing an injury in an impact where the occupant was restrained. However, there are other risks that could cause serious injury. Figure 47 shows two potential hazards for these vehicles, the first is the solid steel door handle and the second is the array of control levers.
The dashboard design of these vehicles is also potentially hazardous with many sharp corners. In the newer vehicles the design is much more user friendly with fewer sharp corners.

### 6.3 ANALYSIS AND DISCUSSION

During the vehicle inspections a number of common features were identified as potential hazards. The three common features found for each vehicle were:

1. The cab B-pillars.
2. Grab handles.
3. The window edge.

All of the above could pose less of a risk to the operator if they were designed in a different way. The B-pillars are an essential structure of the cab, but are often not covered with any energy absorbing material. The key to offering head protection for these features is to provide a mechanism by which the head can be decelerated over a longer period of time, to allow a substantial part of the energy to be absorbed before the head strikes the actual metal substructure. There are a number of ways to do this, and one solution used in passenger cars is to fit a ‘honeycomb’ energy absorbing structure placed under a plastic trim, as shown in Figure 48 below.

![Figure 48 Photographs of the ‘Honeycomb’ structure that offers protection in cars](image)

The grab handles are a major hazard and one which could be avoided particularly if staircase access is present. The visits found that grab handles were placed in areas where there was a space and where they were needed. The manufacturer had not necessarily thought of the risks to the driver during the design phase. The grab handles were mostly all steel, which would not yield significantly under a head impact. This could be changed to a plastic moulding that would yield under a set load if it was hit or could be more solid if it was placed in a position where it could not get impacted. Again this may add a small additional cost to the manufacturer because they may have to set up tooling for plastic handles and redesign handles in the high risk areas.

The window edge has the potential to cause severe lacerations in an impact. It is very important that the driver can open the window, however having the split two pane windows identified in the vehicles inspected, does pose a risk to the vehicle operator. The windows could be redesigned so that they open from the sides and do not have the edge running through the middle. This is the lowest risk hazard that has been identified but even during low speed/low severity impacts the head could catch the window edge and cause severe cuts.

Overall it was found that the vehicle cabs were, on the whole, very similar although the older vehicles were more spacious and the design was more box-like. The type and effectiveness of the restraint worn will have a substantial effect on the likelihood of contact between the operator and the hazardous structures. However, the design of these hazardous structures can only be
safely ignored if it is certain that suitable restraints will always be worn and that contact will never occur.

The risks identified in this study are not new or unique. Similar risks were identified within passenger car interiors many years ago. The passenger car industry has over recent years made very large improvements in interior design for the protection of the occupant. For example, in older cars the rim of a steering wheel was of a relatively small diameter and made from very hard material and the hub often had only a flimsy thin plastic cover over the steering column bolt and these features were known to cause serious injuries in frontal crashes. In addition to using airbags to reduce the chance of contact with the wheel, manufacturers redesigned steering wheels such that the steering column was covered by thick energy absorbing foam, the diameter of the rim was increased and covered with softer material and the supporting structure of the rim was designed so that it would deform if an occupant came into contact with it during a crash.

Similar large improvements in the interior cab design of earth-moving machinery should now be a relatively simple process of transferring the ideas and technology developed in the car industry into the earth-moving equipment market. It is likely that very little research and development costs would be incurred and the cost per cab should remain relatively low because the materials used are also used in high volume car production.

If the development of a Regulation or Standard for cab interiors was to be considered, further work would be required. This assessment was intended as a preliminary study only and has a large subjective content.

**6.3.1 Evaluation of the risks**

To try and identify which features outlined in the vehicle assessments are most likely to be hit, the head trajectories output from the modelling were considered. These were output in the format of a three dimensional, X, Y, Z time plot and a picture as shown in Figure 49. The measurements for the head displacement were taken from the centre of the steering wheel and are the relative change over the duration of the impact.

![Figure 49 Example of the head trajectories output from the modelling](image)

The head trajectories were obtained for all the vehicle types and for the different accident scenarios. As the modelling is only using one vehicle speed and rollover rate it was seen that there may be some fluctuations in the trajectories and these were taken into account when applying the results to each vehicle. The graphical illustrations of the areas of risk are a two
A full three dimensional analysis was beyond the scope of this research and would be necessary for the development of future design guidelines. The end tipping scenario was not included in this analysis because most of the motion of the occupant was vertical. However, as shown in some of the models, there is a risk of contact with the steering wheel.

6.3.2 Wheel loader

The modelling results provide head trajectories for 90° and 270° rollovers, but have a fixed forward velocity. In reality the forward velocity will vary so there may be more or less forward motion of the head in a rollover. In Figure 50, the areas at risk for static and dynamic rollovers has been estimated and the features that are potential hazards to the occupant are shown. The risk zone for the frontal impact has also been estimated from the modelling. The simulated impact conditions did not include any rotation of the vehicle or occupant, with the head moving straight forward. However, there is potential for the structures to each side of straight ahead to pose a risk if the vehicle is involved in an angled impact, or overlap causes the vehicle to rotate.

Figure 50 Plan view of a wheel loader cab highlighting the areas at risk in static and dynamic rollovers

The features identified in the vehicle assessments and the levels of risk estimated from the modelling are listed below:

- **A-pillar and B-pillar** – The results suggest that the B-pillar will be impacted in slow/static rollover accidents. Where the vehicle has more forward momentum then the A-pillar is more likely to be impacted. There is the possibility that in a multiple rollover that the head could strike both pillars, because the modelling shows the occupant to be thrown around quite vigorously

- **Fire extinguisher** – The modelling shows that this poses a risk during the static rollovers and violent 270° rollovers. The injuries sustained could be quite substantial due to the sharp edges on the handle of the fire extinguisher

- **Window edge** – This is a large risk during the rollovers and the head trajectories suggest that there is a moderate to high probability that a head strike on this feature will occur
• **Grab handles** – The modelling in combination with the measurements taken suggest that the grab handle identified in the JCB wheel loader will almost certainly be struck in a rollover impact and, therefore, carries a major risk. The other grab handles identified pose less of a risk because they are lower down on the door and therefore less likely to be hit

• **Steering wheel** – The modelling indicates that there is a high risk of contact between the steering wheel and the chest in frontal impacts

### 6.3.3 Rigid dump truck

The head trajectories have been analysed for the rigid truck and Figure 51 below shows the areas at risk during static and dynamic rollovers. Estimates of the risk have been made based on the modelling outputs for the features identified as potential hazards to the occupant. As Figure 54 shows, the driver is unlikely to impact the right-hand side of the cab, unless, as in the rollover testing the seatbelt does not lock. There is no zone for the frontal impact because this was not included in the modelling for this vehicle. However, the risk zone is likely to be similar to that of the wheel loader shown in Figure 50.

![Figure 51 Plan View of a rigid dump truck cab, highlighting the areas at risk in static and dynamic rollovers](image)

The features identified in the vehicle assessments and the levels of risk estimated from the modelling are listed below:

• **A-pillar and B-pillar** – The results suggest that the B-pillar will be impacted in slow/static rollover accidents. However, there is only likely to be a risk of head contact with the A-pillar in a frontal impact. There is a possibility that in a multiple rollover that the head could strike both pillars but it is the B-pillar that poses the greatest risk

• **Dashboard** – The forward movement of the dummy depends on the effectiveness of the restraint mechanism. The modelling suggests that the occupant will move forward far enough for knee strike to occur. This means that the key poses a high risk to the occupant along with other hard features within the dashboard

• **Roof Rivets** – These pose a very low risk in the 90° rollovers, however in the accidents where there are multiple rolls there is a higher risk that they may be impacted. Also because of their size it is unlikely that the head will hit one square on, so the impact will not always be worst case

All of the features identified could easily be improved by simply redesigning or moving the feature, thereby reducing the risk of injury.
6.3.4 Articulated dump truck

The head trajectories have been analysed for the articulated dump truck. Figure 52 shows the areas at risk during static and dynamic rollovers. The modelling outputs have been used to estimate the level of risk for the features identified as potential hazards to the occupant. From the vehicles measured, there is more variation in the design of the articulated dump truck between manufacturers, so generic solutions were difficult to identify.

Figure 52 Plan View of an articulated dump truck cab, highlighting the areas at risk in static and dynamic rollovers

The features identified in the vehicle assessments and the levels of risk estimated from the modelling are listed below:

- **A-pillar and B-pillar** – The results show very similar head trajectories to those identified for the wheel loaders. In the newer vehicle (JCB) head strikes will most likely occur on both sides of the cab, however for the older, wider cabs (Moxy) as shown in Figure 52 the head is less likely to strike the off-side of the cab.

- **Window edge** – This is a large risk during the rollovers and the head trajectories suggest that there is a chance that a head strike on this feature will occur.

- **Grab handles** – The grab handles do not pose such an issue in these vehicles as they are not that high up the doors and are not in the main trajectory of the head. Also as shown above in Figure 52, the door handle is right on the limits of the head excursion and will only be impacted if the occupant is tall or is unrestrained.

- **Overhead Storage** – The head trajectories suggest that with a 50th percentile person they are unlikely to impact this feature, but with a taller person this may become a potential hazard. This feature may also become a risk during a multiple rollover where the occupant is thrown upwards out of their seat.

- **Levers and controls** – The levers pose a high risk to the driver because they were found to be on the trajectory of the head.

Again, the frontal impact condition was not assessed for this vehicle. However, the risk zone is considered to be similar to that shown for the wheel loader.

6.3.5 Bulldozer

The bulldozer was the smallest of all the cabs and the driver was able to impact both sides of the vehicle. The head trajectories have been analysed for the bulldozer and Figure 53 below shows
the areas at risk dynamic rollovers only. Static rollovers or frontal impacts were not considered for this type of vehicle. The modelling outputs have been used to estimate the level of risk for the features identified as potential hazards to the occupant.

Figure 53 Plan view of a bulldozer cab, highlighting the areas at risk in static and dynamic rollovers

The features identified in the vehicle assessments and the levels of risk estimated from the modelling are listed below:

- **B-pillar** – The head trajectories suggest that the head will strike the B-pillar, but because the A-pillar is so far forward in the cab it is unlikely that it will be impacted by a restrained occupant

- **Window edge** – This is a large risk during the rollovers and the head trajectories suggest that there is a fair chance that a head strike on this feature will occur

- **Grab handles** – The grab handle poses the same risk as that for the B-pillar, however due to its size it will not always be hit during a rollover

The bulldozer had the largest amount of free space of all the vehicles studied in which the driver could move in a rollover. This was because it has no steering wheel and that the cab was long and thin. With the improvements suggested for the B-pillars and repositioning the grab handle there would be very little risk to the operator as a result of contact with hostile interior structures.

6.4 CONCLUSIONS

- The most common features identified that are hazardous to the operator are the B-pillars, grab handles and the window edges

- A number of the hazards could be excluded by the use of harness type restraints. This would prevent the movement of the upper body and, therefore, reduce the potential for head impacts

- There should be better energy absorbing coverings to the B-pillars to provide a level of protection to the occupant during an impact

- The risks identified can be reduced relatively easily by manufacturers carrying risk assessments of the cab during the design phase and combining this with knowledge and technology from the passenger car industry where issues very similar to these have previously been identified and solutions, such as energy absorbing materials exist
The numerical simulation carried out as part of this project has shown that more comprehensive restraint systems, that restrain the upper body as well as the pelvis, could reduce the likelihood of injury in some accident circumstances. However, this will only provide a net safety benefit if they do not cause other injuries during normal operation and if they are sufficiently comfortable to wear during normal operation to ensure that drivers do wear them.

The objective of this element of work was to identify all of the types of restraint currently available and to consider their attributes in light of the requirements of day to day operation and the concerns of drivers.

### 7.1 RESTRAINT TYPES

The following generic restraint types were identified:

- **Two-point (lap belt):**
  - In two-point, lap belt restraints, belt webbing lies over the thighs of an occupant. In an accident the thighs or pelvis of the occupant are held in position by this strap of webbing.

- **Rigid two-point system:**
  - As an alternative to a lap belt, the webbing can be replaced by a bar or more rigid material. These systems may be as effective in holding the occupant down in a rollover but may not interact with the bony pelvis of an occupant in quite the same manner in a frontal impact.

- **Three-point belt (lap and diagonal):**
  - Three-point belts are similar to a two-point belt but with an additional shoulder section. This shoulder section will run from a lap anchorage point, across the torso of the occupant and be effectively anchored behind the opposite shoulder of the occupant, as found in modern cars.

- **Three-point inertia locking retractor harness:**
  - This is similar to a four-point harness, with the exception that the torso restraints are combined at a point behind the shoulders of the operator and feed into an inertia locking retractor fitted in the seat. This is the type of restraint that was assessed in the full scale test and modelling work.

