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**TRL667**

Creating the future of transport

# The safety of child wheelchair occupants in road passenger vehicles

C Visvikis, M Le Claire, O Goodacre,
A Thompson and J Carroll

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## Abstract

This report presents the findings of a study carried out by TRL for the UK Department for Transport (DfT). The aim of the study was to examine the safety of children in wheelchairs in road passenger vehicles. The key question was whether children who remain seated in their wheelchairs are afforded a level of protection that is comparable to that for children travelling in a vehicle based restraint system.

The study comprised a number of elements leading to a dynamic sled test programme with instrumented child dummies. The research found that children in wheelchairs do not receive a level of protection that is comparable to that for children in child restraints or vehicle seats. Changes in legislation are therefore required to address and hence improve their protection. There are three key influences: the vehicle, the restraint system and the wheelchair. All three areas must be addressed for improvements in protection to be made, and for the greatest improvements, vehicle, restraint system and wheelchair manufacturers must work together.

## Glossary of terms

| | |
|---|---|
| AIS | Abbreviated Injury Scale |
| ANSI | American National Standards Institute |
| CCIS | Cooperative Crash Injury Study |
| CHILD | CHild Injury Led Design |
| COST | Cooperation in the field of scientific and technical research |
| DHSS | Department of Health and Social Security |
| DfT | Department for Transport |
| EC | European Commission |
| ECWVTA | European Commission Whole Vehicle Type Approval |
| EuroNCAP | European New Car Assessment Programme |
| FMVSS | Federal Motor Vehicle Safety Standard |
| HIC | Head Injury Criterion |
| ISF | TRL's Impact Sled Facility |
| ISO | International Organisation for Standardisation |
| M1 vehicles | Vehicles with ≤ 8 seats in addition to the driver's seat |
| M2 vehicles | Vehicles with > 8 seats in addition to the driver's seat and a maximum mass ≤ 5 tonnes |
| M3 vehicles | Vehicles with > 8 seats in addition to the driver's seat and a maximum mass > 5 tonnes |
| MADYMO | Proprietary 'multi-body' numerical modelling code |
| MHRA | Medicines and Healthcare products Regulatory Agency |

| | |
|---|---|
| NEISS | National Electronic Injury Surveillance System |
| NHTSA | National Highway Traffic Safety Administration |
| NPACS | New Programme for the Assessment of Child restraint Systems |
| OPCS | Office of Population Census and Surveys |
| PMHS | Post Mortem Human Subject |
| RESNA | Rehabilitation Engineering and Assistive Technology Society of North America |
| SI | Statutory Instrument |
| SAE | Society of Automotive Engineers |
| TRL | Transport Research Laboratory |
| UNECE | United Nations Economic Commission for Europe |

## Executive summary

The safety of children who remain seated in their wheelchairs when they travel raises a number of issues. The UK Department for Transport (DfT) commissioned TRL to investigate these issues for children travelling in road passenger vehicles involved in front impact collisions. The DfT also wished to examine the stability of children's wheelchairs within the protected space in buses during normal driving manoeuvres.

The study compared the level of protection afforded to children seated in their wheelchair with that afforded to children travelling in a vehicle based restraint system. The aim was to develop the knowledge needed to inform policy decisions on appropriate requirements for M1, M2 and M3 vehicles (i.e. private vehicles, taxis, minibuses, coaches and urban buses).

The study began by reviewing published literature and existing legislation and standards. This review was supplemented with information gained from organisations involved in the transport of children. A field study was then carried out to examine the way children and their wheelchairs interact with real vehicles and restraint systems. The final stage was to carry out physical observations and sled testing; firstly, looking at wheelchair displacement in low floor buses during normal driving conditions; secondly, comparing the level of impact protection provided for children in wheelchairs with that provided for children in vehicle based restraint systems.

For the purposes of the research, the vehicles were grouped as follows:

- M1 and M2 vehicles with forward facing wheelchair passengers.
- M1 and M2 vehicles with rear facing wheelchair passengers.
- M3 vehicles with forward facing wheelchair passengers.
- M3 vehicles with rear facing wheelchair passengers.

M category vehicles are defined in the European Commission Directive 2007/46/EC (Annex 2). Previous research carried out by TRL for the DfT using adult dummies demonstrated that there is a lower risk of injury in M3 vehicles compared with M1 and M2 vehicles. While it would have been desirable to examine all vehicle categories in the impact test programme, it was necessary to prioritise M1 and M2 vehicles. This allowed thorough investigation of M1 and M2 vehicles with a more comprehensive range of children's wheelchairs. Recommendations were made for M3 vehicles, but these were based on observations of the vehicles and on the test results for M1 and M2 vehicles.

The study found that children in wheelchairs do not receive a level of protection that is comparable to that for children in child restraints or vehicle seats. Changes in legislation are therefore required to address and hence improve protection. There are three key influences: the vehicle, the restraint system and the wheelchair. All three areas must be addressed for improvements in protection to be made, and for the greatest improvements, vehicle, restraint system and wheelchair manufacturers must work together.

The vehicle must provide sufficient space to reduce the risk of the child's head striking the interior during a collision. A head and back restraint must be provided for children in wheelchairs, irrespective of the direction they face in a particular vehicle. This is the only means of ensuring that the head and neck of a child in a wheelchair are afforded a comparable level of protection as the head and neck of a child in a vehicle based restraint system. It is essential that children in wheelchairs are provided with at least a three point seat belt. The best practice is to anchor the diagonal part of a three point belt to the vehicle above the shoulder level. The seat belt should distribute the restraint forces over the strongest parts of a child's anatomy. It is critical that wheelchairs do not interfere with or obstruct the path of the belt. Wheelchairs must be capable of withstanding the forces in a collision of appropriate severity, if they are intended to be used in a vehicle. The dynamic test conditions in United Nations Economic Commission for Europe (UNECE) Regulation 44 are appropriate to examine the performance of safety equipment in M1 and M2 vehicles.

# 1 Introduction

Access for disabled people is an important aspect of the Department for Transport's (DfT) strategy and vision for the future of transport. Disabled people should have the same access to transport as non-disabled people and they should be provided with a comparable level of protection during driving manoeuvres and in the event of a crash. Access to transport can determine whether a person can live independently, find a job, attend education, see friends and family and take part in leisure activities. It can mean the difference between social inclusion and exclusion within a community and can therefore have a strong impact on an individual's quality of life.

More than ten years ago, the Disability Discrimination Act 1995 was passed into UK law. The Act is intended to end discrimination against disabled people and allows the Government to make regulations in this respect. Accessibility regulations have since been introduced for rail vehicles and public service vehicles, and measures for taxis are currently being considered.

These provisions will ensure that both vehicles used for personal use and public transport will be accessible to wheelchair users who wish to remain seated in their wheelchairs when they travel. In previous research for the DfT, TRL investigated the safety of travelling in a wheelchair in a range of M category vehicles (see Section 2.2.2). This work helped to establish the relative level of safety afforded to wheelchair seated adults compared with passengers travelling in vehicle seats.

The number of children using wheelchairs in the UK has now risen above 100,000 (www.wheelchairchildren.org.uk). In many cases, when travelling in a vehicle, younger children can be transferred to a conventional child restraint system; however, this becomes more difficult as they grow older. As a result, parents and children report that their access to services, social activities, education and employment broaden or narrow depending on the accessibility of transport (Audit Commission, 2003). Since disabled children are also protected from discrimination under the Act, the DfT needs to ensure that they are provided with an appropriate level of safety compared with children restrained by conventional means.

A great deal of research has been carried out on the protection of children in child restraint systems, but the relative safety of children using wheelchairs is less clear. Children are not simply small adults; they are proportioned differently, their key organs are in different places and their tissues have different biomechanical properties. Measures introduced to improve access and safety for wheelchair seated adults must also be compatible with children using wheelchairs and crucially, they must not increase the risk of injury.

## 1.1 Existing regulatory framework

### *1.1.1 Wheelchair restraint in vehicles*

In the past, people who wished to remain seated in their wheelchair during transit were excluded from most forms of public transport. There were no boarding aids to get on and off the vehicle and no space for the wheelchair inside. Since that time, regulations passed under Part 5 of the Disability Discrimination Act 1995 have led to growing numbers of new accessible vehicles coming into service on Britain's roads and railways. This section outlines the way in which the 1995 Act deals with transport and how wheelchair users are affected. It also describes the changes introduced by the Disability Discrimination Act 2005 and its supporting regulations. Finally, having established the legislative framework for the vehicle, it sets out the requirements for the wheelchair, in accordance with the Consumer Protection Act 1987.

Technical requirements for some M category vehicles are covered by the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended). The Regulations benefit transport industries by providing clear dimensions and other requirements (such as the need for restraints) for different vehicles. They benefit disabled people by ensuring vehicles used for public transport have adequate provision for them and by setting 'end dates' by which all vehicles must comply. Since the end of 2000, all new buses that carry more than 22 passengers on local and scheduled services have had to meet these Regulations. This is achieved by providing a protected space for a wheelchair user who, in most buses, faces rearwards against a padded backrest. Coaches on local and scheduled services have to meet the same regulations as buses. New coaches that carry more than 22 passengers have had to meet general accessibility requirements since the end of 2000. However, unlike buses, the wheelchair accessibility requirements for coaches were deferred until January 2005. All coaches within the scope of the Regulations must be compliant with both the general and wheelchair accessibility requirements by 2020. The wheelchair faces forwards in a coach and must be restrained by a tie-down system and the occupant must be provided with a seat belt.

The Government recognises the vital role that taxis play in the transportation of disabled people, and is committed to bringing forward requirements for taxis. Consideration is currently being given as to how this might be achieved, and this will comprise evaluation of all the options, including both regulatory and non-regulatory approaches. All licensed taxis in London have had to be wheelchair accessible since January 2000 and some local authorities will only give new licences to taxis that can carry wheelchairs. In London taxis (traditional 'black cabs'), wheelchair users face rearwards against the bulkhead that separates the driver and passenger compartments. The wheelchair is restrained with a tie-down system, adequate to prevent the wheelchair from moving during the rebound phase of a crash. A seat belt is also provided for wheelchair seated passengers. Elsewhere, London taxis are sometimes used, but adapted people carriers or van based vehicles are also allowed. In some of these vehicles, the wheelchair user will travel facing forwards with a wheelchair and occupant restraint system in place.

Part 5 of the Disability Discrimination Act 1995 provided the framework for very specific technical regulations to be introduced. However, disabled people could still be refused entry to an accessible vehicle because transport vehicles were excluded from Part 3 of the Act. This is the part of the Act that deals with access to goods, facilities, services and premises. When the Act was passed in 1995, Parliament introduced the exemption because there were very few accessible public transport vehicles, especially for wheelchair users. The Disability Discrimination Act 2005 enabled the Government to pass regulations to lift the exemption for certain vehicles. The Disability Discrimination (Transport Vehicles) Regulations 2005 (SI 2005 No. 3190) were made under this power and came into force on 4$^{th}$ December 2006. As a result, it is unlawful for public transport operators to discriminate against disabled people or to offer a service at a lower standard or on different terms to a disabled person because of their disability. For the first time, transport providers will have to take positive steps to make their services in respect of transport vehicles accessible to disabled people (Disability Rights Commission, 2005).

Wheelchairs themselves are subject to the Consumer Protection Act 1987. This gave Ministers the power to make the Medical Device Regulations 2002. As part of their CE marking process (which indicates that one or more of the procedures referred to in the Regulations have been followed), manufacturers of wheelchairs must undertake a risk analysis. For the transportation elements of their risk management, many wheelchair and seating manufacturers look towards the ISO

Standards for wheelchair transportation safety to show they have reduced the risks and met some of the essential requirements of the Regulations (Lynch, 2003).