- **Four-point/Harness:**
  - Four-point harnesses consist of two torso sections. Two possible arrangements for these double torso belts are, either crossing the torso diagonally, like two conventional shoulder belts, or running vertically down the torso and linking with the lap portion of the belt. Figure 57 later in this section shows this latter type of four-point harness.

- **Five-point/Harness:**
  - A five-point harness would also include a crotch strap pulling any lap portion of the restraint down and preventing it from riding up onto the abdomen of the occupant. Six point harnesses are also currently available and are used in motorsport.
Most belt types are available as either static or retractable systems, although static systems are far more common for harness restraints. In a retractable system the belt is free to spool out and retract with the occupants motion until the mechanism is shaken (such as in an accident), or in certain systems until the belt begins to retract, upon which, the belt is caused to lock. In static systems the belts will be a set length of webbing adjusted manually by the occupant for a tight and correct fit. These systems, once adjusted, remain at a fixed position regardless of operator or vehicle motion.

7.2 VEHICLE TYPES

_Staff transport:_

- For transporting staff around a quarry ‘off-road’ passenger vehicles may be suitable. These vehicles would be expected to come fitted with three-point seatbelts as standard. Typical journeys undertaken using such transport might include:
  - Taking operators to their vehicles in the morning. For these journeys, passengers could be wearing full protective clothing and in winter, additional warm clothing
  - Making inspection visits. These journeys may be interrupted by frequent stops to get out and look at work in progress. This would have the effect of breaking one long tour into many very short journeys

_Utility vehicle:_

- Road vehicles, such as vans and trucks, are often on site. These vehicles are often driven by contractors that fix equipment and they can also be used for transporting staff, equipment or smaller quantities of produce

_Dumpers – large load-carrying trucks:_

- Used to carry large quantities of quarry produce. These may either be rigid or articulated. At the collection and delivery points, these trucks may be required to negotiate rough terrain or potentially hazardous ground

_Loaders (wheeled or tracked loaders and earth movers)_

- As it is assumed that such vehicles will reside at the quarry face for most of the time, these vehicles are expected to be exposed most of all quarry vehicles, to uneven, rough terrain and hazardous working conditions

_Dozers_

- Used to construct tips, level out areas and build edge protection. These vehicles are often used on inclines where it is not possible for other vehicles to work

7.3 METHODOLOGY

The project is not only focusing on the performance of a number of restraint designs. The aim was also to carry out a practical review of restraints in order to assess the feasibility of fitting these systems into the existing vehicle designs. The study investigated limitations on where the restraint can be tethered within the confines of the vehicle, and in what accident scenarios different restraint types are appropriate.

Following the assessment of the safety performance of the restraints, a review was carried out to address best practice issues and limitations that may be encountered when attempting to fit these systems into existing vehicle designs. This review also considered the approaches that may be adopted to overcome these problems.
The location of the attachments for the restraints can have an influence on the safety performance of the restraint and the occupant kinematics and hence such fitting details were considered.

The study has been conducted in two stages, as listed below:

- **Literature review** – This part of the study was aimed at collecting information on different restraint types and their effectiveness in various impact conditions
- **Consultation with industry** – This part of the study involved visiting operational quarries and experiencing the operating conditions and talking with the drivers to get a view of what types of restraint are practical for everyday use. The visits also allowed vehicles to be inspected to evaluate anchorage attachment positions, both current and possible locations

### 7.4 LITERATURE REVIEW OF RESTRAINT TYPES AND EFFECTIVENESS

A brief summary of each of the papers reviewed, regarding restraint types and their effectiveness, can be found in Appendix E. The main findings from this review are collated in the following section.

#### 7.4.1 Summary of literature review findings

- Failure of drivers to use seatbelts was identified as a cause of serious injuries in rollover accidents or collisions with other vehicles or objects
- Some form of restraint is required to reduce the likelihood of occupant ejection in rollover accidents
- Three-point belts may offer a greater level of protection to an occupant in rollover accident situations than a two-point belt. This is as a result of controlling the upper body motion and excursion during the rollover. Several authors commented on the directional limitations of lap diagonal belts in rollover and an increased risk of neck injury, supporting the results from the modelling carried out in this project
- Several authors concluded that a four-point harness would offer a greater level of protection to an occupant in rollover accident situations than a three-point belt. This was considered likely to be a result of offering the same level of torso restraint for left and right sided rollovers. This also supports the findings of the numerical simulation, reported in Section 5. One author compared different types of four-point harness and showed that the protection offered could differ between different designs
- For improved effectiveness, lower anchorage points for belt systems should be mounted to the seat as opposed to the cab structures. Examples of three and four-point seatbelts, integrated with the seat are shown in Figure 54 and Figure 55
  - Lap belt anchorage points should be positioned at a steep angle to the hip of the occupant to limit occupant excursion. This is also a requirement of the ISO (ISO, 1990), Australian (Standards Australia, 1983) and SAE (SAE, 1997) earth-moving or off-road vehicle seatbelt standards. Details of the requirements contained in each of these standards can be found in Appendix A, together with diagrams showing the areas allowed for anchorage points
  - Whilst the Australian seatbelt standard and SAE Information Report J292 include an upper torso anchorage requirement (see Figure 64, Appendix A), the range of acceptable angles for mounting this anchorage (with respect to the shoulder of the occupant) is quite large. For rollover protection, the upper
anchorage should be positioned close to the shoulder and at a shallow angle to limit vertical excursion of the occupant

- The amount of slack in a belt system is critically important to the effectiveness of the restraint. This has been demonstrated in both frontal and rollover accident simulations

- Retractor belts may not be suitable in all quarry vehicles
  
  o Due to the sensing mechanisms used to lock the reel, retractor belts may not lock, or lock quickly enough, to offer full protection to the occupant. For example, retractors that lock based on the feed out of the webbing may not lock, particularly if fitted to a lap belt only because this would require the pelvis to be accelerated out of the seat with an acceleration of 0.8g

  o Locking retractor belts if fitted with a vehicle sensitive locking mechanism may also lock when driving over rough terrain. This may become irritating, uncomfortable or even injurious for the occupant

- By reducing the slack inherent in a belt system and drawing the occupant into the seat, away from upper contact surfaces pre-tensioning, as currently used in passenger cars, can increase the effectiveness of belt restraint systems

- The application of a pre-tensioner triggered in a rollover crash might offset the use of belt comfort features that allowed a degree of slack for the occupant

- Belt load limitation may reduce the risk of injury from a belt restraint system. However, an increase in excursion may result. To prevent injurious contacts with the vehicle interior, belt load limiting should be accompanied with consideration of using other restraint technologies as well, such as belt pre-tensioning and the potential use of airbags. Airbag use in quarry vehicles may be appropriate and should be evaluated further before adoption of this technology

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**Figure 54** Three-point seatbelt mounted to seat structure (TEK seating)  
**Figure 55** Four point seat belt (harness) mounted to seat structure (TEK seating)

### 7.5 CONSULTATION WITH INDUSTRY

An important source of information regarding restraint systems was from the operators of the vehicles. The operators were able to describe the practicalities of using them ‘day in, day out,’
and situations where they have found particular restraints beneficial or a hindrance. To gain this information visits were made to working quarries to speak with the operators, as follows:

1) **Torr Quarry, East Cranmore** – The quarry had a range of vehicles including large rigid dumpers, articulated dumpers, wheel loaders and bulldozers. The produce of the quarry was aggregate for roads etc.

2) **Aggregate Industries, Cornwall** (Blackpool Sand Plant, Melbur Quarry and Little Johns Quarry.) – The operators at the quarries drove wheel loaders, articulated dumpers and rigid dumpers.

The visits to quarries enabled TRL researchers to gain experience of the type of operations undertaken in quarries and the practical problems experienced by operators. However, the quarries visited do not necessarily constitute a representative sample of all those in the UK and the number of drivers spoken to were relatively small. This cannot, therefore, be considered a scientific survey of the views of quarry operators or managers and is intended only to flag potential issues and difficulties associated with restraint use that might need further investigation.

It was found during the visits that there was a range of opinions of restraint needs/usage and it often depended on the age and experience of the operator. A number of the older drivers who have tried all the restraint types often complained that they were restricted whilst using a harness and that lap belts were cumbersome and often impractical. The younger drivers were more positive toward harness systems, but did stress that it depends on the job being done. If it is just a standard drive and tip job then with the introduction of reversing cameras and good wing mirrors there was little need to move about the cab and hence a harness would not be too restrictive. The degree of movement required does depend on the operating environment. In the china clay pits the vehicle’s mirrors often became covered in mud and restricted the driver’s view, so they often had to lean out the window. In this situation the operators often said that harnesses were restrictive and were often not worn as a result.

An example of where a harness and even the lap belt proved impractical was experienced whilst on one of the visits. Figure 56 is a picture of a bulldozer working on an embankment. To operate the machine on such a surface required the driver to constantly turn around in his seat. In such a situation the operator mentioned that a lap belt at most, was all that was practical whilst operating in that manner. The operator also went on to say that often the seatbelt is not used because when operating on a slope the operator often sat on the arms of the chair to keep himself level. In this situation the lap belt dien dug in and was uncomfortable due to the irregular seating position.

The main concern that was evident from most of the drivers was to do with the ease of use whilst wearing protective clothing. A number of the drivers were larger than average and when they were wearing warm clothing, jacket, gloves, etc. it became very difficult to operate even a lap belt and as a result, they often went without. This problem was also reported during for trips made around the sites in ‘off-road’ passenger vehicles. Even the standard three-point belts were not always long enough to fit a larger person with full, warm, protective clothing on.

It is surprising that quarry vehicle seatbelts are not large enough to fit a number of the drivers, because the requirement in the ISO (ISO, 1990) and SAE (SAE, 1997) standards is that the restraint fits over an arctic clothed 95th percentile male. However, if there is a genuine need for larger restraints, then maybe the requirement in the standards needs to be increased, for instance, to the 99th percentile male.
Often in the harsh environment of a quarry the ride gets exceptionally rough and a number of the operators complained of severe rubbing of the restraint. This was particularly evident with a harness type restraint since it was constantly preventing the upper body from moving with the motion of the vehicle. The operators also stated that the locking of the belt on rough terrain also occurred with lap belts and operators often have to take off the belt and then put it back on to reset the retractor. With the motion of the vehicle and the locking of the restraints, some of the operators and managers claimed that there has been an increase in the occurrence of bad backs. The quarry manager questioned if the costs associated with an increase in back injury, due to harness use, would be more expensive to the industry, in the long term, than the occasional fatal accident. He also asked whether it was fair to put the driver at risk of potentially career threatening injuries, such as a severe bad back. This appears to be an issue of some concern to the industry and one that may be worthy of further investigation before harness type restraints are introduced.

In order to more objectively assess whether the issue of restraints causing back injury in ordinary operation is a genuine concern, a monitoring study could be implemented. The severity of loading to the operator in a vehicle during normal use could be measured by means of fitting in-service vehicles with instrumentation and measuring items such as seatbelt load, vehicle acceleration, seat acceleration, vehicle roll, etc. These conditions can then be used to evaluate the risk of injury to the operator from wearing appropriate or inappropriate restraints. They could also be used to specify requirements (conditions that must be considered) for new restraint designs.

The risk of bad backs and lack of comfort are obviously important to the small number of operators consulted and all have said that they believe that the actual belt design could be improved to address these issues. The operators state that restraints currently fitted to in-service vehicles tend to be retrofitted to the vehicle and often do not interact well with the wide range of vehicle setups available. Operators mentioned that the current designs are difficult to adjust and as a result, harnesses are often worn incorrectly adjusted. There are many issues with the way the belts work and are adjusted. The current designs used in one of the particular quarries visited involve the manual adjustment of the shoulder straps and the lap portion of the belt, as shown in Figure 57. The manual adjustment of the straps takes time and the drivers say that if they have just jumped into the cab the last thing they want to do, is waste time adjusting the restraint. In general they believed that in quarries where one person uses the same vehicle all
day, every day, this would not be an issue. However, in a number of the quarries visited, operators sometimes used two or three different vehicles each day and would often not bother adjusting the restraint correctly or even wearing it at all. The buckles on the restraint also often became difficult to move due to a build up of mud and dust; this again caused the operator not to use it correctly.

A couple of the drivers consulted, mentioned that under heavy braking the belt had dug into their abdomen. It is possible that this was a feature of the specific harness restraint design used by those operators, where the lap belt may be able to ride up over the abdomen of the operator and therefore, potentially cause injury. The drivers suggested that this could be avoided by having a 5-point belt instead. This is a potential design feature that is used in motorsport harnesses and could be added to harness restraints for large quarry vehicles.

Another example of operators citing situations where they do not use belts because of the time taken to fit them is the use of inspection vehicles where frequent stops are made and the operator is expected to have to get out and back into the vehicle. Typically, ‘off-road’ passenger vehicles may be used for this purpose. Even with the conventional three-point retractor belts, which are not very time consuming to put on and take off, operators still expressed that they would often not bother to wear the belt in order to save time. If the subsequent journey is very short, over even ground, free from obstacles, then this decision may appear to them to be justifiable. However, it is suggested that the potential benefits of wearing a restraint over not wearing a restraint more than make up for the time taken to put a belt on.

The accessibility of the restraint is also cited as a major problem. As highlighted above, drivers often wear gloves and so cannot get to a belt easily. It was the case in most of the vehicles seen during the visits that the anchorages were located low down on the seat and often tucked under an armrest. As a result they were difficult to operate if they had to be taken on and off frequently, so as a result restraints were often not used to avoid these impracticalities. Figure 58 is a picture of the lap belt retractor reel location in a bulldozer. The armrest interferes with the accessibility of the lap belt making it difficult to use. However, having inspected the vehicle, it is difficult to see how the anchorage location could be changed because there was limited space around the seat.

The comment about the difficulty in accessing a restraint whilst wearing gloves is interesting because the ISO and SAE standards both include a requirement that the operator must be able to fasten a buckle with a mittened hand. This raises the issue as to whether the standards are being met and whether this requirement is being enforced. This problem appears to be genuine and
could be investigated more objectively to determine how widespread this accessibility problem is and whether a review of the requirement in the standards may be necessary.

![Image of retractor reel]

**Figure 58 Location of retractor reel**

The restraints also have to be resilient to the dusty environment in which they operate; the lap belt in the figure above was not able to retract due to dust in the retractor. There is a maintenance policy on seatbelts operated by the quarry, but operators claim that maintenance cannot be carried out too regularly because the vehicle would be out of operation for too long.

The problem of seatbelt anchorage positions may require clever and innovative design, because it is largely vehicle dependent. In the example of the bulldozer retractor reel shown in Figure 58 there is very little space between the seat and the vehicle structure, so any seatbelt anchorage would be difficult to get to. On the larger more spacious cabs this problem does not occur and there is little difficulty in accessing the seatbelt. A few of the seatbelts had two-point, aeroplane-type belts (as shown in Figure 59), which meant that the user did not have to always reach down to the retractor to pull on the belt. This may mean that it is easier to put on the belt if it has been left on the seat, but if it falls down the sides of the seat, then similar problems may occur as found with a retractor belt. Figure 59 also shows that on this type of vehicle the seat is not located so close to the vehicle structure, so even if the standard retractor type belt was fitted to the vehicle, then it would still be accessible.
From the consultations with the operators and experiencing the ride in the vehicles, it appears impractical to mount the anchorages to the floor or vehicle structure. This is due to the motion of the vehicles and the driver whilst in operation. If a restraint is mounted to the rigid vehicle structure then the retractor reel would have to be tuned to allow for the motion of the air sprung seat and not lock up if the driver goes over rugged terrain. In practice it has been found that reels lock during standard operation, when seat mounted, so the problem would be worse and possibly cause injury if mounted to the vehicle structure.

There are situations with tracked vehicles, such as the bulldozer, where there is not such a rough ride as the articulated or rigid vehicles, where the restraint could possibly be mounted to the vehicle structure if this would help with some of the issues identified above in this report.

7.6 DISCUSSION
A summary of the benefits and disadvantages of the various restraint types for different impact configurations is given in Table 16. To summarise this:

**No restraint:**
- Having no restraint or not wearing a restraint offers no protection in the event of an accident

**Lap belt only (two-point belt):**
- A lap belt will reduce the level of excursion of an occupant in both frontal and rollover accidents and may prevent ejection from the vehicle. However, the torso is unrestrained and therefore the head and chest may still make contact with interior surfaces of the vehicle cab

**Three-point belt**
- A three-point belt should offer decreased head and chest excursions over a two-point belt in frontal crashes and rollovers that result in the occupant turning into the shoulder portion of the restraint
**Four-point/Harness:**

- A four-point harness should offer at least the protection of a three-point belt, but in addition should be effective in rollovers in both lateral directions

**Table 16 Summary of restraint advantages and disadvantages**

<table>
<thead>
<tr>
<th>Accident Type</th>
<th>Restraint</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rollover</td>
<td>No restraint</td>
<td>-</td>
<td>Concentrated loading through single belt</td>
</tr>
<tr>
<td></td>
<td>Lap belt</td>
<td>Reduced risk of ejection over ‘no restraint’</td>
<td>Large movement of upper torso still possible, Possibility of belt riding up and causing abdominal injury</td>
</tr>
<tr>
<td></td>
<td>three-point belt</td>
<td>Constraint of torso when rolling into shoulder belt</td>
<td>Risk of neck injury from interaction with shoulder belt Only effective when rolling into the belt</td>
</tr>
<tr>
<td></td>
<td>Harness</td>
<td>Constraint of torso when rolling either way</td>
<td>The risk of neck injury from interaction with the shoulder belt should be decreased over the three-point belt.</td>
</tr>
<tr>
<td>Frontal</td>
<td>No restraint</td>
<td>-</td>
<td>Concentrated loading – belt force is only distributed though a single belt Lap belt may ride up onto abdomen</td>
</tr>
<tr>
<td></td>
<td>Lap belt</td>
<td>Pelvis restrained</td>
<td>Lap belt portion may ride up onto abdomen</td>
</tr>
<tr>
<td></td>
<td>three-point belt</td>
<td>Pelvis and torso restrained Excursion of head and chest limited further</td>
<td>Poor geometry may cause concentrated loading Lap belt may ride up onto abdomen in four-point systems</td>
</tr>
<tr>
<td></td>
<td>Harness</td>
<td>Potential for belt forces to be distributed better than with other belt systems</td>
<td></td>
</tr>
<tr>
<td>Rear impact</td>
<td>Lap belt</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>three-point belt</td>
<td>Torso controlled during rebound phase Occupant may sit closer to seat back and head restraint, initially</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harness</td>
<td>As three-point belt Occupant may sit closer to seat back and head restraint, initially</td>
<td></td>
</tr>
</tbody>
</table>

Limitation of the applicability of these restraint systems in quarry vehicles is closely linked with the type of actions the operator needs to perform whilst driving the vehicle:

**Utility vehicles:**

- In most cases drivers need only perform tasks as would be expected of a passenger car driver. Therefore a three-point restraint (as would be expected as standard in such a vehicle) should not be too cumbersome

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• For trips made whilst wearing full, protective and warm clothing, operators suggested that standard belts may not be large enough. In these circumstances, alternatives should be sought and provided.

• For inspection vehicles, making frequent stops, for the operator to get out and back in, then mandatory wearing of a seatbelt may annoy the driver. However, this should not justify the decision of a driver not to wear a restraint.

**Dumpers and fast-moving wheeled loaders:**

• Good visibility is essential for operators of this type of vehicles and is required by an HSE sector information minute. If the required field of view is provided by cameras and well-sited large mirrors then the operator may not need to move around in the seat very much. In such vehicles a three-point or four-point restraint should not be too restrictive.

• Where the field of view requirements can be met with direct vision only, or where additional viewing systems are poorly sited in relation to the driver, the operator will need to be able to look all around the vehicle, requiring a relatively large amount of upper body motion. This has been cited as a reason for not wearing restraints at all, particularly more restrictive shoulder or harness restraints.

• Operators highlighted a perceived issue with the use of locking retractor belts while driving on rough terrain, where there was a concern that they would lock and apply load to the operator, thus causing injury.

**Tracked vehicles (or slow-moving wheeled vehicles):**

• In tracked vehicles, the main issue highlighted by operators was the need to adopt unusual seating positions, particularly when traversing relatively steep slopes.

In addition to these specific issues, the operators raised a few general concerns such as the belts riding up around their abdomen, the size of the restraint, the access to buckles, dirty and malfunctioning restraints and rubbing of the webbing against them.

Observation of the small number of operators studied performing their duties did suggest that many of these concerns were genuine. However, even within such a small group there was a diverse range of opinion and it was apparent that younger operators tended to be more positive about the use of restraints than older operators.

The fact that some operators have highlighted concerns with restraints in general and specifically harnesses merits further investigation but should not preclude implementing them. There are currently no standards governing the design of upper body restraints so it is possible that many problems could be solved by the use of improved belt geometries, mechanisms and materials.

The principles of good restraint design are well established in the passenger car industry and the state of the art in restraint and occupant protection in that industry is far higher than for earth-moving machinery. Although the use of machinery does present some specific problems unlikely to be encountered in passenger cars, a number of problems could be solved with innovative application of technology already used elsewhere.

For example, operators have complained of locking retractor belts being activated on rough terrain. This can be tackled in many ways. Most seats in earth-moving machinery are suspended. The effectiveness of such suspension will depend on the spring rate and damping of
the seat in relation to the occupants mass. In order to be effective the suspension must be tuned to the mass of the operator. This adjustment could, if not already, be fitted as standard allowing the operator to adjust the seat to tune out much of the vibration. In passenger cars, there are many examples where the car monitors seat adjustment for different individuals and stores settings in a memory such that when a driver enters they simply enter their ID and the seat adjusts automatically. Furthermore, the use of sensors that are relatively common could allow this optimisation to be carried out fully automatically such that the settings adjust according to the characteristics of whoever is in the seat and the terrain the vehicle is travelling on. This could have the additional benefit of reducing the overall exposure of the operator to noise vibration and harshness (NVH).

An alternative approach would be to consider alternative methods of locking retractor belts in the event of a collision. In cars, airbags are triggered by a simple accelerometer. It would be possible to use such a sensor to trigger the locking mechanism in the event of a forward collision while reducing its sensitivity to vertical vibration. Sensors have been developed for the detection of rollover in HGVs by measuring the individual wheel load on an axle. Similar sensors could be easily adapted to trigger belt locking in the event of rollover.

A third approach would be to permit relatively loose fitting belts to be worn and then use a pre-tensioner system, virtually standard in today’s cars, to tighten the restraints in the event of a collision or a rollover. These systems could also be combined with airbags, either fitted in the seat or to the vehicle structure.

These ideas are just examples of possible solutions to problems but they illustrate the point that the operational difficulties need not prevent implementation of improved restraints. Many of the possible solutions that could be drawn from other industries may need adaptation to be suitable for use in Earth-moving Machines but there are no obvious technical reasons why all of the difficulties could not be solved, given sufficient incentive.

7.7 RECOMMENDATIONS

Based on the functional advantages of the restraint systems and the limitations imposed on the systems by the users, to make them acceptable, the following restraints are recommended:

- Where possible, the best level of restraint that can be offered should be employed. For slow-moving, tracked vehicles a four-point harness is encouraged strongly.

- Because of the nature of the environment that such vehicles may operate in, existing retractor belts may not be suitable: Firstly, the slow rate expected with rollover accidents may not lock the retractor mechanism or not lock it quickly enough to protect the operator. Secondly, the ride may cause them to irritate the operator and thirdly, they may be susceptible to failure through dirt ingestion, if they are not readily and frequently serviced and well-maintained. Where existing retractor belt technologies are not considered suitable, the development of alternative locking systems that are suitable for quarry vehicles should be investigated. These potential improved retractor mechanisms may make use of better accident detection. It is believed that through use of existing seat vibration damping and development of current restraint technologies, then it should be possible to design a restraint system that works efficiently with retractor belts.

- Restraint systems in vehicles to be used on rough terrain, where possible, should be mounted on the seat structure rather than the vehicle interior. This should optimise restraint efficacy and minimise conflict with the operator and the seat bouncing up and down. It is recommended that the conditions experienced in quarry vehicles, during normal use, be evaluated quantitatively. This evaluation could then lead towards design of more appropriate restraints.
• If suitable pre-tensioner systems are available, that can be triggered by a rollover event, then they should be adopted as they should offer increased restraint performance

• Airbags and load limited systems, where integrated with belt restraints, may also offer increased occupant protection benefits

• Rigid restraints, while offering a mechanism to fit interlocks to ensure that they are worn during machinery operation, should not be adopted unless the level of protection they offer the occupant is shown to be equal or in excess of the belt-based restraint options that are also available for that application

• For load transporting/delivering (‘drive and tip’) vehicles, shoulder portions of three or four-point belts may be too inhibiting for the driver, based on existing restraint designs. If they are not too inhibiting then they should be fitted and used. However, where they are unsuitable, some alternative restraint solution must be provided and should be worn at all times. If an existing retractor belt is suitable then these may be used, otherwise a manual fastening belt or improved retractor belt design may be needed

• For staff transportation, then where possible, the standard restraints should be worn. If the fit of these belts is inadequate, then an alternative restraint system should be provided. Where frequent stops and short journeys are made, then the restraint should be quick and easy to put on and adjust, in order to minimise the inconvenience to the operator

7.8 CONCLUSIONS

• Three, four or five point restraint systems would offer increased protection to the operator in an accident if the use of the vehicle does not preclude the wearing of such restraints. Where possible and appropriate, four or five-point harnesses should be used in tracked vehicles and slow-moving wheeled vehicles. Restraints for ‘drive and tip’ vehicles and fast-moving wheeled loaders should be at least two-point

• Improvement in the functional design of harness-type restraints using existing technology from other types of vehicles could increase the user rate

• No reduction should be made in the restraint provided as standard in ‘off-road’ passenger vehicles, vans, lorries and trucks
8 DISCUSSION

The review of standards found that there were no standards that required the fitment of a restraint system other than a lap belt. The SAE Information Report (SAE J2292) and Australian Standard (AS 2664:1983) contained information on the requirements for torso restraint anchorages, which was not present in any of the other standards that were reviewed. In New Zealand, the requirement to fit seatbelts is dependant upon risk of rollover, and the South African code of practice does not include information about seatbelts. Under the Quarries Regulation (1999) it is the responsibility of the quarry operators to specify safety requirements. Through consultation with industry, examples of in-house standards specified that seatbelts must be worn, but there was no specification for the type of belt. Consultation with industry also highlighted that some operators are considering fitting harnesses to vehicles and are currently running trials.