### *1.1.2 Child restraint in vehicles*

Seat belts provide a high level of protection for adults as they are designed for people 150 cm (about 5 ft) and taller. Smaller occupants cannot achieve the correct placement and fit (of the adult belt) over the shoulders and pelvis and for some children, such as infants, it is necessary to apply the restraint force over altogether different areas of the body. For these reasons, a dedicated child restraint system must be used to accommodate the needs of a child in a vehicle. However, children in public transport vehicles are likely to be restrained only by a seat belt. This is because their restraint use tends to be driven by the minimum legal requirement. Part of the challenge for public transport vehicles is the difficulty of having a supply of suitable child restraints on hand. The following section outlines the way in which the Road Traffic Act 1988 affects children. It covers the technical requirements for seat belts in vehicles and describes the law on restraining children (and the Government's proposals to change the law). Finally, it sets out the safety standards for child restraints sold in the UK and explains how these standards are applied.

The Road Vehicles (Construction and Use) Regulations 1986 (SI 1986 No. 1078; as amended) were made under the Road Traffic Act. These Regulations set out the minimum legal requirements for seat belts in motor vehicles. In fact, most vehicles on the road today are likely to have seat belts fitted; however, the application of the law depends on the type of vehicle and the year of manufacture. For instance, seat belts have been mandatory in the front seats of all new cars since 1965 and in rear seats since 1987. Before 1987, child restraints were attached to the car by means of straps bolted to the floor and parcel shelf. This gave a stable installation, but relied on parents to take the time and effort to modify their cars and fit the devices and led to many older children travelling unrestrained. Since then, child restraints have been attached to the car with seat belts. Although this is a simple and universal method of attaching the child restraint, the original function of seat belts was to restrain adult occupants. Some aspects of the belt assembly design such as the anchorage locations, buckle size and length of the belt can be in conflict with the need to secure child restraints.

The 1986 Regulations did not require seat belts to be fitted in the rear of minibuses and coaches. However, the Regulations were amended in

1996 (SI 1996 No. 163), which set requirements for minibuses and coaches to be fitted with seat belts, when used in certain circumstances. The new Regulations stated that children (aged three to 15 years) on organised trips must be provided with a seat belt and a forward facing seat. Both the complete assembly and the belt anchorages were required to meet the relevant European Standards.

Further Construction and Use Regulations were made in 2001 (SI 2001 No. 1043), to extend mandatory fitting requirements to minibuses and coaches (except those designed for urban use with standing passengers). As a result, three point seat belts have to be installed in all forward facing seats in new minibuses. In coaches, two point belts are permitted, provided that an appropriate energy absorbing seat is present in front.

Although many vehicles now have seat belts fitted, the law does not always require passengers to use them, and in the case of children, the law does not always require the most appropriate form of restraint to be used. The Motor Vehicles (Wearing of Seat Belts) Regulations 1993 (SI 1993 No. 176; as amended) set out the law on using seat belts and child restraints. The law says that children must use an appropriate child restraint when travelling in a car (except in a taxi when a child restraint is not available). The law also says that any passenger aged three years and over must wear a seat belt (if one is installed) in a minibus or coach.

From May 2008, where the Regulations call for the use of a child restraint, it must meet the requirements of United Nations Economic Commission for Europe (UNECE) Regulation 44.03 (or subsequent versions). In fact, all child restraints sold in the UK must conform to the Regulation, which includes a front impact test and a rear impact test, although the rear impact test is required for rear facing devices only. Side impact is not currently part of the Regulation; however, a side impact test procedure for child restraints has been developed as part of a consumer assessment and rating scheme for child restraints called NPACS (New Programme for the Assessment of Child restraint Systems).

### *1.1.3 Project aim*

The DfT wished to examine the safety of children in wheelchairs in vehicles. The project objectives were to develop the knowledge about the effects on the safety of child wheelchair occupants travelling in road passenger vehicles and inform policy decisions on appropriate requirements for M1, M2 and M3 vehicles.

### *1.1.4 Scope*

The project investigated the issues for children travelling in M category vehicles involved in front impact collisions. The key question for the project was whether children who remain seated in their wheelchair are afforded a level of protection comparable to that for children travelling in a vehicle based restraint system. The project focused on children aged from three to ten years inclusive. Infants and very young children were considered more likely to transfer to a child restraint system than travel in a wheelchair. Older children are comparable in size to small adults; hence their protection was addressed in the previous DfT project.

# 2 Overview

## 2.1 Literature and information review

### *2.1.1 Approach*

A literature review was necessary to establish the relevance of any previous research that had been carried out. The review comprised published research from the UK and abroad and any other information that it was possible to obtain.

TRL recognised that a review of this nature would highlight what was known about the safety of children in wheelchairs from a science and engineering point of view. It would also highlight any gaps in the knowledge that should be addressed in the project. However, TRL was concerned that the requirements of end users – children, parents and transport operators – may not be found in the literature in any depth. To give a feel for these practical issues, the literature review was extended to gather relevant information and experiences from other organisations.

The literature and information review can be found in Appendix A, but a summary is provided in the following section.

### *2.1.2 Summary*

The literature review was divided into four sections. The first section of the review examined the legislative and policy background relevant to the carriage of children in vehicles, including children in wheelchairs. This revealed that legislation is in place (or coming into force) that covers the type and specification of wheelchair tie-down and occupant restraint systems in certain vehicles. However, the technical requirements for the performance of the restraint system (including the wheelchair) do not address the protection of children directly in the way that UNECE Regulation 44 does. It was also noted that there is no legislation in place governing the use of a restraint system by children in wheelchairs.

The second section of the literature review examined the biomechanics of children. This highlighted the significant amount of research in child biomechanics that can be drawn on by designers of child restraint systems. This has led to solutions in restraint design that are tailored to the child's level of growth and development. The performance of these solutions in real accidents confirms that children can withstand the forces in a collision when they are restrained appropriately and according to their level of development. No relevant literature could be found on the biomechanical characteristics of children that use wheelchairs. Nevertheless, it seems likely that some of the same principles for restraint design would apply.

Another section of the literature review examined current practices in the restraint of children in wheelchairs in M category vehicles. This was based on discussions with organisations involved in the carriage of children in wheelchairs and also on observations made of wheelchair transportation at a special school. It was not intended to be a scientific study, but instead provided a useful insight into some of the issues. This revealed that parents and carers of children in wheelchairs would appreciate any advice on the most appropriate way to restrain their children including when it is safe for them to travel while seated in their wheelchair. It would also appear that there is a wide variation in the quality of the vehicles and equipment used to transport children in wheelchairs. Transport operators would benefit, therefore, from further guidance on the ideal vehicle and restraint system specifications for the carriage and restraint of children in wheelchairs. Their drivers and escorts would benefit from further guidance on the need for and use of this equipment.

The final section of the literature review examined research carried out to investigate the performance of children's wheelchairs and restraint systems during collisions. Unfortunately, there was no information about their performance in real accidents. It is possible that very few accidents have occurred involving children seated in their wheelchair in a vehicle; however, it is also the case that accident databases are not usually detailed enough to record whether an occupant was seated in a wheelchair. Although some laboratory studies were identified in the review, these were relatively few in number and tended to focus on manual wheelchairs with a dummy that represented a six year old child.

## 2.2 Field study

### *2.2.1 Approach*

The field study investigated the way children and their wheelchairs interact with real vehicles and restraint systems. A range of representative wheelchairs and vehicles was used to identify potential problems in the orientation of the wheelchair, the location of vehicle structures and the geometry of the (wheelchair and occupant) restraint system. In each case, a dummy was seated in the wheelchair and restrained in a vehicle using whatever means were provided or recommended by the manufacturer. A qualitative assessment was then made of the potential problems within the vehicle environment or with the restraint system. A selection of the worst or most common problems that were identified in each vehicle fed directly into the test programme for further investigation.

### *2.2.2 Vehicles*

The project considered the safety of wheelchair occupants when travelling in M category vehicles which are defined according to the European Commission Directive 2007/46/EC (Annex 2). M category motor vehicles with at least four wheels used for the carriage of passengers are categorised as follows:

- M1: ≤ 8 seats in addition to the driver's seat.
- M2: > 8 seats in addition to the driver's seat and a maximum mass ≤ 5 tonnes.
- M3: > 8 seats in addition to the driver's seat and a maximum mass > 5 tonnes.

A number of different M category vehicles were examined for the field study. These were grouped as follows:

- M1 and M2 vehicles with forward facing wheelchair passengers. These included both converted small multi-purpose vehicles and minibuses.
- M1 and M2 vehicles with rear facing wheelchair passengers. In fact, no M2 vehicles were found in which a wheelchair user regularly travels rear facing. The vehicles examined were all M1 vehicles that were purpose built or specially adapted to function as a taxi.
- M3 vehicles with forward facing wheelchair passengers. These were coaches.
- M3 vehicles with rear facing wheelchair passengers. These were buses used on scheduled urban services.

For each group, a number of different vehicles were examined to ensure that the findings were not influenced by a particular example.

### 2.2.3 Wheelchair types

Four wheelchairs were used during the field study.  The wheelchairs were selected to represent the many different devices that children use. The four wheelchairs were:

- A folding manual wheelchair with a sling canvas seat.
- A rigid manual wheelchair for active users.
- An electric wheelchair with a reclining or tilting function.
- A buggy style wheelchair with a seat comprising a postural positioning system.

All four wheelchairs were production models loaned to TRL by the manufacturers.  The manual wheelchair, electric wheelchair and buggy were suitable for use in a vehicle as stated in the product literature.  The active user wheelchair was not suitable for use in a vehicle; however, this type of wheelchair is popular with some children and may be used in transport despite the manufacturer's instructions.  The wheelchairs are shown in Figure 1.

Basic manual wheelchair

Active wheelchair

Electric wheelchair

Buggy style wheelchair

**Figure 1** Wheelchairs used in the field study

It was understood that these wheelchairs represented a limited cross section of the devices available for children. However, for the purposes of the field study, they included a number of key features shared by the many different designs that are found. It was concluded, therefore, that the selection of wheelchairs covered the widest range of features considered to be important for the investigation of wheelchair interaction with vehicles.

## 2.3 Impact protection

### *2.3.1 Approach*

The impact test programme was carried out in two phases. The first phase was intended to identify any problems in the way children in wheelchairs travel in vehicles and compare their level of protection with that for children in vehicle based restraint systems.

After the first phase was completed, the results were analysed to determine where children in wheelchairs received lower levels of protection. The aim was to propose solutions that could increase the level of protection afforded to children in wheelchairs in line with children in vehicle based restraints. It was anticipated that these solutions could be encouraged through recommendations for vehicle legislation; however, it became apparent that wheelchair design may also need to be addressed. The second phase of testing was carried out to evaluate possible solutions, where necessary.

### *2.3.2 Vehicles*

Impact protection was examined for children travelling forward or rear facing in M category motor vehicles. M category vehicles are defined in the European Commission Directive 2007/46/EC (Annex 2) and in Section 2.2.2 of this report. For the purposes of the project, the vehicles were grouped as follows:

- M1 and M2 vehicles with forward facing wheelchair passengers.
- M1 and M2 vehicles with rear facing wheelchair passengers.
- M3 vehicles with forward facing wheelchair passengers.
- M3 vehicles with rear facing wheelchair passengers.

Previous research with adult dummies demonstrated that there is a lower risk of injury in M3 vehicles compared with M1 and M2 vehicles (Le Claire *et al.,* 2003). While it would have been desirable to examine all vehicle categories in this test programme, it was necessary to prioritise M1 and M2 vehicles. This allowed thorough investigation of M1 and M2 vehicles with a more comprehensive range of children's wheelchairs. Recommendations were made for M3 vehicles, but these were based on observations of the vehicles and on the test results for M1 and M2 vehicles.