The numerical modelling assessed the effectiveness of a number of different restraint systems. The lap belt reduced the severity of injury predictions and controlled the excursion of the occupant over the unbelted condition. Systems that restrained the torso reduced the risk of contact with the interior of the cab and the items identified in the risk assessment for both the 50th and 95th percentile models. However, the effectiveness of the three-point lap-diagonal belt was shown to be dependant on the direction of roll for lateral rollover. The three-point belt also had a tendency to become wrapped around the neck when the occupant was rolled towards the diagonal part of the system. The different restraint systems were shown to have similar effectiveness in the different vehicle types assessed.

The analysis of accident data predicted that some fatal accidents may have been reduced in severity by fitting a harness-type restraint system. The modelling showed that the harness was generally effective at reducing the risk of injury in all of the accident conditions considered. However, sometimes the loading to the chest was increased over that predicted for the lap belt, but these remained within the dummy performance limit of 50 mm for chest compression.

The 95th percentile occupant behaved in a similar manner to the 50th percentile. However, because of the additional height and mass for the 95th percentile occupant, contact was made with structures that the 50th percentile did not reach. Although the injury predictions for the 95th percentile were similar to those of the 50th percentile, the 95th percentile was considered to be at greater risk from the items identified in the risk assessment.

The effectiveness of a restraint system is partially dependant upon how the motion of the occupant is controlled throughout the impact. If the torso is not controlled sufficiently there is increased potential for the occupant to make contact with interior fixtures such as grab handles and levers as identified in the risk assessment (Section 6). An alternative to restraining the torso could be to ensure there are design requirements for the interior of the cab. These could include minimum radii and maximum stiffness for parts and/or exclusion zones where particular items cannot be positioned. However, the chaotic nature of the accidents considered here may result in design requirements and exclusion zones that are less practical than wearing a torso restraint. Ideally, improved restraints would be combined with occupant friendly design to maximise the protection offered.

The risk assessment identified that there are a variety of different cab designs. However a number of features such as grab handles, fire extinguishers and levers were present in most cabs. Some of the cabs studied presented a lower risk to the operator than others as a result of the placement of features. No specific safety guidelines for cab design of the vehicles studied was identified. If there are no current guidelines, a code of practice for designing cabs may reduce the risk of injury in both serious and minor accidents.
It is also important to ensure that there is sufficient survival space within the cab. The majority of accidents studied involved vehicles that were fitted with ROPS, the integrity of which was maintained in the impacts. It is worth considering, however, that the ROPS standards allow a survival space based upon a seated arctic clothed 95th percentile and that theoretically, an out of position occupant, such as one wearing a lap belt, may be at higher risk from intrusion than one wearing a harness.

The modelling showed that overall, the harness provided the most effective restraint of the torso over the three-point lap-diagonal belt. The harness would also prevent the occupant impacting a number of the hazards identified during the risk assessment of the cab designs.

One of the main concerns about the fitment of harnesses to earth-moving machinery is the acceptance and use by the vehicle operator. The consultation with vehicle operators that have used both lap belts and harnesses indicated that the acceptance of a restraint system was very dependant on the type of work being carried out and the other types of equipment (mirrors, cameras etc.) fitted to the vehicle. There were also differences in the perception of risk from operators of different ages, with younger operators more willing to try new ideas. Specific issues raised by operators that are likely to need to be resolved before widespread implementation of harness restraints can be achieved include:

- Use on rough terrain may cause retractors to lock and apply loads through the spine and abrasion in the belt areas which cause discomfort and potentially injury
- Use where large occupant movement is required, for example close manoeuvring or traversing a slope where the occupant may sit on the arm of the seat in order to be vertically seated
- Size of belts and use of fastening mechanisms for large winter clothed operators

It is likely that most of these issues can be resolved through improved design of vehicles, seats and restraints but further, more objective, investigation of the issues will be required.
9 CONCLUSIONS

A study of the performance of seatbelts in selected quarry vehicle incidents has been completed. This work included numerical simulation and full scale rollover testing under controlled conditions. Analysis of standards, accidents and restraint systems, as well as risk assessments and consultation with operators have been combined to conclude that:

1. Current standards require the fitment of lap belts only. However, there is guidance published by the SAE for the design of combined pelvic and upper torso restraints. It is also known that at least a small number of quarry operators do use harness restraints.

2. Accident analysis based on US data suggests that ensuring all operators wear at least a lap belt remains the most effective safety measure but that further improvements in protection should be possible because several fatalities have occurred in vehicles where the ROPS maintained its integrity and a lap belt was being worn. It is important to consider the safety guidance for brake testing, edge protection and end tipping that has been adopted in the UK that may prevent a large number of the accidents considered in this study.

3. Restraining the torso and distributing the loads applied by the restraint system can reduce the severity of injuries sustained, particularly for the end tipping scenario. This was demonstrated for both the three-point lap-diagonal belt and the harness in various conditions. The harness was shown to be more effective because the effectiveness of the three-point lap-diagonal belt was dependant on the direction rolled and it also showed an increase tendency to wrap around the neck.

4. Several practical and operational difficulties associated with the use of restraints have been highlighted and these may offset the accident benefits because operator discomfort and inconvenience may reduce the wearing rate and it is possible that the restraint could actually cause some injuries in some day to day operations. It is likely that many of these problems could be avoided by improved design of vehicles, seats and restraints. Compromise situations would be possible where requirements for an improved restraint depended on the type of vehicle and the operation being carried out.

5. It was found that cab interior design was typically not occupant friendly and that hostile structures (e.g. small radius steel handles) were frequently located in areas that critical body regions such as the head are likely to collide with during a rollover or frontal collision. Improvement in occupant protection could be achieved through improved design (e.g. moving hostile structures or making them softer or less “sharp”) and ideally this would be combined with improved restraint to reduce the size of the envelope into which the head could move during a collision.
10 RECOMMENDATIONS

- This research has identified a potential issue with retractor mechanisms used in lap belts, where sometimes during slow speed rollovers they do not lock. This should be further investigated to ensure that current lap belts are working effectively. This may lead to alternative retractor designs based on sensors. SAE guidance acknowledges that retractors should be sensitive to vehicle motion and should lock during a rollover. However, the guidance also states that the retractors should also provide comfort in rough riding conditions.

- Restraint of the torso, particularly with a harness type restraint, has been shown to provide additional benefits over the current lap belts. It is recommended that wider implementation of more comprehensive restraint systems be encouraged in particular operating conditions. However, before full implementation throughout the industry there are a number of issues that need to be addressed:
  - There are currently no standards, only guidance, governing the design of harness type restraints in quarry vehicles. This allows the possibilities for inappropriate designs to be used. A specification covering the main features of an effective restraint should be developed.
  - It is claimed that harness restraints can cause operator discomfort or lead to injuries during ordinary operation. This should be investigated in order to quantify this risk, identify causes and propose solutions.
  - The range of movement required by operators to perform daily tasks should be quantified to allow appropriate design solutions to be developed to ensure the restraint can be worn without compromising the operators’ ability to work efficiently and safely.

- In comparison to passenger cars, cab designs were found to be relatively hostile environments during an impact. It is recommended that manufacturers should be encouraged to consider occupant protection when designing cab interiors. Measures should include considering positioning of features, materials used and radius of any corners or edges.

- Many of the safety issues identified in this research had previously existed in car design. However many of these have since been overcome, particularly by changing the design of restraint systems and vehicle structures. It may be possible to transfer some of the methods used in the car industry to improve the safety of earth-moving machinery in quarries.
APPENDIX A REVIEW OF LITERATURE AND STANDARDS RELATING TO SEATBELTS

A.1 LITERATURE RELATING TO OCCUPANT RESTRAINT IN OFF ROAD MACHINERY

Appel et al (1984) assessed methods of protecting occupants of earth-moving machines (EMMs) in off-road rollover accidents. This paper refers to work which found that 8% of all German accidents involving EMMs involved rollover. The paper also refers to American research which highlighted the potential benefits of rollover protective structures (ROPS) and seatbelts. The work which forms the main focus of the Appel paper involved laboratory tests to develop a performance specification for restraint systems (seatbelts and anchorages), assess the effectiveness of current restraint systems (current in 1984) and to improve and develop those systems to provide optimal driver protection and comfort. A range of laboratory tests were conducted to quantify the restraint system requirements.

To summarise, it was found that the ISO 6683 (1981) (see Section A3) requirements for a static seatbelt load of 15,000 N should be sufficient to cope with any foreseeable situation. The "worst case" scenario discussed involved a 360 degree rollover on firm soil. The restraint system effectiveness was found to be optimised when a lap belt was used in combination with upper body (shoulder) supports, which help to prevent lateral displacement of the upper body and excessive bending of the cervical spine. Armrests were also found to be beneficial in preventing lateral displacement of the pelvis. Adjustable armrests and shoulder supports allow the operator to move freely in normal driving, but act to prevent excessive movement, and consequent risk of injury from contact with hard/sharp objects within the cab, in the event of a rollover. The paper does not give any indication of current or likely belt wearing rates amongst EMM users, or estimate the likely injury reduction effects of their increased use.

Tomas et al (1996) created a MADYMO model of a dozer, equipped with ROPS, being subjected to a lateral rollover test. The model showed that an unrestrained occupant was likely to be ejected from the machine and crushed under it as it rolled. When the model was run with a restrained occupant (lap belt), the occupant remained within the cab. This was also the case when the simulation was repeated with a three-point lap and diagonal seatbelt. The authors point out the difficulties of inertia reel belts, which they claim are unlikely to lock early enough in the impact to prevent the operator from being displaced from the seat in a slow rollover. The authors conclude that operator adjustable belts would be the most effective option. They go on to state their opinion that optimum protection in a rollover would be provided by a tightly adjusted four-point racing harness because they will prevent the occupant sliding out of the belt, but give no test data or information on the ergonomic/practical implications of such systems.

Robinson et al (1996) studied the provision of seatbelts in agricultural vehicles. This involved the ergonomic assessment of four seatbelt conditions:

- No belt fitted
- Static lap belt
- Retractable lap belt
- Retractable lap belt and arm-rests

The trials involved the driver mounting and dismounting the vehicle five times interspersed with simulated driving tasks. The research showed that the use of seatbelts increased the time to get on and off the tractor. The retractable belt could be unfastened faster than the static belt although the differences were not significant. The armrests had no detrimental effect on the time to manipulate the retractable lap belt.
Edwards and Neale (2000) assessed the effectiveness of lap belts in agricultural tractor rollovers. The research involved numerical simulation of forwards and sideways overturns with belted and unbelted occupants. The 90 degree sideways overturn model was validated by a full scale vehicle test. The modelling showed that the majority of injury criteria for the head and neck were reduced for the belted occupant and were below the thresholds to indicate risk of serious injury.

With the standards that have been identified, all specify a minimum requirement of a two point lap belt. However, there are a number of types of restraint available for earth-moving machines including:

- Two point lap belts
- Three-point lap-diagonal belts
- Harnesses

The lap belts are generally more accepted by vehicle operators because they do not restrict movement as much as the full harnesses, allowing the operator to turn in their seat to look behind the vehicle whilst moving.

One possible solution to this is to use full harnesses that are fitted with inertia locking retractors to allow the operator to move easily while performing their work tasks. Figure 60 shows an example of a seat fitted with a full harness and inertia reels distributed by Spillard Safety Systems.

![Figure 60 Example of seat with full harness incorporating inertia locking retractors](image)

### A.2 REGULATIONS STATING REQUIREMENTS FOR USE OF RESTRAINTS IN OFF-ROAD WORK MACHINES

The following regulations contain requirements relating to the safe use of vehicles in quarries and other work environments.
A.2.1 Quarries Regulations 1999

The following is an extract from the Quarries Regulations (1999).

“Rules controlling risk from vehicles

The operator shall make suitable and sufficient rules (known in these Regulations as the "vehicles rules") which shall lay down in writing measures designed to control the risks to persons at the quarry arising from the use of vehicles at the quarry.”