### *2.3.3 Crash test pulses*

Le Claire *et al.* (2003) highlighted that the dynamic test conditions in UNECE Regulation 44 (Child Restraint Systems) were appropriate to represent a collision in an M1 or an M2 vehicle. The UNECE Regulation 44 test conditions were therefore used in the test programme to examine the level of protection afforded to children in wheelchairs.

It is important to note that the conditions for the dynamic test in UNECE Regulation 44 differ from those in the ISO Standards for wheelchair safety in transport (ISO 7176-19:2001 and ISO 10542-1:2001). The differences are summarised in Figure 2.

UNECE Regulation 44 prescribes separate limits for deceleration and acceleration sleds. For example, the impact speed, deceleration curve and stopping distance of the sled are required for deceleration devices.

The impact speed is the speed of the sled immediately before the impact when no external forces are in action.  The sled deceleration curve must fall within an upper and lower limit, which form a corridor.  Although the limits are relatively wide, it is impossible to achieve a deceleration curve that follows either limit of the corridor with an impact speed of $50\ ^{+0}_{-2}$ km/h and a stopping distance of 650 ± 50 mm.  In the case of acceleration devices, the total velocity change and deceleration curve are required.  The same corridor is used; however, there is an additional requirement (for acceleration devices) which states that the curve must rise above a defined line within the corridor.  This line is also illustrated in Figure 2.

The ISO Standards do not prescribe separate limits for deceleration and acceleration devices.  Instead, there are limits for the velocity change and deceleration curve irrespective of the type of sled.  The overall velocity change is usually determined by integration of the curve and can incorporate the rebound phase of an impact when a deceleration sled is used.  The upper limit that is applied to the sled deceleration or acceleration curve is similar to that in UNECE Regulation 44; however, it does not limit the gradient of the curve during the onset.  The lower limit does not form a fixed corridor.  Instead, the curve must exceed certain levels of deceleration for the periods of time indicated in Figure 2.

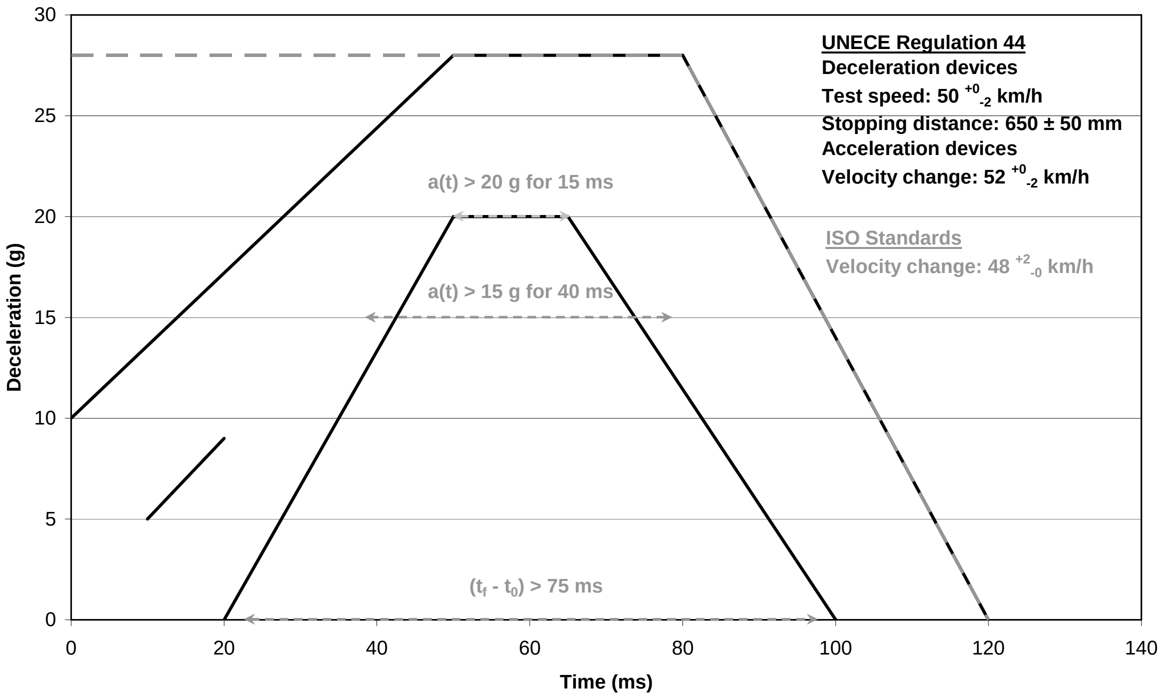



**Figure 2** Comparison of UNECE Regulation 44 test conditions with ISO Standards

The key difference in the test conditions is the use of impact speed or increased velocity change (for acceleration sleds) in UNECE

Regulation 44 and velocity change (irrespective of the sled type) in the ISO Standards. For instance, an impact speed of 50 km/h results in a total velocity change in excess of 50 km/h due to the contribution of the rebound speed. While the velocity change in the ISO Standards is $48^{+2}_{-0}$ km/h, kinetic energy increases as a function of the square of the velocity. Hence this moderate difference can influence the severity of the test quite markedly.

This is illustrated further by Figure 3, which compares the mean sled deceleration in a sample of five UNECE Regulation 44 tests with a sample of five ISO tests. The higher impact speed and consequently velocity change in the UNECE Regulation 44 tests resulted in higher levels of sled deceleration than the ISO tests. Furthermore, the higher levels of deceleration were maintained for a longer period, which included the phase of the impact when the occupant was in contact with the restraint system.

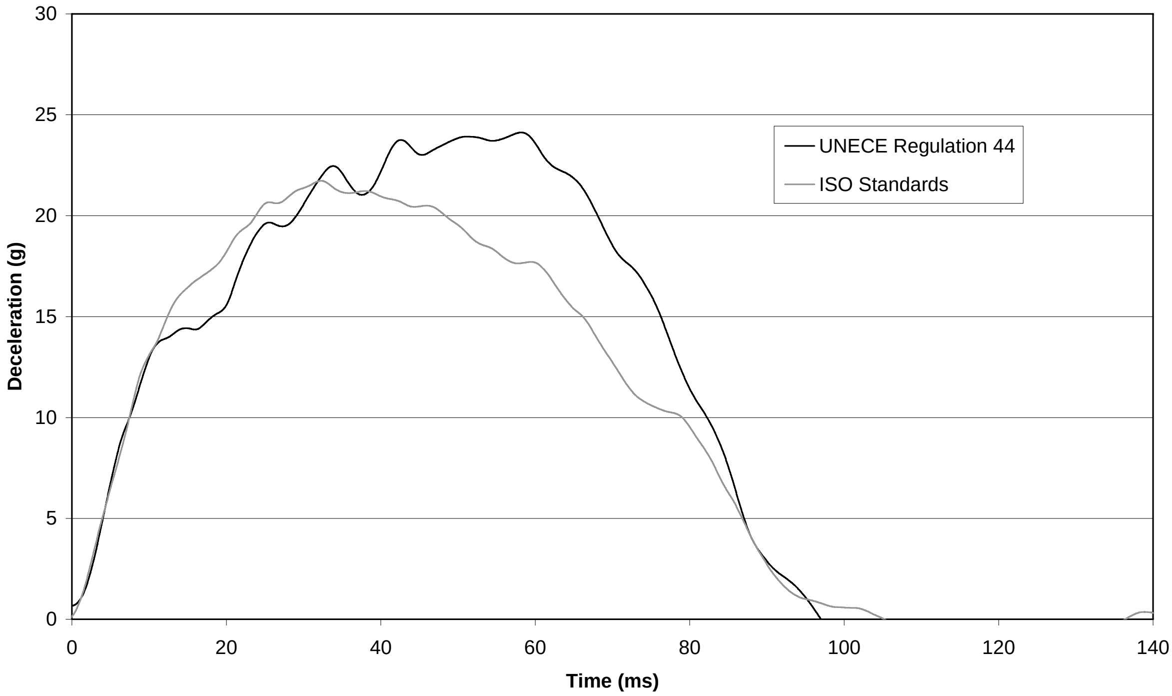



**Figure 3** Comparison of UNECE Regulation 44 deceleration curves with ISO Standards

### *2.3.4 Wheelchair types*

TRL examined the wheelchair market to gain an understanding of the different wheelchairs that children use. The aim was to highlight the key aspects of their design that could affect their performance in a vehicle collision. The outcome of this approach was a selection of wheelchairs to use in the test programme.

There are various ways of classifying the different types of wheelchairs on the market. For the purposes of this project, the following categories were used:

- Buggies.

- Manual wheelchairs.

- Electric wheelchairs.

Some children are provided with a supportive seating system for comfort and posture. These commercial or custom made seating systems fit on the top of a buggy or wheelchair chassis. However, it is sometimes the case that the seating system has a different manufacturer than the base or wheelchair with which it is being used. Seating systems are common in the children's wheelchair market and were therefore included as an additional category for investigation in the project.

The remainder of this section looks at the different wheelchairs within each category and introduces the wheelchairs selected for the impact test programme.

*Buggies*

There are many different buggy models on the market; however, two distinct styles have emerged. Throughout this report, these will be referred to as basic buggies and supportive buggies. Basic buggies have a reinforced nylon or fabric seat without additional support for the child. The key features to examine when children are travelling in a vehicle are:

- The seat is forward facing and can have an adjustable backrest angle.

- The backrest may be tall enough to support the child's head.

- A harness is usually fitted for management of posture.

- The push handles are large on some models and extend rearwards of the buggy.

Supportive buggies are fitted with various support pads that help to keep the child in a stable position. The key features to examine when children are travelling in a vehicle are:

- The seat is usually forward facing, but some rear facing and some interchangeable models are available.

- Postural supports can be fitted near to the child's head, upper body, hips and legs.

- The seat and backrest tend to be rigid to allow the postural supports to be attached securely.

- The backrest may incorporate a headrest.

- A harness is usually fitted for management of posture.

- The backrest is usually adjustable for angle and some models allow the seat and backrest to be fixed while they are tilted rearwards.

- The push handles are large on some models and extend rearwards of the buggy.

TRL used both basic and supportive buggies in the test programme. These are shown in Figure 4 and Figure 5 respectively. The devices were production models and were suitable for use forward facing in a vehicle, as stated in the product literature.

**Figure 4** Basic buggy

**Figure 5** Supportive buggy

*Manual wheelchairs*

There are various terms in use to describe manual wheelchairs. However, in this report, manual wheelchairs are referred to as basic wheelchairs or active user wheelchairs. With the use of the wheelchair in a vehicle in mind, this approach took account of the key differences found between certain models.

Basic wheelchairs are the archetypal or classic wheelchairs familiar to most people. They can be self propelling or attendant propelled. The key features to consider when children are travelling in a vehicle are:

- The backrest is high enough to stabilise the lower thoracic region.

- The backrest is usually upright, but some models can be fitted with a reclining backrest. In comfort wheelchairs, the seat and backrest can be fixed while they are tilted rearwards.

- A headrest can be fitted as an accessory.

- Side guards are fitted to the wheelchair to protect the user's clothes from splashes from the wheels.

- Push handles are usually fitted, even in the case of self propelling models.

Active user wheelchairs are lighter than basic wheelchairs and can be more adjustable. The key features to consider when children are travelling in a vehicle are:

- The backrest is relatively low compared with other wheelchair types.

- A headrest is unlikely to be fitted.

- Side guards are fitted to the wheelchair to protect the user's clothes from splashes from the wheels.

- Push handles are not usually fitted.

TRL used basic and active user wheelchairs in the test programme. The basic wheelchair is shown in Figure 6. A reclining version was also used and is shown in Figure 7. The active user wheelchair is shown in Figure 8.

The basic manual wheelchairs were both suitable for use in a vehicle forward facing, as stated in the product literature.  The active user wheelchair was not suitable for use in a vehicle; however, it was included in the test programme to examine whether it would be possible to develop some means of allowing these wheelchair users to travel while seated in their wheelchairs.

**Figure 6** Basic manual wheelchair


**Figure 7** Reclining basic manual wheelchair


**Figure 8** Active user manual wheelchair

*Electric wheelchairs*

Although there is a wide range of electric wheelchairs available for children, the most common devices are fairly typical in design. The key features to consider when children are travelling in a vehicle are:

- They are powered by rechargeable batteries that are usually positioned at the rear of the wheelchair chassis. This can result in a gap between the rear of the backrest and the rear of the chassis.
- A headrest can be fitted as an accessory.
- The backrest is usually adjustable for angle and some models allow the seat and backrest to be fixed while they are tilted rearwards.

TRL used an electric wheelchair in the test programme. This is shown in Figure 9.

**Figure 9** Electric wheelchair

*Supportive seating systems*

Supportive seating systems help children to achieve a functional seating position. Some systems are modular, while others are permanently moulded to an individual. Modular seating systems are built up from a number of adjustable components. The key features to consider when children are travelling in a vehicle are:

- Postural supports can be fitted near to the child's head, upper body, hips and legs.
- A headrest is likely to be fitted to the seating unit.
- A harness is usually fitted to assist posture.
- Many systems aim to achieve a stable, upright, seated position; however, some children are provided with a tilt-in-space unit. These allow the seat and backrest to remain fixed while they are tilted rearwards.

Moulded seating systems are unique to each user's anatomy. The key features to consider when children are travelling in a vehicle are:

- The moulded seat follows the contours of the body very closely.
- A harness is also fitted to assist posture.

Two modular seating systems were used in the test programme; one was used with an upright base, while the other was used with a tilt-in-space base. These are shown in Figure 10 and Figure 11 respectively. A moulded seating system was not used in the project. A child in a moulded seat would not be accommodated easily by a standard wheelchair tie-down and occupant restraint system. Furthermore, current test dummies would not permit a full investigation of the situation. Although a seat could be moulded to a crash test dummy, it could not reproduce the physical characteristics and issues associated with certain medical conditions.

**Figure 10** Supportive seating system with an upright base

**Figure 11** Supportive seating system with a tilt-in-space base

*2.3.5 Anthropometric dummy selection*

TRL considered three types of child dummies for the impact test programme: the P Series, the Q Series and the Hybrid III Series. Each dummy approximates the weight and size of children at the age they are intended to represent. There are, however, differences in their geometry and material properties such that dummies representing the same age can display markedly different behaviour in dynamic tests. This is because part of the challenge of designing a child dummy is the lack of biomechanical data for children. In an attempt to address this, the biomechanical response requirements for adult dummies are scaled to give corresponding requirements for children. Unfortunately, the techniques used and the assumptions made can influence the dummy requirements.

For these reasons, the P, Q and Hybrid III Series of child dummies differ greatly, both in terms of their degree of biofidelity and also their measurement capacity. The P Series was developed in the late 1970s alongside UNECE Regulation 44, which came into force in 1982. The Regulation describes a full range of dummies representing children from birth to ten years. The P Series has subsequently been adopted by the European New Car Assessment Programme (EuroNCAP) and a great deal of experience has been gained in the use and capabilities of this dummy.  The advantage of the P Series is its low cost and robustness for routine testing of restraint systems; however, it is not biofidelic and has very limited measurement options.  Instrumentation is fitted in the head, chest and in some cases the neck, but the head acceleration is known to be unreliable and is not part of the Regulation.  Although there are no injury criteria for the dummy, limits are applied to the head excursion and chest acceleration in Regulation 44.

The Q Series was developed as a potential successor to the P Series.  It represents a significant improvement in terms of its measurement capacity; however, a number of issues remain to be resolved before the dummy can be considered as a replacement for the P Series in regulation.  Research carried out by TRL showed that the behaviour of the Q Series in dynamic tests is different to the P Series.  However, no comment can be made on the biofidelity of the Q Series, because it is yet to be agreed and published.  Although its measurement capacity is an advantage, there are no injury criteria or regulatory limits that can be used with this dummy.  Progress towards injury risk curves was started by the European Commission CHILD project, but the curves were not developed fully within the project and the work is ongoing.

The Hybrid III Series was developed in the USA by the Society of Automotive Engineers' Biomechanics Committee and the National Highway Transportation Safety Administration (NHTSA).  The dummy has been adopted by the Federal Code in the USA (49 CFR Part 572 Subparts N and P) and is mandated for use in testing child restraint systems to meet Federal Motor Vehicle Safety Standard No. 213 (FMVSS 213).  The dummy has demonstrated robustness in private wheelchair tests carried out by TRL and has the capacity for greater measurement than the P Series.  The main advantage of the Hybrid III Series, however, is the availability of regulatory performance limits from FMVSS 213 and additional published injury criteria in the literature.

Table 1 summarises the differences between the three dummies.  TRL selected the Hybrid III Series for the project because it represents the best option in terms of measurement capacity and injury criteria.

## Table 1 Comparison of child dummies

| | P Series | Q Series | Hybrid III Series |
|---|---|---|---|
| **Robustness** | Significant damage unlikely | Not established for this type of testing | Used by TRL in private wheelchair testing without damage |
| **Availability** | Full range from birth to 10 years | Birth to 6 years | 3 years to 10 years |
| **Measurement capacity** | Chest acceleration. Head unrealistic except in P1.5 | All body regions | All body regions |
| **Injury criteria** | None, but has regulatory limits for chest acceleration | None | Scaled injury criteria available and some regulatory limits |
| **Cost of use, calibration and damage** | Low | High | Medium |

### *2.3.6 Injury criteria*

The performance limits for the dynamic test in FMVSS 213 apply to the Head Injury Criterion (HIC) and resultant chest acceleration recorded with the Hybrid III Series. However, additional injury criteria have been proposed in the literature for these and other body regions of the dummy (Eppinger *et al.,* 2000; Mertz *et al.,* 2003).

Injury criteria and their associated limits can be a useful means of interpreting dummy measurements. They are usually derived from Post Mortem Human Subject (PMHS) tests occasionally supplemented with volunteer tests. Animal tests and accident reconstructions are also techniques that are used, but much less frequently. The standard method is to replicate the human tests with the dummy and then compare the dummy measurements with the presence or absence of injury. Statistical methods are used to create injury risk curves, from which the injury limits are taken to represent a percentage risk of injury.

The PMHS samples available for such research tend to be elderly adults. There are a number of ethical considerations that have limited the use of PMHS children to a few tests, while the use of children in volunteer testing is impossible. For these reasons, there are few data available from which to develop injury risk functions and subsequent limits for child dummies. However, this is sometimes resolved by scaling injury limits for adults to take into account the differences in mass, size and stiffness between adults and children.

Eppinger *et al.* (2000) presented a set of injury criteria and limits for several dummies including the Hybrid III three year old and the Hybrid III six year old. The Hybrid III ten year old had not been developed at that time. Mertz *et al.* (2003) presented a set of updated injury limits for the Hybrid III three and six year old dummies and also provided limits for the ten year old dummy. Some of the limits presented by Mertz *et al.* (2003) differed slightly from Eppinger *et al.* (2000), possibly because different assumptions were made during the scaling process or because the values were chosen to represent a slightly different risk level.

Exceeding an injury limit does not necessarily imply that a child would experience the associated injury. It is usually the case that the limit values are chosen to represent a relatively low risk of injury, typically a 5 percent risk of Abbreviated Injury Scale (AIS) ≥ 3 injury. Furthermore, the relationship between injury and the corresponding injury criteria and scaled limit is not well established for children. It is essential, therefore, to take a pragmatic approach when applying the injury criteria and limits to child dummy measurements.

A summary of the injury criteria and associated performance limits is given in Appendix C.

### *2.3.7 Impact test equipment*

The Impact Sled Facility (ISF) at TRL was used for the test programme. The ISF comprises a rail mounted sled which is accelerated by elastic cords and decelerated by polyurethane deceleration tubes and olives. Dummy measurements were recorded by a DTS data acquisition system. The data were analysed using the frequency response classes described in SAE J211 (2003).

Two high speed digital cameras (500 fps) were used to record each impact test. One camera was positioned perpendicular to the sled to show the dummy at the point of impact and during its subsequent motion. Another camera was positioned to observe lap belt penetration in the forward facing tests or interactions with the bulkhead in the rear facing tests.

## 2.4 Non-impact protection

### *2.4.1 Background*

The Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended) allow a wheelchair user on an urban bus to travel rear facing in a protected area, against a back restraint or bulkhead. The Regulations also demand a method for restricting lateral movement of the wheelchair into the gangway, such as a vertical stanchion. Previous research carried out for the DfT by TRL examined the extent of such movement during normal driving conditions (Le Claire *et al.*, 2003). A dummy was seated in a wheelchair, while a bus was driven through a manoeuvre that generated levels of lateral acceleration similar to those recorded on real bus routes. Wheelchair displacement was observed, but it was restricted by the vertical stanchion on the edge of the wheelchair space. Children's wheelchairs are narrower than those for adults and some have pushchair style handles. It was necessary to examine, therefore, whether the back restraint or methods for restricting lateral movement described in the Regulations are adequate for children's wheelchairs.

### 2.4.2 Approach

A child dummy was seated in a wheelchair in the wheelchair space of a low floor bus. The vehicle was then driven through a manoeuvre that generated up to 0.4 g of lateral acceleration. Similar acceleration levels were recorded in real journeys by Stone (1999; unpublished Project Report).

Different sized dummies and different wheelchair types were used to examine whether the key features of the wheelchair space in current vehicles are appropriate for children. The study methodology and findings are presented in detail in Section 7.

### 2.4.3 Vehicles

Two low floor vehicles were used for the study; one was fitted with a vertical stanchion, the other with a retractable rail.

### 2.4.4 Driving conditions

The vehicle was driven in a semicircle with a radius of 20 metres, at a speed of 21 - 23 miles per hour.

### 2.4.5 Wheelchair types

The wheelchairs used for these experiments were those used in the field study. These are shown in Section 2.2.3 in Figure 1.

# 3 M1 and M2 forward facing

## 3.1 Field study

The field study included several M1 and M2 vehicles in which a passenger in a wheelchair travels forward facing. In each vehicle, dummies representing children aged three, six and ten years old were seated and restrained in a range of wheelchairs. An overview of the methods was given in Section 2.2 and the results of the study are described in detail in Appendix B.

The study highlighted three main areas of concern: the geometry of the occupant restraint system, the protection of the child's head behind the wheelchair and finally the amount of clear space around the child. In previous research with adult dummies, the location of the diagonal belt anchorage was an important factor in the performance of both the wheelchair and the restraint system (Le Claire *et al.,* 2003). Dynamic sled tests demonstrated the benefit of an upper anchorage point compared with a floor mounted anchorage. While the location of the diagonal belt anchorage was also important for children, the field study revealed that the path of the lap belt was the critical aspect of the restraint geometry.

The geometry of the lap belt was influenced by the location of the anchorages in the vehicle, but also by the design of the wheelchair. In M1 vehicles with a permanent wheelchair space, the lap belt anchorages were relatively wide to allow access to the space from the rear and to accommodate a range of wheelchairs and occupants. However, this tended to reduce the contact area between the lap belt and the dummy's pelvis, which might have affected its performance in a collision. In M1 and M2 vehicles with a flexible wheelchair space, the lap belt anchorages and consequently the seat belt buckle were attached to floor tracking behind the wheelchair. As a result, it was sometimes the case that the diagonal part of the seat belt passed around the ribs of the dummy before joining the lap belt at the buckle. The wheelchair influenced the geometry of the lap belt by obstructing its path. These obstructions were caused by side guards fitted to the wheelchair to protect the user's clothes from wheel splash and by hip support pads fitted to the wheelchair to meet the user's postural needs.