The Approved Code of Practice (ACOP) for this regulation states that, “the rules need to cover fitting and use of safety devices, including seatbelts and visibility aids (PUWER regulations 17, 26, 28, paragraphs 352, 369, 370)”, (HSE, 1999)

Many of the quarry operators have documentation relating to the safe use of vehicles in quarrying operations. These documents include minimum specifications when purchasing vehicles and codes of practice relating to their use. Examples of these minimum specifications and codes of practice were obtained by consultation with industry and are shown below:

- “The number of passengers does not exceed the design specification for a given vehicle.”
- “Seatbelts are installed and worn by all occupants.”
- “Persons and unsecured material and equipment are not being transported together in the same compartment.”

These minimum specifications are defined by the operators and refer to generic seatbelts. There is no specific mention of the types of belt that should be fitted, which means that any type of belt can be fitted, from a non-adjustable lap belt to a full harness.

A.2.2 The Supply of Machinery (Safety) Regulations 1992

The Supply of Machinery (Safety) Regulations (1992) is the UK implementation of the EC Machinery Directive 98/37/EC. This Regulation applies to all relevant machinery, where “machinery” is defined as:

a) “an assembly of linked parts or components, at least one of which moves including, without prejudice to the generality of the foregoing, the appropriate actuators, control and power circuits, joined together for a specific application, in particular for the processing, treatment, moving or packaging of a material;”

b) “an assembly of machines, that is to say, an assembly of items of machinery as referred to in paragraph (a) above which, in order to achieve the same end, are arranged and controlled so that they function as an integral whole notwithstanding that the items of machinery may themselves be relevant machinery and accordingly severally required to comply with these Regulations;” or

c) “interchangeable equipment modifying the function of a machine which is supplied for the purpose of being assembled with an item of machinery as referred to in paragraph (a) above or with a series of different items of machinery or with a tractor by the operator himself save for any such equipment which is a spare part or tool.”

However, there are a large number of exclusions from the Regulations, including agricultural and forestry tractors and machines designed and constructed for police and military requirements.

Machinery first supplied after 1st January 1996 must comply with this Regulation, which requires that the machinery must satisfy the relevant essential health and safety requirements. The main health and safety requirement that is relevant to this review concerns the seating and an extract of the relevant section is shown below:
“3.2.2. Seating
The driving seat of any machinery must enable the driver to maintain a stable position and be
designed with due regard to ergonomic principles.
The seat must be designed to reduce vibrations transmitted to the driver to the lowest level that
can be reasonably achieved. The seat mountings must withstand all stresses to which they can
be subjected, notably in the event of rollover. Where there is no floor beneath the driver’s feet,
the driver must have footrests covered with a slip-resistant material.
Where machinery is fitted with provision for a rollover protection structure, the seat must be
equipped with a safety belt or equivalent device which keeps the driver in his seat without
restricting any movements necessary for driving or any movements caused by the suspension.”

This means that all vehicles supplied after 1st January 1996 that are able to have ROPS fitted,
must be fitted with a driver restraint system.

A.2.3 CFR30 part 57 - safety and health standards underground metal and non-
metal mines
Part 57 of the Code of Federal Regulations Title 30 states the minimum health and safety
requirements for metal and non-metal mines in the USA, including surface operations. Sub-part
M of the regulation relates to Machinery and equipment and the relevant requirements are
summarised in the following sub-sections.

Paragraph 57.14130 Rollover protective structures (ROPS) and seatbelts for
surface equipment
This part of the regulation states that the following vehicles must be fitted with ROPS,
conforming to either SAE J1040 or SAE J1194, and seatbelts:

• Crawler tractors and loaders
• Graders
• wheel loaders and tractors
• the tractor portion of semi-mounted scrapers, dumpers, water wagons, bottom-dump
  wagons, rear dump wagons and towed fifth-wheel attachments
• skid steer loaders
• agricultural tractors

The ROPS must be maintained so that it meets the performance requirements applicable to the
equipment in service.

Paragraph 57.14131 seatbelts for surface haulage trucks
This part of the regulation requires that seatbelts that meet SAE J386 shall be provided and
worn in haulage trucks.

A.2.4 Guidance to ensure safe use of large vehicles and earth-moving equipment
in quarries
This document is available to download from the Irish Health and Safety Authority website.
Section 1.4 outlines guidance for the use of seatbelts:

“Many injuries are the result of vehicles overturning. All drivers should therefore wear
appropriate seatbelts, preferably with a full harness, as should passengers when reasonably
practicable.”
A.2.5 Codes of Practice (CoP)

The following codes of practice have been identified:

- New Zealand – Approved Code of Practice for operator protective structures on self-propelled mobile mechanical plant (Department of Labour, 1999). This code of practice requires that a seatbelt must be fitted and worn if there is a risk of rollover or tip-over and a protective structure is fitted. The document contains guidance on assessing the type of protective structure that is required based on the risk of rollover. The seatbelt requirements are stated in the CoP.

- South Africa - guideline for the compilation of a mandatory code of practice on trackless mobile machinery (Mine Health and Safety Inspectorate, 2000). The guidelines include a section on requirements for fitting protective structures but there is no specific mention of seatbelts only personal protective equipment (PPE).

A.3 INTERNATIONAL STANDARDS FOR RESTRAINT SYSTEMS

There are two international standards that describe requirements for restraint systems for vehicles like those used in quarrying operations:

- SAE J386: Operator restraint system for off-road work machines
- ISO 6683: Earth-moving machinery – seatbelts and seatbelt anchorages (also a British standard)

The requirements of these standards are outlined in the following sections.


This is an international standard that applies to earth-moving machinery that is fitted with ROPS as specified in ISO 3471. This standard is also applied to specially designed forestry machines.

The standard specifies that the seatbelt system can be an adjustable assembly with or without a retractor. This implies that adjustment and retraction are optional and a non-adjusting static belt would still conform. There are specific requirements relating to the belt webbing, which must:

- Adjust in length for arctic clothed 5th and 95th percentile operators
- Have a minimum width of 46mm
- Whatever material is used must be as good as or better than untreated polyester fibre in terms of its resistance to:
  - Abrasion
  - Temperature
  - Mild acids
  - Alkalies
  - Mildew
  - Ageing
  - Moisture
  - Sunlight

Polyester fibre is defined within the standard.
It must be possible to release the buckle in a single motion with one hand that is wearing a mitten. The buckle must remain closed unless an intentional actuation force of 75±65N is applied to the buckle with a 670±45N force applied to the belt loop.

Anchorage points must allow the seatbelt assembly to be easily installed or replaced. Figure 61 shows the anchorage points (SIP, seat index point, is defined in ISO 5353). Where the seat does not swivel or have suspension, the belt assembly may be attached to either the seat or to the machine at any point within the hatched zones shown in the Figure. For other types of seat, the belt assembly must be attached to anchorages on the seat that are positioned near the rear of the seat within the hatched area so that the assembly moves with the seat at all times. Seatbelt assembly loads may be transferred from the seat anchorages to the machine by the use of belts, cables or other similar flexible devices.

![Figure 61 Seatbelt anchorage areas](image)

*See ISO 5353*

**Figure 61** Seatbelt anchorage areas

Any metallic components within the seatbelt assembly or anchorages must resist corrosion and not have sharp edges or corners.
The performance of the installed seatbelt assembly is assessed by loading the buckled system with a force of not less than 15kN for 10 seconds. The force is applied, typically using a canvas covered foam rubber block of specified dimension referred to as a “body block”, in a forward and upward direction at 60°±15° from the horizontal, with the line of force approximately passing through the SIP. When this force is applied the length of the seatbelt assembly must not increase by more than 20%. Permanent deformation of any seatbelt assembly component or anchorage is permitted. However, failure that allows the release of the seatbelt system, seat assembly, or seat adjustment locking mechanism is not permitted. After the force has been applied the buckle must still comply with the opening force requirements as described previously.

A.3.2 SAE J386: Operator restraint system for off-road work machines

This standard incorporates the requirements for testing seatbelt anchorage forces for earth-moving machinery that are described in ISO 6683. However, SAE J386 also includes requirements for testing the seatbelt anchorages of industrial machines and the testing of seatbelt assemblies.

The standard applies to lap belts (defined as pelvic restraint systems in the standard) that are fitted to self-propelled work machines that are commonly used in construction, mining, forestry and earth-moving. The restraints must be considered in conjunction with rollover protection structures (ROPS). The standard focuses on restraint systems where the mass of the seat system is 70kg or less.

The seat system is tested on-machine or in an equivalent manner. The test is carried out with the seat system adjusted to the operating position that produces the most severe loading to the restraint system prior to any structural deflection. A 15kN force is applied in the forward and upward direction at an angle of 60°±15° from the horizontal which produces the most severe loading condition. The force is applied for between 10 and 30 seconds. There must be no rupture, release or failure of any element within the restraint system, however, permanent deformation is permitted. Figure 62 shows the test procedure.

Figure 62 Test procedure (SAE J386)
The general requirements for the seatbelt assembly are:

- The assembly shall be designed for use by only one occupant at any time
- The assembly must have a buckle or latch that:
  - Is easily accessible by the occupant. The buckle must be easily and rapidly released in a single motion with one bare or mittened hand
  - The possibility of accidental release by operator movement, inertia or external forces shall be minimised by the design of the buckle
  - Shall be released by a force of no more than 130N applied to the release mechanism
  - Satisfies the requirements of SAE J141 for corrosion resistance, temperature resistance, compression, latch operation, adjustment force, tilt lock adjustment
  - Where a buckle is less than the width of the strap and in an area that may be uncomfortable for the operator, padding that covers the entire buckle area and is the full width of the strap must be permanently attached to the assembly. The padding must not be injurious or uncomfortable to the operator and must not hinder the operation of any part of the seatbelt or present a rough surface to the operators clothing
- The seatbelt may be self adjusting or be readily adjusted with mittened hands by means that are within easy reach of the occupant. It must be possible to adjust the belt to a snug condition in all operating positions for a US \(5^{th}\) percentile female to a winter clothed US \(95^{th}\) percentile male. The overall length of the belt may vary depending on the anchorage points
- Two seatbelt assemblies are tested for creep by applying a small load (5kg) and reciprocating motion at 5Hz for 1000 cycles. There must be no more than 25 mm of creep at each adjusting device and the total creep for all adjusting devices must not exceed 40 mm
- The breaking strength of the complete seatbelt assembly is assessed by applying a loop force of not less than 22kN to the centre of the loop using a machine specified in the standard
- There are specific requirements for the strap material:
  - Resistance to mild acids, alkali’s, mildew, aging moisture and sunlight as ISO 6683
  - The strap material shall be woven and/or treated to provide stiffness in the transverse direction that is effective for the usable life of the strap. The strap has to be flexible in the longitudinal direction and allow adjustment at -40°C
  - Preferred colours are those specified by the manufacturer as being less sensitive to ultraviolet rays
  - The strap must have a minimum width of 46 mm when measured with no force applied
  - The ends of the straps must be treated or protected to prevent unravelling or being pulled through the adjustment device at the maximum size adjustment
  - Breaking strength not less than 26.7kN and not less than a median of 20kN for abraded specimens
- Elongation shall not exceed 20% at 11.1kN when measured during the test for breaking strength

- Any metal or rigid plastic parts generally have to meet requirements in SAE J141 or be tested to SAE J140
  - When tested for temperature resistance, plastic or other non-metallic parts must not deteriorate to cause the seatbelt assembly to operate improperly or to not comply with release, adjustment of creep requirements described previously
  - Mounting bolts tested to SAE J140 must withstand a force of 22.2kN
  - End fittings (mounting brackets) must withstand a loop force of 22.2kN
  - Retractors must meet the seatbelt assembly breaking strength requirement, withstand a loop force not less than 22.2kN

- Technical requirements for the anchorages are:
  - Meet the 15kN force requirement
  - The anchorages on the seat system or machine must allow the belt assembly to be readily installed or replaced.
  - Where a seat does not swivel or have suspension, the seatbelt assembly may be fixed to the seat or machine at any point within the hatched area shown in Figure 63.
  - Where the seat has a suspension system, the assembly shall be attached in such a way as to prevent the loop size of the belt changing with the travel of the suspension
  - Adjustable belts, cables or similar flexible devices may be used to transfer seatbelt assembly forces from the seat anchorages to the machine. These belts must meet the 15kN force requirements
  - The seatbelt assembly shall be installed so that in all operating positions, when the seatbelt is in a straight line through the SIP, the angle from the horizontal will be in the range 60°±15° as shown in Figure 63

Figure 63 Location of seatbelt anchorages (SAE J386)
The standard also includes requirements for marking and provision of usage and maintenance instructions.

**A.3.3 SAE Information Report J2292: Combination pelvic/upper torso (type 2) operator restraint systems for off-road work machines**

This guidance applies to seatbelt assemblies that provide restraint of the upper torso, either as one system which includes the pelvic restraint (type 2) or in combination with a pelvic restraint (type 2A). Figure 64 shows the area in which the upper anchorage can be fitted.