None of the vehicles examined provided a head and back restraint for the wheelchair user. Furthermore, in the smaller vehicles the rear of the dummy's head was in close proximity to the vehicle structure or boarding

aid. In a collision, a child would have been at risk of neck injury through overextension or of head injury through contact with the vehicle.
The amount of space in front of the wheelchair user was also important, but varied significantly between vehicles. In one of the smallest vehicles, the space was limited and the legs of the dummy were adjacent to rigid parts of a folded seat. It was possible that the head of a child in a similar position may also have been able to contact these parts in a collision.

## 3.2 Scope of testing

The aim of the test programme was to examine whether children in wheelchairs and children in vehicle seats or child restraints are likely to receive a comparable level of protection in a collision. When children travel forward facing, their protection is influenced by their wheelchair, the vehicle they are travelling in and also by the restraint system.

When it is used in transport, a wheelchair takes the place of a vehicle seat. It must, therefore, be able to withstand the forces in a crash without transferring excessive forces to the child, to the same extent as a vehicle seat. This is partially explored by the dynamic test in ISO 7176-19:2001; however, the Standard does not address occupant loading. Since children use a range of different wheelchairs, as highlighted in Section 2.3.4, it follows that the type of wheelchair could influence their risk of injury in a collision. Furthermore, each wheelchair type has various features and adjustments that could also affect the risk of injury. With these points in mind, it was considered important for the project to include all types of wheelchairs in common use by children. It was also considered important to investigate the effect of the features and adjustments that were most relevant for transport.

Assuming that the vehicle is crashworthy and there is no passenger compartment intrusion, the layout of the interior is the main way that the vehicle can influence the risk of injury. The environment must be compatible with children's needs during a collision. However, the field study revealed that this can vary from vehicle to vehicle. Once again, it was considered important for the project to address these issues.

The restraint system comprises a wheelchair restraint to hold the wheelchair in place and an occupant restraint to prevent ejection and reduce the risk of contact with the vehicle interior. It is vital that the occupant restraint also absorbs and distributes the impact forces over the strongest parts of a child's body. This is partially explored by the dynamic test in ISO 10542-1:2001, but again, the Standard does not address occupant loading. As a result, there are several devices on the market with a similar performance in terms of occupant excursion, but they may perform differently in terms of occupant protection. For instance, there are static belt systems, single inertia reel systems and double inertia reel systems. Some include a third point, similar to the upper anchorage point in cars, while others do not.

A very large test programme would be required to examine every combination of wheelchair, vehicle and restraint system, particularly when all the various types and adjustments are considered. TRL and the DfT agreed a more pragmatic approach, which was to test a series of common worst cases. This approach was used for the wheelchair and vehicle issues; however, a different approach was used for the restraint system.

Most wheelchair restraints on the market are four point webbing restraints. These can include adjustable straps or retractable straps; however, their performance is similar; hence this feature is unlikely to influence the risk of injury. Clamps were available in the past, but are now discontinued. With this in mind, a typical four point webbing restraint with adjustable rear straps was used in all the forward facing tests.

Most wheelchair occupant restraints include a lap and diagonal seat belt. Some offer a better fit while others offer better energy absorption. TRL considered the likely performance of different systems with children and also their market share in the UK and Europe, but there was no clear choice of which to use in the test programme. Following consultation between TRL, the DfT and two of the leading manufacturers in the UK, a surrogate occupant restraint was developed. The advantage of the surrogate restraint was that it displayed the characteristics of several production devices.

The surrogate occupant restraint consisted of a single inertia reel and an upper anchorage point. The relative merit of an upper anchorage point compared with a diagonal belt attached directly to the floor was established for adults by Le Claire *et al.* (2003). It seemed likely that dynamic tests to investigate this issue for children would make the same observations. Diagonal belt anchorage location was not, therefore, investigated in the test programme.

The surrogate occupant restraint, like many market products, could be installed with a range of belt angles. There is a great deal of research and knowledge to draw from when recommending the most appropriate angles for seat belt webbing. Hence this aspect of the restraint system was not investigated in the test programme.

In summary, a worst case approach was adopted when selecting the wheelchair and vehicle issues to examine in the test programme. In each test, the wheelchair was restrained by a common four point webbing system while the occupant was restrained by a surrogate lap and diagonal seat belt with upper anchorage. The seat belt was installed to achieve the best fit possible for the particular wheelchair.

## 3.3 Test design – phase 1

As a starting point, the key wheelchair and vehicle design issues were combined in order to determine which issues should be examined in more depth. The next step was to take these issues and construct a matrix for each type of wheelchair. Each matrix displayed all the tests that would be required to complete the picture for the particular wheelchair when it was used forward facing in an M1 or M2 vehicle. The final step was to apply our knowledge of impact biomechanics and injury mechanisms to identify priorities within each matrix. These priorities would be used to develop solutions for all combinations of wheelchair type, adjustment and child occupant size, etc. The following sections outline this process.

### *3.3.1 Key issues*

Tables 2 to 5 each represent a type of wheelchair. The first row in each table lists the key issues for that device when it is used forward facing in an M1 or M2 vehicle. There were a number of different options or adjustments for each issue that might affect a child's risk of injury in a crash. The most important issues for a particular wheelchair were selected on the basis of their frequency and likely influence on injury. In each table, a tick means that the issue was examined in the test programme and a square means that the most common or worst case was adopted during the test set up, as appropriate. A shaded cell means that no option or adjustment was possible for that wheelchair.

Table 2 describes the key issues for buggies when children travel forward facing in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in a buggy and were therefore considered for the test programme. When a backrest is reclined, the child's pelvis is tilted rearwards. This could increase the likelihood of the lap belt slipping off the pelvis in a collision and loading the abdomen. When a backrest is upright (i.e. 80 - 90˚), the lap belt can engage better with the pelvis, but head excursion will be greater so the space in front of the wheelchair becomes more important. When the seat and backrest are fixed but tilted rearwards, there is also a risk that the lap belt could slip off the pelvis. This risk might be mitigated by the angle of the seat, but it is more likely that the seat cushion would compress or the buggy would deform during the collision. The size of a child affects the way they load the wheelchair and restraint system. It also affects the amount of clear space needed in the vehicle around the wheelchair.

Most children using a buggy will have a positioning harness. This might interfere with the path of the seat belt and could increase loads to the child if the harness buckle rests under the belt. Although the presence of a harness could be important, differences in design may not affect the injury mechanisms greatly. A typical positioning harness was therefore fitted in all tests with a buggy.

The seat is usually forward facing in a buggy, but some models have rear facing seats while others have dual facing seats. Although the effect of the seat orientation could be significant, only a few products display this feature and it seems likely that most buggies will be used with the seat installed forward facing. Seat orientation was not, therefore, investigated in the test programme.

In some vehicles, the lower seat belt anchorages are positioned outboard of the wheelchair. When this is the case, the contact area between the lap belt and the pelvis is reduced and the path of the belt is potentially more susceptible to obstruction from the side structure of the wheelchair. Although the position of the lower anchorages could be important for children in buggies, it was not possible to investigate the issue with every wheelchair type.

Table 3 describes the key issues for manual wheelchairs when children travel forward facing in M1 or M2 vehicles. Backrest angle, occupant size and seat belt lower anchorage position were identified as having the greatest potential to affect the injury mechanisms in a manual wheelchair and were therefore considered for the test programme. As discussed above, the backrest angle can affect the likelihood of the belt remaining on the pelvis and it can affect the dummy excursion. Occupant size can affect the wheelchair and restraint loading and the space needed in the vehicle.

When the lower anchorages of the seat belt are outboard of the rear wheels, the contact area between the lap belt and the pelvis is reduced. It may also be the case that the lap belt needs to pass through the side of the wheelchair.  This may be difficult if large side guards are fitted. Seat belt anchorage location was considered for the basic manual wheelchair to examine whether there was an increased risk of abdomen injury in a collision.

Although tilt angle may affect the likelihood of the belt remaining on the pelvis, tilting manual wheelchairs (i.e. comfort wheelchairs) are not used widely by children.  This issue was not investigated in the test programme.

Most manual wheelchairs are fitted with side guards to protect the child's clothes from spray thrown up by the wheels.  Although they perform an important function, they can complicate the fitment of the occupant restraint in a vehicle.  This aspect of the wheelchair design is not necessarily covered when a wheelchair is assessed for ISO 7176-19:2001.  Side guards were fitted, therefore, in all tests with manual wheelchairs.

**Table 2 Buggies – key issues**

| Seating type | Backrest angle | Tilt angle | Postural belts | Seat direction | Occupant size | Lower anchorages |
|---|---|---|---|---|---|---|
| **Basic** | ✓ | ✓ | □ | | ✓ | □ |
| **Supportive** | ✓ | ✓ | □ | □ | ✓ | □ |

**Table 3 Manual wheelchairs – key issues**

| Frame type | Backrest angle | Tilt angle | Side guards | Occupant size | Lower anchorages |
|---|---|---|---|---|---|
| **Basic** | ✓ | □ | □ | ✓ | ✓ |
| **Active user** | ✓ | | □ | ✓ | □ |

Table 4 describes the key issues for electric wheelchairs when they travel forward facing in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in an electric wheelchair and were therefore considered for the test programme. As discussed above, the backrest angle can affect the likelihood of the belt remaining on the pelvis and it can affect the dummy excursion. Tilt angle may also affect the likelihood of the belt remaining on the pelvis. Occupant size can affect the wheelchair and restraint loading and the space needed in the vehicle. The location of the lower seat belt anchorages can affect the contact area between the lap belt and the pelvis; however, this was not identified as a priority for electric wheelchairs.

**Table 4 Electric wheelchairs – key issues**

| | **Backrest angle** | **Tilt angle** | **Occupant size** | **Lower anchorages** |
|---|---|---|---|---|
| **Electric** | ✓ | ✓ | ✓ | □ |

Table 5 describes the key issues for supportive seating systems when they travel forward facing in M1 or M2 vehicles. Moulded seating systems were not investigated in the test programme. A child in a moulded seat would not be accommodated easily by a standard wheelchair tie-down and occupant restraint system. Furthermore, current test dummies would not permit a full investigation of the situation. Although a seat could be moulded to a dummy, it could not reproduce the physical characteristics and issues associated with certain medical conditions. The restraint of a child in a moulded seat may require a bespoke solution to meet their particular needs. However, it was impossible to examine individual cases within the project.

Tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in a modular seating system and were therefore considered for the test programme. As discussed above, tilt angle may affect the likelihood of the belt remaining on the pelvis. Occupant size can affect the wheelchair and restraint loading and the space needed in the vehicle.

There are various types and levels of support used within modular seating units. Although it would be desirable to understand the effects of the different levels of support that are available, the number of tests required for such an assessment was too high to consider for this project.  As such, this issue was not examined in detail, but a modular seating system was used with the full range of support equipment fitted.

Most children using a modular seating system will have a positioning harness.  This could interfere with the occupant restraint system in the vehicle, but the type of harness may not affect the injury outcome greatly.  A common positioning harness was fitted in all tests with modular seating systems.

The position of the lower anchorages could be important for children in seating systems because the contact area between the lap belt and the pelvis is reduced and the path of the belt is potentially more susceptible to obstruction from the side structure of the wheelchair.  However, it was not possible to investigate this issue for seating systems.

**Table 5 Supportive seating systems – key issues**

| Seating system | Tilt angle | Supports | Postural belts | Occupant size | Lower anchorages |
|---|---|---|---|---|---|
| **Modular** | ✓ | □ | □ | ✓ | □ |
| **Moulded** | | | | | |

*3.3.2 Final test selection*

Having identified the key issues that demanded further investigation, the next step was to take these issues and construct a matrix for each type of wheelchair.  These are shown in Tables 6 to 9.  Each matrix displays all the tests that would be required to complete the picture for the wheelchair when it is used forward facing in an M1 or M2 vehicle.  While it would be desirable to perform all the tests in each table, a number of priorities were identified, which could be used to investigate the issues and develop solutions for all combinations.  A tick meant that a test was selected for the final test matrix.