![Figure 64 Anchorages for upper torso belts (see SAE J383)](image1.png)

The information report provides guidance on test forces for breaking strength and anchorages shown in Figure 65.

![Figure 65 Test method for type 2 seatbelt anchorages](image2.png)

The 1997 version of this document states that retractors that are only sensitive to webbing feed out should not be used for these types of restraints. This was revised in 2000 to allow these types of retractors to be fitted if the lap portion of the belt meets the load requirements for Type
1 and 2A assemblies. Emergency locking retractor should have a vehicle sensitivity that provides comfort in rough riding conditions, but still provide adequate locking in rollover conditions. The retractor should also meet the environmental test requirements consistent with the environment in which they will be used.

For suspended seats, the pelvic portion should be attached to prevent the loop size from changing with seat oscillations. The upper torso restraint can change with seat oscillations and should be positioned to minimize contact between the seat belt assembly and the neck and to avoid slipping off the shoulder of the operator when the seat is at a maximum reclined position of 15º.

Retractors that are only sensitive to webbing feed out should not be used for these types of restraints and emergency locking retractor should have a vehicle sensitivity that provides comfort in rough riding conditions, but still provide adequate locking in rollover conditions. The retractor should also meet the environmental test requirements consistent with the environment in which they will be used.

For suspended seats, the pelvic portion should be attached to prevent the loop size from changing with seat oscillations. The upper torso restraint can change with seat oscillations and should be positioned to minimize contact between the seat belt assembly and the neck and to avoid slipping off the shoulder of the operator when the seat is at a maximum reclined position of 15º.

A.3.4 AS 2664 - 1983 Earth-moving machinery – seatbelts and seatbelt anchorages

This is an Australian standard that sets out requirements for seatbelt assemblies that are primarily intended for earth-moving machines that are fitted with ROPS and falling object protection structures (FOPS). This standard closely follows ISO 6683 with some requirements being modified to account for local conditions and standards. The differences between this standard and ISO 6683 are described below. Seatbelt systems that meet ISO 6683, BS 6218 (identical to ISO 6683) or SAE J386 APR 80 are deemed to comply with this standard. The scope of the standard states that the performance requirements are necessary to restrain an occupant within a ROPS in the event of a machine rollover.

The requirements of this Australian Standard that are different to ISO 6683 are:

- The definition of the seatbelt assembly. This is “belt including any buckle, length adjuster, and means for securing to an anchorage, that fastens across the pelvic area to provide pelvic restraint during operating and rollover conditions. It may also include webbing to provide upper torso restraint. Note: this definition does not include retractors.” Therefore this standard requires lap belts but also provides standards relating to lap-diagonal belts
- In addition to the requirements specified in ISO 6683, the webbing must comply with AS 1753 “webbing for restraining devices for occupants of motor vehicles”
- The webbing for the pelvic restraint must have a minimum width of 75 mm and be class D22 according to AS 1753
- The webbing for the torso restraint must have a minimum width of 46 mm and be class D16 or D22 according to AS 1753
- The width of webbing connectors that are likely to touch the wearer during normal use shall not exceed 100 mm measured at right angles to the length of each attached webbing
- Anchor fittings:
Where the seatbelt assembly is intended to be fitted by someone other than the machine manufacturer, each fitting shall include a device for attachment to the machine and such parts as are required to reinforce the structure at that point.

Threaded fasteners shall include provision for locking to prevent loosening under vibration.

Fittings designed to minimize the possibility of causing injury.

Fittings designed so that webbing is loaded through its approximate centreline when the seatbelt is being worn.

Webbing shall be permanently attached to each fitting, but does not need to be fixed in position.

Fittings shall be designed to prevent inadvertent detachment from the strap.

Where practicable, belts, cables, or similar flexible devices shall be used to transfer the seatbelt assembly loads from the seatbelt anchorages to the machine.

The upper torso restraint anchorage may be common with the pelvic restraint anchorage. When the seat is in the lowest rearmost position the upper anchorage(s) shall be located within the acceptable range shown in Figure 64.

A.4 INTERNATIONAL STANDARDS RELATING TO ROLLOVER PROTECTION (ROPS)

Both the seatbelt and ROPS standards make it clear that they are each intended to work with the other so it is essential that the effectiveness of seatbelts is considered in relation to the performance of ROPS.

The Supply of Machinery (Safety) Regulation (1992) specifies that rollover protection structures (ROPS) must be tested using “appropriate tests”. The following standards have been approved and can be considered as appropriate tests:

- AS 2294.1 (1997), Australia
- SAE J1040, International

These standards contain laboratory tests and performance criteria which are very similar to each other and are described below.

A.4.1 ISO 3471:1994 including amendment 1:1997, BS EN 13610

This standard applies to dozers (crawler and wheeled), graders, loaders (crawler and wheeled), earth- and landfill compactors, skid-steer loaders and backhoe loaders, tractor portion of scrapers and articulated steer dumpers, rollers and rigid frame dumpers.

The standard provides reproducible means of evaluating the load carrying characteristics of ROPS under static loading (i.e. the rate of load deflection at the point of application must be no greater than 5 mm per second) and prescribes performance criteria for a representative specimen. The evaluation procedure is not intended to reproduce the structural deformations of a specific rollover event. However investigations on ROPS that have performed their intended function in a variety of actual rollovers have been used to derive specific requirements. The compatibility between the ROPS and the machine frame to which it is attached was also considered. It is intended that ROPS that meet this standard will offer crush protection to a seatbelted operator in at least the following conditions:
• An initial forward velocity of 0km/h to 16km/h on a hard clay surface of 30° maximum slope
• 360° of roll about the longitudinal axis without losing contact with the slope

The requirements of the standard are:
• force resistance in the lateral, longitudinal and vertical directions
• energy absorption in the lateral direction
• limited deflection in lateral, longitudinal and vertical directions

The energy absorption and limited deflections are intended to ensure that when the vehicle rolls over and the ROPS is in contact with a non-deformable surface, the ROPS will deform and absorb energy. The ROPS must also retain sufficient strength so that subsequent impacts do not cause excessive deflection which would compromise the driver's survival space.

The ROPS is considered acceptable if:
• The specific lateral force, lateral energy, vertical load carrying capacity and longitudinal force requirements are met. The values of force and energy are different depending on the type of vehicle being assessed. Examples of these values shown in for crawler loaders and dozers
• The force and energy requirements under lateral loading do not need to be obtained simultaneously. If the force requirement is obtained before the energy, the force may decrease, but shall meet the required level again when the lateral energy requirement is met or exceeded
• No part of the ROPS shall enter the Deflection –limiting volume (DLV) at any time during loading. The DLV is defined by a separate standard (ISO 3164 (2000)) and is described as “an orthogonal approximation of a large seated male operator wearing normal clothes and a hard hat”, as shown in Figure 66
• Lateral and vertical simulated ground planes (defined by the Regulation) must not enter the DLV except where during lateral loading with a side mounted operator seat or for longitudinal loading with the operator facing the direction in which the ROPS will deflect. In these situations, the upper portion of the DLV is permitted to deflect 15° about its locating axis. The forward rotation may be limited to less than 15° by interference with components
• The ROPS shall not break away from the machine frame because of failure of the machine frame or mounting
Figure 66 Definition of deflection limiting volume (DLV) ISO 3164(2000)

1) May be reduced to accommodate position of floor plates.
2) Machine parts or controls may cause feet to be separated. As a minimum, the
   crush-proof volume for feet and legs in ISO 3411 shall be maintained on both sides.
3) Feet may move 45 mm rearward.
### Table 17 Example force and energy requirements for ROPS assessment

<table>
<thead>
<tr>
<th>Machine mass, ( M ) (kg)</th>
<th>Lateral load force, ( F ) (N)</th>
<th>Lateral load energy, ( E ) (J)</th>
<th>Vertical load force, ( F ) (N)</th>
<th>Longitudinal load force, ( F ) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawler dozers and loaders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 &lt; ( M = 4630 )</td>
<td>6M</td>
<td>13000  ( \frac{M}{10000} )(^{1.25})</td>
<td>19.61M</td>
<td>4.8M</td>
</tr>
<tr>
<td>4630 &lt; ( M = 59,500 )</td>
<td>70000 ( \frac{M}{10000} )(^{1.2})</td>
<td>13000  ( \frac{M}{10000} )(^{1.25})</td>
<td>19.61M</td>
<td>56000 ( \frac{M}{10000} )(^{1.2})</td>
</tr>
<tr>
<td>( M &gt; 59,500 )</td>
<td>10M</td>
<td>2.03M</td>
<td>19.61M</td>
<td>8M</td>
</tr>
</tbody>
</table>

The test method stipulates the order in which the loads must be applied. It is not permitted to straighten or repair the ROPS between load applications. Localised penetration can be prevented by using a device to distribute the load, however, it must not impede the rotation of the ROPS.

The first load to be applied is the lateral load, for which the load distribution may not be over more than 80% of the length of the device. The initial direction of loading shall be horizontal and perpendicular to a vertical plane through the longitudinal centreline of the machine and show typical loading requirements.

![Diagram](image)

NOTE: Load distributor and socket are to prevent local penetration and to hold end of load-generating device.

**Figure 67** Two post ROPS with falling object protection (FOPS) - lateral load application point

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Loading is to be applied to the side nearest to the operator’s seat if it is not positioned centrally. If the seat is centrally mounted, and different results are expected from loading different sides, then the load shall be applied to the side which will place the most severe loading on the ROPS. The force should initially be applied horizontal and perpendicular through the longitudinal centreline of the machine. The direction of loading is allowed to change if this is a result of deformation of the ROPS or machine. Lateral load application points are shown in Figure 67 and Figure 68.

The values of force and deflection should be recorded at deflection increments no greater than 15 mm at the point of application until the ROPS has met the force and energy requirements.

After the lateral loading has been completed, the vertical load is applied to the top of the ROPS. For a rollbar ROPS, the vertical load is applied in the same plane as the lateral load described above. For one or two post ROPS the centre of the vertical load application shall not be any nearer to the ROPS posts than for the lateral load. So long as the load is applied symmetrically, there are no further limitations on the manner of loading. Figure 69 shows an example of vertical loading.
Once the vertical load has been removed, a longitudinal load is applied to the upper structural members of the ROPS along the longitudinal centreline. The direction of loading is selected to place the most severe requirements on the ROPS/machine frame assembly. The initial direction of the load shall be horizontal and parallel to the original longitudinal centreline of the machine. The location of the ROPS relative to the DLV, structural characteristics and the possibility of longitudinal tipping or skew about the longitudinal axis during an actual rollover should also be considered when determining the direction of load.

Figure 70 shows the point application of the longitudinal load before deformation of the ROPS. The longitudinal load should be applied to the deformed location of the original point. Where there is no rear cross-member, the load distribution device may span the width of the ROPS, in all other cases it must not distribute the load over more than 80% of the width as shown in Figure 70.
A.4.2 SAE J1040: 1994 – Performance criteria for rollover protective structures (ROPS) for construction, earth-moving, forestry, and mining machines

This SAE standard contains the same technical requirements as ISO 3471. There are some minor differences that relate to definitions, level of details and exclusions that do not affect the test method or performance requirements so are not described here in further detail.

A.4.3 AS 2294:1997 Earth-moving machinery – protective structures

This Australian standard specifies requirements for ROPS and FOPS. The requirements for ROPS are identical to those in ISO 3471(1994).

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**Figure 70** Longitudinal load application point

1) \( b = W/2 \)

**NOTE 1**: Load distributor and socket are to prevent local penetration and to hold end of load-generating device.

**NOTE 2**: Typical but not mandatory layout.
APPENDIX B  RESTRAINT SPECIFICATIONS
Low frequency air suspension with air spring and double acting damper.
This seat has an integrated full harness roll over restraint inertia reel belt, suitable for quarry and mining vehicles. The integration into the seat of the belt prevents the possibility for it to become loose or snatch as the seat operates within the suspension stroke.

**FEATURES**
- Spilload R.o.R. (Full harness roll over restraint inertia reel belt)
- Double depth lumbar cushions
- Upper backrest height adjustable
- Back angle fully adjustable (45 position)
- Adjustable damper
- Seat height adjustment 76mm
- Weight adjustment 50 - 150kg
- Suspension stroke 90mm
- Fore-aft slides travel 160mm
- Hardwearing fabric or vinyl cushions
- Heavy duty double lock slides
- Suspension cover
- Seat cushion filler
- Armrests support
- Performance ISO 796 Class 3& Class 4

**OPTIONS**
- 12/24vorno intercoolers
- Adjustable North American wheels
- Tumble
- Seat heater 12 or 24v
- Operator presence switch

These seats and components meet the following test loads:
1. Tsi=5/2693 applied to the belt (578N)
2. Tsi=12/12kN applied simultaneously on the seat (12kN)
   - applied concurrently to the shoulder sections,
   - All loads are to horizontal
Spillard Safety Systems Ltd
Sears Seat Harness
RSSPL005

Note position of Reel
SIDE VIEW

There are 2 escutcheons
1 on Harness here
and 1 in kit

Shoulder Strap

Buckle & Tongue

Waist Strap to anchor point

NO.8 Reflex Label Sewn here on reverse side

1 90 DEG RETRACTOR
2 ANTI SNAG PLA. GUIDE
3 ADJUSTER ASSEMBLY
4 WEBBING TIDY
5 TONGUE K12 STD
6 BUCKLEHEAD K12
7 15 DEG SWIV ANC.PLATE
8 REFLEX LABEL
A-E 47mm RED PANEL WEB.

LAST UPDATE 08/03/04
1 SINGLE SENSE REEL
2 WITH COVER
3 REFLEX LABEL
4 ARROWHEAD STD TONGUE
5 Arrowhead Webbing Buckle with Flat Fixed arc plate and elect switch
6 155MM SLEEVE
A+6 47mm YELLOW WEB
7 FLAT FIXED
8 SWITCH AND CABLE
APPENDIX C  NUMERICAL SIMULATION - MODEL EVALUATION

The model evaluation was used to refine the setup of the models and to test the credibility of their predictions. It was expected that the form and magnitude of the models’ predictions should be comparable to equivalent values measured in the rigid truck rollover tests. However, accurate predictions of the test results could not be expected because the details of the vehicle model were based on generic details of a rigid truck and not on the specific details of the vehicle used in the rollover tests. However, many other internal characteristics of the separate cabs inspected could be considered comparable, for example, the contact stiffness of the cab glazing and internal trim. These parameters were identical in each cab model and as such it was expected that the evaluation would also test the credibility of the predictions from the other quarry vehicle models that had been generated.

Predictions from the rigid truck model were evaluated against the following three rollover tests:

- Anti-clockwise 90° static rollover of a rigid truck with the ES-II dummy wearing a lap belt
- Anti-clockwise 90° static rollover of a rigid truck with the ES-II dummy fitted with a three-point harness
- Clockwise 90° static rollover of a rigid truck with the ES-II dummy wearing a lap belt

In order to match the test setup version 2.6 of the MADYMO faceted ES-II dummy model was settled into the rigid truck model. In the tests the ES-II dummy was fitted with a lap belt and a harness, comparable belt systems were represented in the simulations. The majority of the belt segments were modelled using Finite Elements (FE) as opposed to multibody belt segments in order to more accurately simulate the interaction between the belt and ES-II dummy model. Multibody belt segments were used to tether the FE belt systems to the modelled seat.

Figure 71 shows the setup of the two belt systems on the ES-II dummy model.

Figure 71 Set up of the belt systems fitted over the ES-II dummy models

In the rollover tests the ES-II dummy was held in the vehicle seat up to 300 ms prior to the impact of the side of the vehicle with the ground. It was rationalised that this methodology would approximate the fact that a real driver is likely to hold onto the steering wheel and attempt to restrain himself in the seat for as long as he is able. This same setup was approximated with the model by locking the motion of the dummy model to that of the cab until
approximately 300 ms prior to the impact of the side of the rigid truck model with the ground. Post 300 ms, the motion of the occupant model was released from the motion of the cab allowing the occupant model to freely interact with the internal walls and features of the modelled cab.

Examples of the plots used for the evaluation of the model are shown in Figure 72. Consideration of the cab acceleration in the x-direction shows that the data was comparable during the initial part of the impact until the high magnitude oscillations in the test data that are not present in the models. The cab acceleration in the y-direction had a similar peak magnitude and matched the general shape well, including the secondary rise that occurred late in the impact event. The head acceleration showed good correlation with the magnitudes of the peak accelerations in both x and y directions, although there was a slight phase shift in the timing of the peaks. Evaluation was also conducted against the results from the harness and anti-clockwise tests with very similar trends of good correlation of peak magnitude and general shape.

![Graphs of Cab and Head Accelerations](image)

**Figure 72** Comparison of test results and model predictions for the anti-clockwise rollover with lap belt

It was evident from the evaluation of the model that its predictions were comparable in magnitude to, and show some similarities to, those measured in the rollover tests. Although in many instances the absolute accuracy of the models’ predictions was different from the measurements made in the tests, this was to be expected because the vehicle model was a generic representation and not a specific model of the tested vehicle. The chaotic nature of rollover conditions and the relatively long duration of the impact event (>1 second) would also deteriorate the accuracy of the models’ predictions. In addition, the severities of the impact conditions were relatively mild and as such the scale of the differences in the evaluation were relatively small. However, having been able to match the higher injury predictions measured for the lap belt in the tests, the evaluation showed that the model was capable of predicting the relative benefits of one restraint system compared with another. This confirmed the suitability
for using the developed models in a parametric investigation for assessing the benefits of restraint systems under a variety of impact conditions.
<table>
<thead>
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<th>Armrests</th>
<th>Restraint system</th>
<th>Head $HIC_{16}$</th>
<th>3ms exceedance (g)</th>
<th>Extension (N.m$^{-1}$)</th>
<th>Neck Shear (N)</th>
<th>Neck Tension (N)</th>
<th>Neck Compression (mm)</th>
<th>Chest Belt loads (N)</th>
<th>Lap left (N)</th>
<th>Lap right (N)</th>
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<td>60 (37)</td>
<td>45 (16)</td>
<td>378 (90)</td>
<td>3464 (1432)</td>
<td>3 (8)</td>
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<tr>
<td></td>
<td>Lap</td>
<td>31 (195)</td>
<td>25 (50)</td>
<td>4 (8)</td>
<td>204 (131)</td>
<td>339 (341)</td>
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<td>2569 (2367)</td>
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<tr>
<td>Without</td>
<td>Three-point</td>
<td>10</td>
<td>10.3</td>
<td>8.2</td>
<td>174</td>
<td>103</td>
<td>12</td>
<td>2167</td>
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<td></td>
<td>Reverse three-point</td>
<td>13</td>
<td>14 (20)</td>
<td>10.5 (6.6)</td>
<td>155 (185)</td>
<td>493 (369)</td>
<td>5 (8)</td>
<td>2856 (2171)</td>
<td>2025 (2025)</td>
<td>2752 (1657)</td>
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<td></td>
<td>Harness</td>
<td>8 (11)</td>
<td>9.47 (13.2)</td>
<td>4.44 (6.66)</td>
<td>122 (159)</td>
<td>126 (120)</td>
<td>5 (5)</td>
<td>2763 (940)</td>
<td>1434 (2681)</td>
<td>1703 (1645)</td>
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Table 19 90° Dynamic rollover model predictions

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<th>Armrests</th>
<th>Restraint system</th>
<th>Head</th>
<th>Neck</th>
<th>Chest</th>
<th>Belt loads (N)</th>
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<td>HIC&lt;sub&gt;36&lt;/sub&gt;</td>
<td>3ms exceedance (g)</td>
<td>Extension (N.m&lt;sup&gt;1&lt;/sup&gt;)</td>
<td>Shear (N)</td>
</tr>
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<td>288</td>
<td>66</td>
<td>22</td>
<td>430</td>
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<tr>
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<td>Lap</td>
<td>58</td>
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<td>Three-point</td>
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<td>22</td>
<td>665</td>
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<tr>
<td>Without</td>
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<td>414</td>
<td>82</td>
<td>22</td>
<td>401</td>
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<tr>
<td></td>
<td>Lap</td>
<td>144</td>
<td>47</td>
<td>22</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>Three-point</td>
<td>15</td>
<td>18</td>
<td>28</td>
<td>698</td>
</tr>
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<td></td>
<td>Harness</td>
<td>117</td>
<td>42</td>
<td>22</td>
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### Table 20 270° dynamic rollover model predictions with armrests

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<th>Restraint system</th>
<th>Head</th>
<th>Neck</th>
<th>Chest</th>
<th>Belt loads (N)</th>
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<td>$3\text{ms exceedance (g)}$</td>
<td>Extension (N.m$^{-1}$)</td>
<td>Shear (N)</td>
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<td>133</td>
<td>47</td>
<td>46</td>
<td>1014</td>
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<td>Lap</td>
<td>131</td>
<td>35</td>
<td>39</td>
<td>980</td>
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<td>73</td>
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<td>39</td>
<td>980</td>
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<tr>
<td>Harness</td>
<td>249</td>
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<td>40</td>
<td>832</td>
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### Table 21 End tipping model predictions with armrests

<table>
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<th>Restraint system</th>
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<th>Neck</th>
<th>Chest</th>
<th>Belt loads (N)</th>
</tr>
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<td>HIC $36$</td>
<td>$3\text{ms exceedance (g)}$</td>
<td>Extension (N.m$^{-1}$)</td>
<td>Shear (N)</td>
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<td>101</td>
<td>1093</td>
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<td>836</td>
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<td>1037</td>
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<td>Restraint system</td>
<td>Head</td>
<td>Neck</td>
<td>Chest</td>
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<td>-------</td>
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<td>HIC₃₆</td>
<td>3ms exceedance (g)</td>
<td>Extension (N.m⁻¹)</td>
<td>Shear (N)</td>
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<tr>
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<td>70</td>
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<tr>
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<td>Harness</td>
<td>82</td>
<td>33</td>
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<td>270° dynamic</td>
<td>Lap</td>
<td>267</td>
<td>62</td>
<td>12</td>
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<tr>
<td></td>
<td>Reverse three-point</td>
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<td>50</td>
<td>17</td>
</tr>
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<td></td>
<td>Harness</td>
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<td>81</td>
<td>48</td>
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<tr>
<td>Impact type</td>
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<td>Head</td>
<td>Neck</td>
<td>Chest</td>
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<td>------</td>
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<td>HIC$_{36}$</td>
<td>3ms exceedance (g)</td>
<td>Extension (N.m$^2$)</td>
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<td>Chest</td>
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<td>Harness</td>
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<td></td>
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<td>Neck</td>
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<td>3ms exceedance (g)</td>
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<td>Rigid dump ruck</td>
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<td>52</td>
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<tr>
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<td></td>
<td>Harness</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Harness</td>
<td>233</td>
<td>60</td>
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<tr>
<td>Wheel loader</td>
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<td>101</td>
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<tr>
<td></td>
<td></td>
<td>Harness</td>
<td>32</td>
<td>23</td>
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Zuppichini (1990) tested after-market web-locking devices in simulated frontal impacts, at 50 km/h, to experimentally determine the effect that adding 100 mm of slack into the three-point belt system had on its performance. Zuppichini found that the seatbelt broke in seven out of 35 tests. Nearly all the remaining tests showed a worsening of belt performance, with values of chest and pelvis displacement increasing by around 20 and 40%, respectively, over the standard belt.

For the Holmes Safety Association (HSA) report by the Mine Safety and Health Administration (Fesak et al., 1996), a total of 4,397 surface haulage accidents were considered in an attempt to identify the major factors that led to the accidents and recommend accident prevention methods to reduce the frequency of such accidents. The focus of the report was narrowed to study, in detail, 1,300 truck haulage accidents (‘trucks’ consisting of water trucks, front-end loaders, tractors/scrapers, ore carrier/large trucks, ore haulage trucks, or other utility trucks).

Failure of drivers to use seatbelts was identified by Fesak et al. as a cause of serious injuries in rollover accidents or collisions with other vehicles or stationary objects. In 200 of the accidents reviewed by Fesak et al. (15%), the drivers of equipment had failed to use their seatbelt.

Fesak et al. also comment on a misconception held among equipment operators, that it is better to jump from an out of control piece of equipment than to ‘ride it out’. They cite that fatalities have occurred when equipment operators apparently jumped from the vehicle. According to Fesak et al., in nearly every instance, the condition of the equipment operator’s compartment indicated that the driver would have been protected if they had worn their seatbelt. Apparently, the Mine Safety and Health Administration has documented testimonials from equipment operators who have survived falling from high-walls, benches and roadways, because of their use of seatbelts.

Herbst et al. (1996) simulated rollover tests with three volunteers, selected to represent a small female, average male and large male. The testing apparatus consisted of a ‘buck’ that included a driver’s seat and restraint system. The buck was mounted on a spit fixture and allowed to rotate about its longitudinal centre. Herbst et al. found that shoulder belts, if properly placed and functioning, can maintain an occupant in a reclined position as if normally seated. It can also provide restraint of the upper torso in all directions between the head/neck complex and the roof. This should provide a further reduction in injury potential.

They discuss that many production cars have pre-tensioners on front belts and that many of these could be triggered by rollover sensors to provide increased occupant restraint. According to Herbst et al., pre-tensioning can reduce the slack inherent in a belt system, while simultaneously drawing the occupant into the seat and away from upper contact surfaces.