Table 6 shows all the tests that would complete the picture for children travelling forward facing in buggies in M1 or M2 vehicles.  Backrest angle, tilt angle and occupant size were identified as key issues for both types of buggy.  The pelvis is tilted rearwards when a backrest is reclined. Hence, there is a greater risk of the lap belt slipping off the iliac crests and loading the abdomen.  This risk is reduced when a backrest is upright, but the risk of head injury might increase because a child's head is further forwards in the wheelchair space.  There might also be a risk of the lap belt loading the abdomen when the seat and backrest are tilted rearwards.

Buggies are usually available with different seating dimensions and some can be adjusted. The smallest seat size for a typical basic buggy would hold a six year old child dummy and the largest size would hold a ten year old dummy. The smallest seat size for a typical supportive buggy would hold a three year old child dummy and the largest size would hold a six year old dummy. There might, of course, be some exceptions; however, these sizes seemed to reflect the seats in most buggies.

If a basic buggy was used upright during an impact, the head excursion with a larger child would be higher than the head excursion with a smaller child. Although it could be argued that a smaller child would have a lower tolerance to injury if head contact occurred, the larger child represents the worst case in terms of the space required. The ‘upright’ test with the ten year old dummy was therefore selected as the priority in Table 6.

If a basic buggy was reclined during an impact, the lap belt would be more likely to slip off the pelvis if the child was small, because their iliac crests would be less well developed. The ‘reclined’ test with the six year old dummy was therefore selected as the priority.

A similar approach was taken for supportive buggies. If the backrest was upright during a collision, a larger child would experience greater head excursion than a smaller child. The ‘upright’ test with the six year old dummy was therefore selected as the priority. If a supportive buggy was reclined, the lap belt would be more likely to slip off the pelvis of a small child. The ‘reclined’ test with the three year old dummy was therefore selected as the priority.

Although some buggies are available with a tilting seat, TRL concluded that the issues around tilt-in-space could be investigated better with another type of wheelchair. As a result, no ‘tilted’ tests were prioritised for either type of buggy.

**Table 6 Buggies – test selection**

| Buggy | Backrest or tilt angle | Dummy | Priorities |
|---|---|---|---|
| Basic | Upright | 6 year old | |
| | | 10 year old | ✓ |
| | Reclined | 6 year old | ✓ |
| | | 10 year old | |
| | Tilted | 6 year old | |
| | | 10 year old | |
| Supportive | Upright | 3 year old | |
| | | 6 year old | ✓ |
| | Reclined | 3 year old | ✓ |
| | | 6 year old | |
| | Tilted | 3 year old | |
| | | 6 year old | |

Table 7 shows all the tests that would complete the picture for children travelling forward facing in manual wheelchairs in M1 or M2 vehicles. Backrest angle, lower anchorage position and occupant size were identified as key issues for manual wheelchairs.

As described above, the wheelchair backrest angle can influence the head excursion and path of the lap belt in a collision. The position of the seat belt lower anchorages can influence the contact area between the pelvis and the lap belt and might make the path of the lap belt more prone to obstructions from the wheelchair.

It was not the intention to carry out a large study of the effect of anchorage location. There is a significant amount of research on the subject and a range of angles for lap belts and lap belt anchorages are outlined in ISO 10542-1:2001. Instead, the intention was to investigate a specific situation observed during the field study whereby the lower anchorages were relatively wide to allow access to a permanent wheelchair space from the rear. This situation was represented by the outboard anchorage tests in Table 7.

The inboard location in Table 7 refers to M1 vehicles and M2 vehicles with a flexible wheelchair space where the lap belt anchorages are attached to floor tracking behind the wheelchair. This was the normal anchorage location for the test programme.

Basic manual wheelchairs usually have an upright backrest, but some models can be fitted with a reclining backrest. Active user wheelchairs have a small upright backrest only. Both types are usually available with different seating dimensions and active user wheelchairs can sometimes be adjusted. The smallest seat in a typical basic wheelchair with an upright backrest would accommodate a child similar in size to a three year old child dummy. The largest seat would accommodate a child similar in size to a ten year old dummy. The smallest seat in a typical basic wheelchair with a reclining backrest would accommodate a child similar in size to a six year old dummy and the largest seat would accommodate a child similar to a ten year old dummy. The corresponding dummies for a typical active user wheelchair are a six year old and a ten year old.

Children travelling in a basic upright manual wheelchair, with inboard lower anchorages, might be at risk of abdominal injury from submarining and head injury from head contact with the vehicle structure. Smaller children are more likely to submarine because their pelvises are less well developed; however, larger children experience greater head excursion and are more likely, therefore, to strike the vehicle or another wheelchair. In this instance, both the smallest and the largest needed to be considered because they are very different in terms of their level of development and therefore have different injury mechanisms. The three year old and the ten year old were therefore selected as the most important for children travelling in upright basic manual wheelchairs with inboard lower seat belt anchorages.

When the lower anchorages are outboard of the wheelchair, there is an added risk of poor lap belt fit and abdominal injury. The smallest children are most at risk, so the three year old dummy was selected as the most important for upright standard manual wheelchairs and outboard lower seat belt anchorages.

The risk of submarining could be greater in reclining wheelchairs because the pelvis is tilted rearwards. This could be an issue with both inboard and outboard lower seat belt anchorages, but smaller children are most at risk because their pelvises are less well developed and may not fully engage with the seat belt. Tests with the six year old dummy with inboard seat belt anchorages and also with outboard seat belt anchorages are therefore selected as most important in a reclined wheelchair.

The low backrest in active user manual wheelchairs places an additional risk to the back and spine of a child due to the lack of support in rebound. Larger children are likely to receive the least protection from the small backrest; hence the ten year old was selected as the priority for active user manual wheelchairs.

**Table 7 Manual wheelchairs – test selection**

| Manual wheelchair | Backrest angle | Lower anchorages | Dummy | Priorities |
|---|---|---|---|---|
| Basic | Upright | Inboard | 3 year old | ✓ |
| | | | 6 year old | |
| | | | 10 year old | ✓ |
| | | Outboard | 3 year old | ✓ |
| | | | 6 year old | |
| | | | 10 year old | |
| | Reclined | Inboard | 6 year old | ✓ |
| | | | 10 year old | |
| | | Outboard | 6 year old | ✓ |
| | | | 10 year old | |
| Active | Upright | Inboard | 6 year old | |
| | | | 10 year old | ✓ |

Table 8 shows all the tests that would complete the picture for children travelling forward facing in electric wheelchairs in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as key issues for electric wheelchairs. Based on the dimensions of the seat, electric wheelchairs are used by children that correspond in size to six year old and ten year old child dummies.

A child restrained in an electric wheelchair with an upright backrest during a collision would be at risk of head injury if their head struck the interior of the vehicle. It is also possible that wheelchair displacement might occur and apply loads to the child, which could result in chest and abdomen injuries. Younger children would be more susceptible to the risk of injury from wheelchair movement, while older children would experience greater head excursion and hence a greater risk of head contact. The level of risk perceived meant that it was necessary to consider both the youngest and oldest children. The six year old and the ten year old dummies were selected, therefore, for electric wheelchairs with an upright backrest. While it would be desirable to perform tests with reclined or tilted electric wheelchairs, it was decided not to include these devices after taking their prevalence for children into account.

**Table 8 Electric wheelchairs – test selection**

| **Wheelchair** | **Backrest or tilt angle** | **Dummy** | **Priorities** |
|---|---|---|---|
| Electric | Upright | 6 year old | ✓ |
| | | 10 year old | ✓ |
| | Reclined | 6 year old | |
| | | 10 year old | |
| | Tilted | 6 year old | |
| | | 10 year old | |

Table 9 shows all the tests that would complete the picture for children travelling forward facing in supportive seating systems in M1 or M2 vehicles. Tilt angle and occupant size were identified as key issues for supportive seats. Based on the dimensions of the seat, these are used by children that correspond in size with a range of child dummies from the three year old up to the ten year old.

If a seating system was used with an upright backrest during a collision, a child would be at risk of head injury if their head struck the vehicle interior. They would also be at risk of abdominal injury if the seat belt did not remain on the top of their thighs. Younger children are particularly at risk from poor belt fit and performance while older children experience greater head excursion. Both the youngest and oldest children needed to be considered to investigate both these risks because the injury mechanisms are different. The three year old dummy and the ten year old dummy were selected, therefore, as the priorities for supporting seating units with upright bases.

If a seating system was used with a tilt-in-space base during a collision, a child might be at risk of abdominal injuries due to submarining. Younger children are more likely to submarine; however, larger children would apply greater loads to the wheelchair seat base, which could increase their risk of submarining. Both the three year old and the ten year old dummies in a fully tilted wheelchair base were selected, therefore, as the priorities for seating systems with tilt-in-space wheelchair bases. While it would be desirable to perform tests across the full range of seat angle adjustment, fully tilted represented the greatest risk.

**Table 9 Supportive seating systems – test selection**

| Seating system | Tilt angle | Dummy | Priorities |
|---|---|---|---|
| Modular | Upright | 3 year old | ✓ |
| | | 6 year old | |
| | | 10 year old | ✓ |
| | Tilted | 3 year old | ✓ |
| | | 6 year old | |
| | | 10 year old | ✓ |

### *3.3.3 Test matrix*

The final step was to compile the tests identified as priorities from Tables 6 to 9. These are shown in Table 10, along with some baseline tests with the dummy restrained in a vehicle based restraint system. These tests represented the minimum required to investigate the key issues.

This vehicle scenario was intended to represent the range of vehicles in which wheelchairs travel in this way, from small converted vehicles (M1 vehicles) for the private market or for the taxi market up to minibuses (M2 vehicles) used for community transport.

In many ways, the wheelchair user travels in the same way in each of these M1 and M2 vehicles. The wheelchair is held in place, usually by means of a four point webbing restraint system attached to tracking in the floor of the vehicle. The wheelchair user wears a seat belt, which is also attached to this tracking. Occupant contact with the vehicle interior is possible during an impact, but there is no initial direct contact between the wheelchair (or user) and the vehicle walls or bulkheads. There was no need, therefore, for any representation of the interior surfaces of the vehicle in the test programme. The risk of contact was examined from dummy displacement measurements.

In some M1 vehicles, the lower seat belt anchorages are positioned outboard of the wheelchair to allow rear wheelchair access to the vehicle. When this is the case, it is possible that the lap part of the seat belt will fit less well on the child's abdomen. While it was desirable to combine M1 and M2 vehicles, this issue was also examined separately as shown in Table 10.

Whereas a wheelchair user may travel in similar circumstances irrespective of the vehicle category, this is not the case for other children. For instance, the vehicle seat in an M1 vehicle is different to that in an M2 vehicle and may, therefore, affect the level of protection afforded to the child. Furthermore, there is a legal requirement to use an additional child restraint system in an M1 vehicle (with some limited exceptions), but in an M2 vehicle, a child restraint must be used only if one is available.

The implication for the test programme was that a high number of baseline tests would be needed to cover each scenario. TRL and the DfT agreed a more pragmatic approach in order to maximise the number of tests available for the wheelchairs. It seemed likely that the effect of the vehicle seat and/or child restraint would be greatest with the three year old dummy. It was agreed, therefore, that the main baseline tests would use a minibus seat with the three, six and ten year old dummies. However, additional tests would be carried out with the three year old dummy seated in a child restraint on a car seat and with the three year old dummy seated in a child restraint on a minibus seat. If the results displayed significant differences, then the possibility of further baseline tests would be discussed.

**Table 10 Test matrix – M1 or M2 forward facing**

| **Wheelchair** | **Backrest or tilt angle** | **Lower anchorages** | **Dummy** |
|---|---|---|---|
| Buggy – basic | Upright | Inboard (M2) | 10 year old |
| | Reclined | | 6 year old |
| Buggy – supportive | Upright | | 6 year old |
| | Reclined | | 3 year old |
| Manual – basic | Upright | Inboard (M2) | 3 year old |
| | | | 10 year old |
| | | Outboard (M1) | 3 year old |
| | Reclined | Inboard (M2) | 6 year old |
| | | Outboard (M1) | 6 year old |
| Manual – active user | Upright | Inboard (M2) | 10 year old |
| Electric | Upright | Inboard (M2) | 6 year old |
| | | | 10 year old |
| Supportive seating system – modular | Upright | Inboard (M2) | 3 year old |
| | | | 10 year old |
| | Tilted | | 3 year old |
| | | | 10 year old |
| M1 vehicle seat (car seat) and child restraint | | | 3 year old |
| M2 vehicle seat (minibus seat) and child restraint | | | 3 year old |
| M2 vehicle seat (minibus seat) | | | 3 year old |
| | | | 6 year old |
| | | | 10 year old |

### *3.3.4 Test set up*

Figure 12 shows the set up in typical tests with forward facing wheelchairs. The image on the left shows a baseline test with the six year old dummy, while the image on the right shows a corresponding wheelchair test.

The wheelchairs were restrained by a production model four point webbing system that was secured to the floor by aluminium track fittings. The dummy was restrained independently by a three point seat belt. The seat belt included an inertia reel and an upper anchorage point. The seat belt was a surrogate model developed for the test programme by a manufacturer of commercial wheelchair tie-down and occupant restraint systems through consultation with another manufacturer of wheelchair and occupant restraint systems. The performance of the surrogate seat belt was verified with the four point webbing restraint during a dynamic test according to ISO 10542-1:2001. The wheelchair

tie-down and occupant restraint system was replaced following each test.
All test pieces were installed according to the manufacturer's instructions and to the ISO Standards, unless there was a strong reason for not doing so. Any deviations from the Standards were documented. In particular, the occupant restraint was installed to achieve the best possible belt path for the child dummy, although it was recognised that this was not always the case in the real world. However, it was not within the scope of the project to investigate potentially unfavourable belt routes and misuse. Reclined or tilted wheelchairs were adjusted to the limit of the mechanism. This produced a backrest angle of around 30˚ to the vertical.

**Figure 12** Forward facing six year old child dummy restrained in a vehicle seat (left) and electric wheelchair (right)

The main aim of the tests was to investigate occupant loading in a range of common children's wheelchairs and compare these loads with a vehicle seated baseline. This included the measurement of seat belt forces.

In one test, the wheelchair anchorage forces were recorded. The electric wheelchair with the ten year old dummy was selected as the priority for measuring the forces at the restraint anchorages. Previous research with adult dummies proposed vehicle anchorage strength requirements for wheelchair restraint systems (Le Claire *et al.,* 2003). The heaviest wheelchairs for children are likely to generate lower forces than wheelchairs for adults. Although separate requirements for vehicles which depend on the weight of the occupant or of their wheelchair would introduce a range of issues, it was considered useful to obtain some comparative data. For instance, it might be considered inappropriate to ask someone to buy a larger or stronger vehicle than necessary, if it is a privately owned vehicle used to carry a child. It might be appropriate, in these circumstances, to have less stringent requirements for anchorage strength.

## 3.4 Findings – phase 1

### *3.4.1 Relative safety of current situation*

The test programme highlighted a number of issues for children travelling forward facing in a wheelchair in an M1 or an M2 vehicle. These issues related to the geometry of the occupant restraint, the stiffness of the wheelchair and the environment within the vehicle. The seat belt was installed to achieve the best possible fit for the child dummy in each test (within the limits of possibility when a tracking based system is used). Nevertheless, the lap part of the belt tended to rest higher on the pelvis and abdomen than desirable. The path of the belt was influenced by the location of the anchorages in the tracking and by the design of the wheelchair. Film analysis revealed that the belt loaded the abdomen of the dummy in most tests. The forces in a lap belt would result in serious abdominal injuries for a child in these circumstances. The initial position of the belt was important, but another factor was the deformation of the wheelchair during the impact. When the dummy was seated on a vehicle seat, it was noted that the path of the lap belt could be improved. However, the belt remained on the pelvis during the impact tests and did not load the abdomen of the dummy.

The stiffness of the wheelchairs affected their capacity to withstand the forces of the impact. A number of wheelchairs deformed during the tests to the point where additional loads were transferred to the dummy. In addition, the likelihood of the belt loading the abdomen increased when the wheelchair deformed. In contrast, the vehicle seat maintained its integrity during the tests and although the management of the dummy's loads could be improved, the dummy was not exposed to any additional loading in vulnerable body regions.

The environment created to represent a typical M1 or M2 vehicle did not include a head and back restraint. As a result, the dummy received no additional support above that provided by the wheelchair backrest or headrest (when provided). In the absence of an effective head restraint, the dummy head extended rearwards during the rebound phase of the impact. A child travelling in this way would be exposed to the risk of head contact with the interior of the vehicle and soft tissue injuries to the neck. A child in a vehicle seat would usually be provided with a head and back restraint and would not, therefore, be exposed to these risks.

The amount of space in front of the wheelchair user is another important aspect of the environment within a vehicle. The dummy displacement measurements were used to derive space requirements for children in wheelchairs.

The following sections examine the effects of restraint geometry, wheelchair stiffness, head and back restraint and occupant space in more depth.

### *3.4.2 Effect of restraint geometry*

An effective occupant restraint system absorbs and distributes the restraint forces over the strongest parts of the body. The anterior superior iliac spines of the pelvis (i.e. the wings) provide an anchor for the lap part of a seat belt and are strong enough to withstand the forces in adults and older children. However, it is important that the belt fits correctly. This means it must pass low over the hips, touching or even lying flat over the thighs. The shoulder provides an anchor for the diagonal part of a seat belt and restrains the upper torso. This is important to prevent rapid bending and stretching of the spine, which has been linked to the risk of injury in lap only seat belts.

A restraint system designed for adults will not fit children so well. Furthermore, their underdeveloped anatomy means that their natural anchor points are smaller and may not engage with the seat belt in the same way. Younger children are most at risk, but the key development of the pelvis, the formation of the iliac wings, is not complete until at least ten years of age. Since the level of protection is likely to change as a child develops, this section examines the effect of restraint geometry at each dummy ‘age’ in the test programme.

It must be noted that the Hybrid III Series of child dummies was not equipped with instrumentation in the abdomen. Hence the investigation of the effects of seat belt geometry on the protection afforded to the abdomen was based on analysis of high speed films of each test. It must also be noted that the abdomen of the dummy is stiffer than that of real children; hence any effects may be greater in the real world.

Figure 13 shows the path of the seat belt during selected tests with the three year old dummy. The image on the left of the first row shows the dummy seated on a booster seat on a standardised test seat that represents a modern passenger car. The image on the right of the first row shows the dummy seated directly on a minibus seat. The image on the left of the second row shows the dummy seated on a booster seat on a typical minibus seat, and the remaining images are selected wheelchair tests to illustrate the findings.


M1 vehicle seat and booster


M2 vehicle seat


M2 vehicle seat and booster


Seating system – tilt-in-space


Basic manual wheelchair

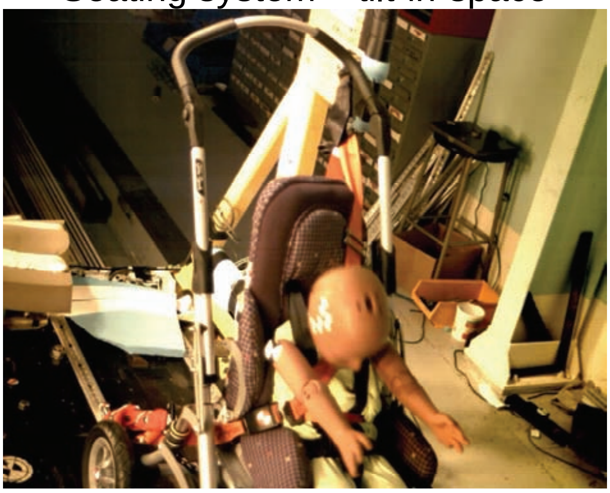

Supportive buggy

**Figure 13** Seat belt geometry in selected tests with three year old dummy

Figure 13 shows that the seat belt remained on the three year old dummy pelvis during the vehicle seated tests. However, when the dummy was restrained in a wheelchair, the lap belt loaded the abdomen. This occurred due to obstructions caused by the wheelchair structure or due to deformation of the wheelchair. For instance, the supportive seating system with tilt-in-space wheelchair base included large hip support pads. This meant that it was impossible to achieve the ideal path for the lap part of the belt. In addition, the tilt-in-space facility did not simply rotate about the seat axis. Instead, it moved the pelvis downwards in an arc by approximately 100 mm with respect to the horizontal. The anchorages could not be moved forwards due to the wheelchair tipping levers; hence the side view belt angle was lower than desired at approximately 45°. These factors, combined with the angle of the pelvis and the compression of the seat cushion, led to the dummy submarining under the lap belt.

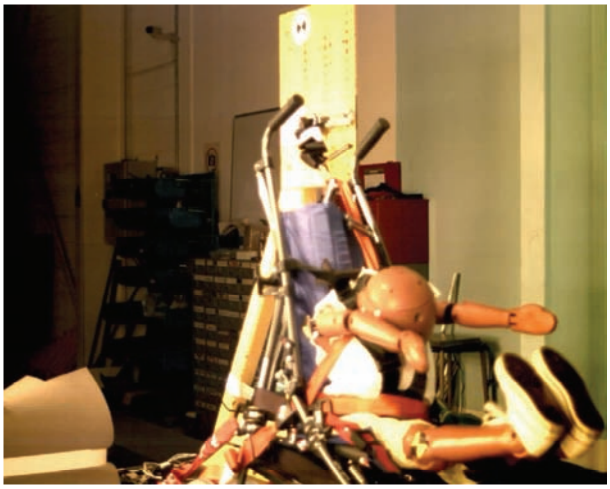
Another example of an obstruction caused by the wheelchair structure was found with the manual wheelchair. The wheelchair was fitted with side guards attached to the seat and backrest. The lap belt had to pass over the top of the side guards, which affected the position of the belt on the dummy pelvis. Finally, the supportive buggy was also fitted with hip pads that obstructed the path of the lap belt. In addition, the five point positioning harness in this wheelchair made it harder to fit the seat belt over the pelvis. During the impact, the buggy compressed, which also contributed to the submarining illustrated in the figure.

Figure 14 shows the path of the seat belt during selected tests with the six year old dummy. The image on the left of the first row shows the dummy seated on a typical minibus seat and the remaining images are selected wheelchair tests to illustrate the findings.

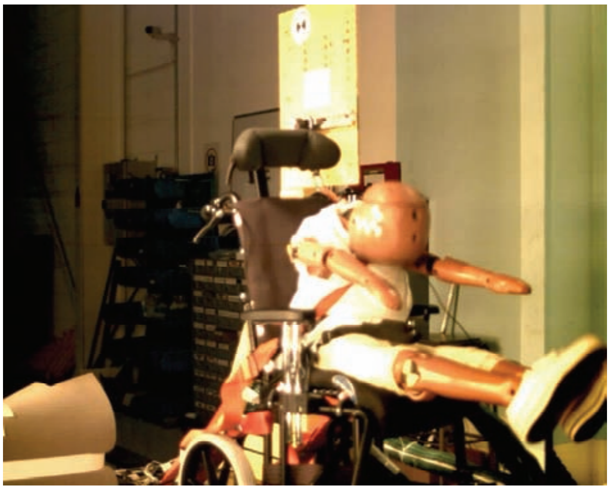
The seat belt remained on the six year old dummy's pelvis during the vehicle seated test. However, problems were observed once again with the path of the lap belt during the wheelchair seated tests. For example, although the basic buggy did not obstruct the path of the lap part of the belt to the same extent as some of the other wheelchairs, the buggy deformed during the impact resulting in the submarining shown in the figure.