Friedman et al. (1996) also used a vehicle buck and volunteers to investigate restraint effectiveness during rollover motion. They found, during testing with a three-point pre-tensioned webbing, that controlling the shoulder with the torso belt was important in reducing head excursion. Friedman et al. comment that this finding is consistent with the lap belt only test, in which much of the head excursion observed was due to the ejection of the torso and was particularly noticeable in tests with a large male. They conclude that strategies for incorporating control of the upper torso motion appear to be an important tool available in providing occupant protection in rollovers. However, the excursions recorded in their lap belt only tests appear to be less than those from the three-point belt tests. This may indicate that the available slack in a belt system is more important than whether the belt is anchored at two or three-points.
Friedman et al. also commented that the use of the space contained within the occupant seat cushion offers opportunities for increasing the occupant survival space by pulling the occupant into the seat, or through other mechanisms to utilise the seat in the occupant protection system approach.

In the report by Robinson et al. (1996), several relevant sources of useful information are reviewed. Apart from published research papers and standards, Robinson et al. present information from consultation with the Agricultural Engineers Association (AEA) and visits to trade shows.

From the AEA opinion, it was deemed that:

- A suspended seat must have seatbelt anchorage points on the seat assembly
- A diagonal belt may be safer in practice but would be too restrictive of the driver’s movements
- Incorporating a three-point belt might require modifications to the tractor and/or seat assembly

Robinson et al. comment on the type of retractor seatbelts that are available. They say that the two most common forms of retractor belt are ‘emergency’ locking retractors and ‘automatically’ locking retractors. The emergency locking retractor allows the belt to spool out or in as the wearer moves, but locks in an emergency, actuated by deceleration of the vehicle, and/or rapid extraction of the strap relative to the retractor. The automatic retractor allows the belt to reel out from the fully retracted state but, once it starts to retract, it will not reel out again until it is allowed to retract fully.

The emergency retractors are suitable and common-place in many cars and other light vehicles. They are unlikely to be suitable for quarry vehicles, however. Deceleration-sensing, emergency retractors are very sensitive to mounting angle. When a quarry vehicle is going up and down steep slopes it is likely that unwarranted retractor locking will result. In a rollover situation, inertia sensing or (longitudinal) deceleration sensing emergency retractors can fail to lock quickly enough, if at all. Automatically locking retractors are therefore the preferred option for quarry vehicles, if retractable belts are to be used, though they too can cause operational problems as they can become over-tightened in off-road conditions, through a process of gradual ratcheting.

Static belts may offer a relatively in-expensive alternative, not suffering from the operational problems associated with retractable belts.

Tomas et al. (1996) conducted simulated rollover protection tests. They investigated the performance of a Crawler Dozer Caterpillar D6, starting with some static tests using an ABAQUS finite-element program to determine the performance of the rollover protection system. Tomas et al. then performed dynamic rollover tests using a MADYMO model. The first dynamic test showed that the operator is likely to be ejected from the machine unless some form of restraint is provided. The addition of a lap belt kept the simulated occupant within the bounds of the Dozer cab and similar results were found with the use of a three-point lap and diagonal belt.

Tomas et al. introduce the concept that the rate of rollover is initially relatively slow, it is unlikely that the automatic retractor system would lock in time to stop the operator from spooling the belt out and sliding off the seat. They therefore suggest that the most effective option would be to have operator adjustable seatbelts fitted to the vehicle.

It is also discussed by Tomas et al. that lap belts do not fix the upper body of the occupant. Potentially this would allow the occupant to be thrown against the inside of the cab, cladding or glazing surfaces and may result in head or thoracic injuries. A three-point belt may help restrain
the upper body of an occupant in rollovers where the occupant is forced into the diagonal section. However, the restraint would be less effective for the other lateral direction of rollovers. Also, if the operator were to slide towards the diagonal belt, a hazardous neck injury could occur. Therefore, Tomas et al. conclude that the best option appeared to them to be a tightly adjusted four-point racing harness belt.

Pywell et al. (1997) conducted quasi-static rollover simulations using a similar set-up to that employed by Herbst et al. and Friedman et al. and a 50th percentile Hybrid III dummy.

By adding a pre-tensioner, the vertical head displacement of the occupant was reduced by 41%.

Pywell et al. discussed that improved belt geometry (such as housing the outboard anchor on the structural seat adjuster as opposed to the B-pillar), reduced belt pay-out before the webbing was locked in the loop mechanism, and the ability of the belt system to share loading between the shoulder and lap loop all contributed to reducing the head excursion of the occupant.

They suggested that the use of belt comfort features that allowed a degree of slack for the occupant might be offset by the application of a pre-tensioner triggered in a rollover crash. A belt restraint system that could claw the occupant down and back into the seat, while tightening the belt restraint sufficiently to minimise or eliminate torso excursion in all planes might reduce occupant contacts to interior and exterior surfaces. A device that could perform this task quickly enough to affect this positioning transformation yet without inducing or exacerbating injury may further reduce occupant injury potential in rollover crashes.

Dynamic rollover tests were conducted by Moffatt et al. using a Hybrid III dummy and a PMHS (post-mortem human subject) to determine the effect of various seatbelt configurations on head position during tests that encompassed approximately 240° of roll. Additionally, static tests were carried out with the Hybrid III dummy, PMHS and human volunteers.

The head excursion test device developed for and used in the study was capable of simulating rolls towards either side. However, only rolls into the shoulder portion of a three-point belt were reported.

To determine the effects of lap belt geometry on vertical head excursion, a range of lap belt angles and lengths (measured between the anchorage point and the hip of the occupant) were tested by Moffatt et al. with the Hybrid III and the PMHS. Head excursion was highest with a shallow angle (30°) and long length (over 500 mm). This combination allowed the lap belt to pivot upwards relative to the seat. At steeper belt angles, increased lap belt length had little effect on maximum head excursion, due to the limited rotation of the belt.

Three-point restraint tests, using the Hybrid III, were also conducted by Moffatt et al. to evaluate the effect different torso belt angles and lengths (measured between the anchorage point and the shoulder of the occupant) had on vertical head excursion. Head excursion was reduced when the torso belt anchor was in close proximity to the shoulder. Increasing the torso belt angle from -10° to -80° added 30 mm of excursion, while increasing the belt length from 100 to 400 mm produced an additional 20 mm of excursion. Moffatt et al. found that the primary benefit of the torso belt was in preventing forward rotation of the torso and providing vertical restraint on the shoulder. All of the torso belt geometries were effective in reducing forward rotation, but only the shallow-angled torso belts provided vertical restraint to the shoulder.

Moffatt et al. evaluated the potential benefit of seatbelt pretensioning by applying pre-test static tension to the buckle anchor and measuring its effect on both lateral and vertical head excursions. The maximum pretension load was 667 N, applied in line with the lap belt angle. For the volunteers, pretensioning typically reduced vertical head excursion by about 100 mm.

Through comparison between volunteer, PMHS and dummy tests, Moffatt et al. concluded that the Hybrid III dummy is stiffer in rollover conditions than human subjects. In their dummy three-point tests, this increased stiffness accounted for about 65 mm greater excursion than in
the comparative tests with volunteers. This difference should be considered when interpreting the results from rollover tests with Hybrid III or other, similarly stiff, dummies.

Foret-Bruno et al. (1998) reviewed an accident database containing 290 accidents. The key feature of this database was the possibility of showing a relationship between the seatbelt tension exerted on an occupant and the type of lesions resulting. In discussing the need for a belt load limiter with a lower limited load value, Foret-Bruno et al. discuss the accident data that they had reviewed showed that a threshold of 6 kN for belt load limitation is not sufficient to prevent a risk of serious injury to the thorax. They suggested that it was necessary to go a step further in reducing the shoulder belt load. However, they add the proviso that, as this reduction will result in an increase in excursions of the head and thorax, it is essential in passenger cars to combine a load limited seatbelt, a pretensioner and an airbag.

Baudrit et al. (1999) assessed the sensitivity of computer simulated models of the human body and two dummies (Hybrid III and ES-II) with regard to some restraint system parameters, including belt load limitation. They found that in frontal impacts, the more limited the belt load is, the larger the displacement is. The maximum head displacement increased by almost 300 mm (50 %) in going from no load limiter to a 4 kN limited system.

Knight et al. (2001) conducted a study using two public databases for the years 1994-1996. These databases were the Utah state-wide motor vehicle crash file and the Utah state-wide hospital discharge database. Based on 103,035 occupants, Knight et al. showed that unbelted occupants experienced the largest proportion of ejection and shoulder-only belted occupants sustained the largest proportion of fatal or hospitalising injuries. In Table 26, lap and shoulder belt systems appear to show the smallest percentage of either ejected occupants or occupants sustaining a fatal or hospitalising injury.

<table>
<thead>
<tr>
<th>Type of seatbelt</th>
<th>Total occupants, N (%)</th>
<th>Ejection, N (row %)</th>
<th>Fatal or hospitalising injury, N (row %)</th>
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<td>276 (0.3)</td>
<td>12 (5.0)</td>
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<tr>
<td>Lap-shoulder belt</td>
<td>76,986 (74.7)</td>
<td>94 (0.1)</td>
<td>1,002 (1.3)</td>
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<tr>
<td>Lap belt</td>
<td>4,568 (4.4)</td>
<td>24 (0.7)</td>
<td>78 (1.7)</td>
</tr>
<tr>
<td>None</td>
<td>21,205 (20.6)</td>
<td>957 (5.2)</td>
<td>1,210 (5.7)</td>
</tr>
</tbody>
</table>

Holding et al. (2001) investigated the performance of potential active adaptive secondary systems in frontal impacts. One of the factors studied included the load limiter maximum force. They concluded that load limiting seatbelts can reduce peak chest loading and the severity of whiplash if combined with a suitable airbag and sensing system.

Rouhana et al. (2003) investigated the frontal impact performance of two four-point restraint system designs. These were a harness style (V-shape) and a ‘criss-cross’-style (X-shape) arrangements. They used MADYMO modelling, frontal sled testing with a variety of crash-test dummies (varying in size from a six-year-old to a 95th percentile dummy) and also full-scale tests using both dummies and PMHS.

Rouhana et al. found that the V-shape restraint loaded the body in a different manner to either the X-shape or conventional three-point restraints. It appeared to them, that the V-shape shifted the load from the chest to the clavicles and pelvis, thereby reducing chest compression and resulting injury. The chest deflection, compared with the three-point belt system, was reduced
by as much as half in dummy tests. The X-shape, however, added to the constraint of the torso and this resulted in an increase in chest deflection and injury risk.

Heudorfer et al. (2005) developed an airbag restraint concept for reducing head and neck loading by hard contact with the roof during vehicle rollovers. The ‘roofbag’ package is mounted in the upper portion of the seat backrest. It is directly attached to the seat frame. The roofbag is designed to move the occupant actively into a “rollover-protected” position.

According to Heudorfer et al. to mitigate rollover injuries effectively, the Roofbag’s rollover protection concept is threefold:

- The roofbag allows the head and neck portion to escape the critical axial load path by flexing in its natural degree of freedom
- The roofbag supplies sufficient padding between the head and roof structure, reducing head injuries caused by direct head/roof contact without trapping the head
- Enclosing the head-neck portion from above, the Roofbag will additionally help to protect an occupant’s head against lateral movement

Ensuring that vehicle occupants wear their seatbelt in a secure and well adjusted manner is paramount to any safety that the belt restraint may offer. An alternative to using belt based restraint systems is to use rigid restraining structures. An advantage of these systems is that operators can be forced to buckle the restraint before using the vehicle.

A Springbelt® is a restraint device specifically designed for forklifts, mining, construction and agricultural machinery (Switched On). It resembles a normal seatbelt in that it has tethers and buckles however instead of a flexible sash it is replaced by spring steel covered in protective padding. Springbelt can be locked into a position so that it springs erect and becomes a nuisance to the operator if he is not wearing it while positioned in the driver’s seat.
APPENDIX F  ACKNOWLEDGEMENTS AND CONTACTS

Acknowledgements

The work described in this report was carried out in the Vehicle Engineering Department of TRL Limited.

We extend our grateful thanks to the companies who provided vehicles, restraint systems for testing and access to their operators. They are Graham Hicks and Aggregate Industries for providing the test vehicle and site and for allowing the project team to interview operators, Spillard Safety Systems Limited for providing seats and restraint systems for testing and Foster-Yeoman who allowed the project team to visit a site and interview drivers. Thank you to Matthias Könnecke of Clausthal University for supplying accident data from Germany. Thank you also to JCB and Komatsu for allowing our team to take measurements from vehicles. A full list of the organisations contacted for information towards this research are detailed below.

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<td>Joran Sobstad</td>
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REFERENCES


Department of Minerals and Energy. www.dme.gov.za


TEK seating. Construction vehicle seating, bus and coach seating. TEK seating internet site (http://www.tekseating.co.uk/construction.html).


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