The six year old dummy also submarined during the tests with the reclined manual wheelchair. This occurred irrespective of the distance between the lap belt anchorages and was a result of the dummy pelvis tilting rearwards in the reclined seat.

M2 vehicle seat



Basic buggy



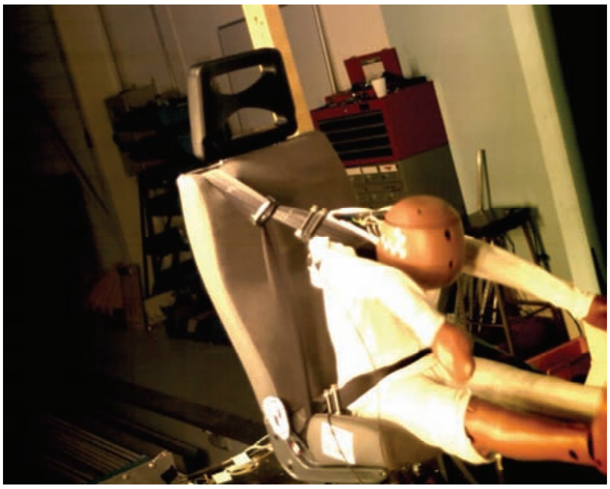
Reclined manual wheelchair

Reclined manual wheelchair – outboard anchorages

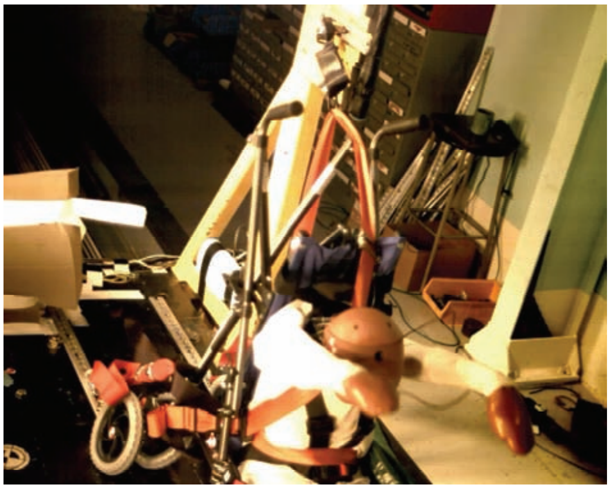
**Figure 14** Seat belt geometry in selected tests with six year old dummy

Figure 15 shows the path of the seat belt during selected tests with the ten year old dummy.  The image on the left of the first row shows the dummy seated on a typical minibus seat and the remaining images are selected wheelchair tests to illustrate the findings.

The seat belt remained on the ten year old dummy pelvis in the vehicle seated test and in the tests with the manual wheelchair and active user wheelchair.  It also remained on the pelvis during the test with the upright supportive seat, although this device was fitted with knee blocks.  However, the seat belt loaded the ten year old dummy abdomen in several wheelchair seated tests.  Some of these are illustrated in the figure.  The same issues emerged: compression of the wheelchair resulted in forward and downward motion of the dummy under the lap part of the belt, or poor geometry brought about by obstructions in the side of the wheelchair.



M2 vehicle seat



Basic buggy

Supportive seat – tilt-in-space

Electric wheelchair

**Figure 15** Seat belt geometry in selected tests with ten year old dummy

The test programme highlighted that children restrained in wheelchairs could be at risk of abdomen injury during a collision. Although the seat belt geometry could also be improved for children in vehicle seats, the lap belt remained on the dummy pelvis during these tests. The path of the lap belt during the impact was influenced by the side structure of the wheelchair and by the capacity of the wheelchair to withstand the impact test.

ISO 7179-19:2001 includes a test procedure to assess the extent to which a wheelchair can accommodate vehicle anchored occupant restraints. However, the test procedure is currently voluntary and will not necessarily address submarining resulting from wheelchair compression or deformation. A better solution might be to establish a performance criterion for abdomen penetration during an impact test. The surrogate occupant restraint was designed to remove any influences of restraint design. It was set up according to the ISO Standards and to achieve the best fit possible for each wheelchair. Nevertheless, it is recognised that wheelchair manufacturers may recommend that a specific make or model of wheelchair tie-down and occupant restraint system is used with their product. It is also recognised that these recommended commercial restraints may differ in fit and performance from the surrogate restraint.

### *3.4.3 Effect of wheelchair stiffness*

All wheelchairs used in the test programme (except the active user wheelchair) were suitable for use forward facing in a vehicle, as stated in their product literature. Although the UNECE Regulation 44 sled test conditions were slightly more stringent than the ISO Standards, it was surprising to find that several of the wheelchairs were unable to withstand the impact test. This was generally the case with the six year old and ten year old dummies, but there were also examples with the three year old, as shown in Figure 16. The image on the left shows the dummy and the modular seating system following a test and the image on the right shows the supportive buggy during a test.

The modular seating system in the image on the left of Figure 16 was fitted to a base supplied by a different manufacturer. There were dedicated attachment points and all fitting was carried out by the seating manufacturer. In addition, the mass of the seating system and dummy were well within the limits stated for the base within its product literature. The seating system had been tested according to ISO 16840, which includes a dynamic test with a surrogate base. The base had been tested with its own seating according to ISO 7176-19:2001. It seems that presence of the modular seating system affected the performance of the base in a manner that would not be evaluated by the ISO Standards. The dummy measurements were generally quite low in the test; however, it is likely that a child in these circumstances would receive multiple fractures, which are not readily predicted by crash test dummies. There would also be a greater risk of the child's head striking the interior of the vehicle.

The supportive buggy in the image on the right of Figure 16 was able to withstand the impact; however, it compressed forwards and downwards. This contributed to the lap belt slipping off the pelvis and loading the abdomen. In addition, the peak head and neck loads corresponded to the maximum compression of the wheelchair. The loads were usually higher than the baseline test and exceeded some published injury limits. For example, the head acceleration exceeded the M2 vehicle seat baseline test by 35 percent. The neck tensile force exceeded this baseline by 90 percent and the limit proposed by Mertz *et al.* (2003) by 194 percent.

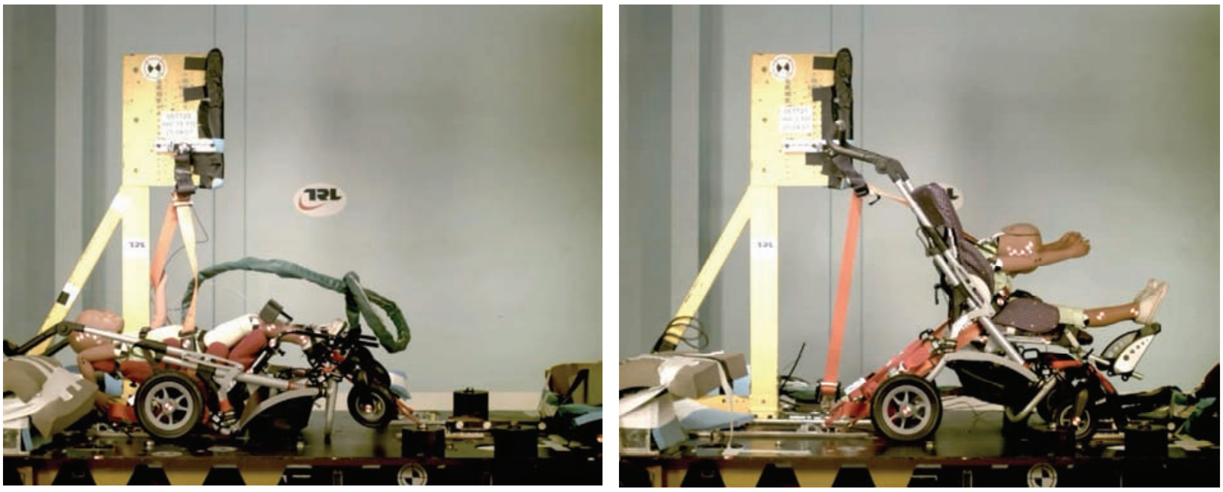


**Figure 16** Wheelchair stiffness in selected tests with three year old dummy

Some examples with the six year old dummy are shown in Figure 17. The image on the left shows the basic buggy during the impact and the image on the right shows the supportive buggy.  Both buggies deformed during the test, which contributed to the lap part of the seat belt loading the abdomen.  The basic buggy seemed to absorb some of the forces without transferring them to the occupant. Nevertheless, it would be undesirable for the structure of a wheelchair to fail in this way.  Some of the neck loads with the supportive buggy displayed a period of increased magnitude that seemed to correspond to the peak compression of the device.  The loads were usually higher than the baseline test and exceeded some published injury limits.  For example, the neck tensile force exceeded the baseline by 60 percent and the limit proposed by Mertz *et al.* (2003) by 154 percent.

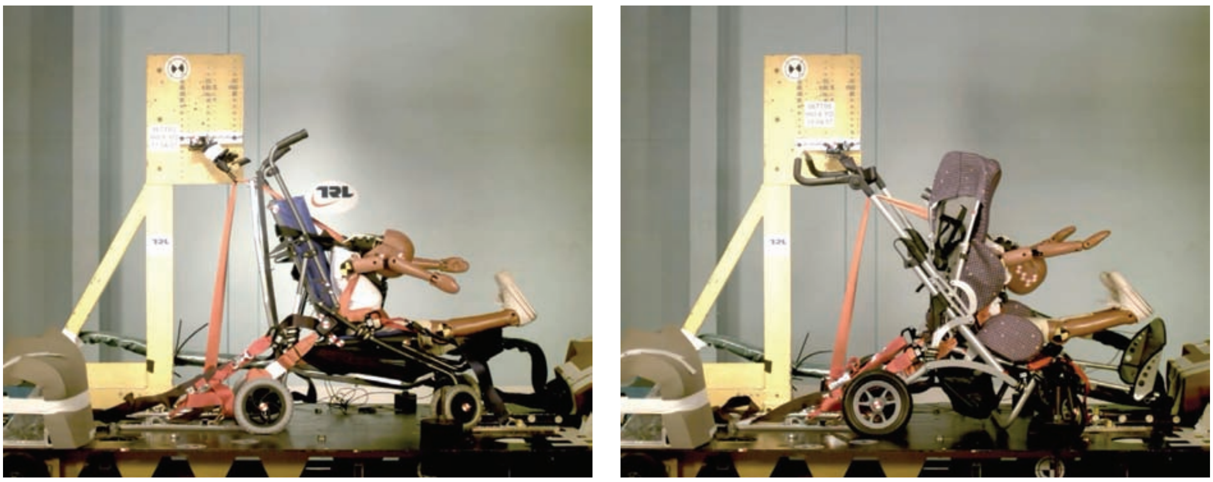


**Figure 17** Wheelchair stiffness in selected tests with six year old dummy

Some examples with the ten year old dummy are shown in Figure 18. The image on the left shows the basic buggy during the impact and the image on the right shows the electric wheelchair. Both devices compressed during the impact, resulting in the dummy submarining under the lap part of the seat belt. In the case of the electric wheelchair, an attachment between the seat and the base failed during the forward motion of the dummy and resulted in rotation of the seat during rebound. It was interesting to note that the electric wheelchair performed adequately with the six year old dummy.

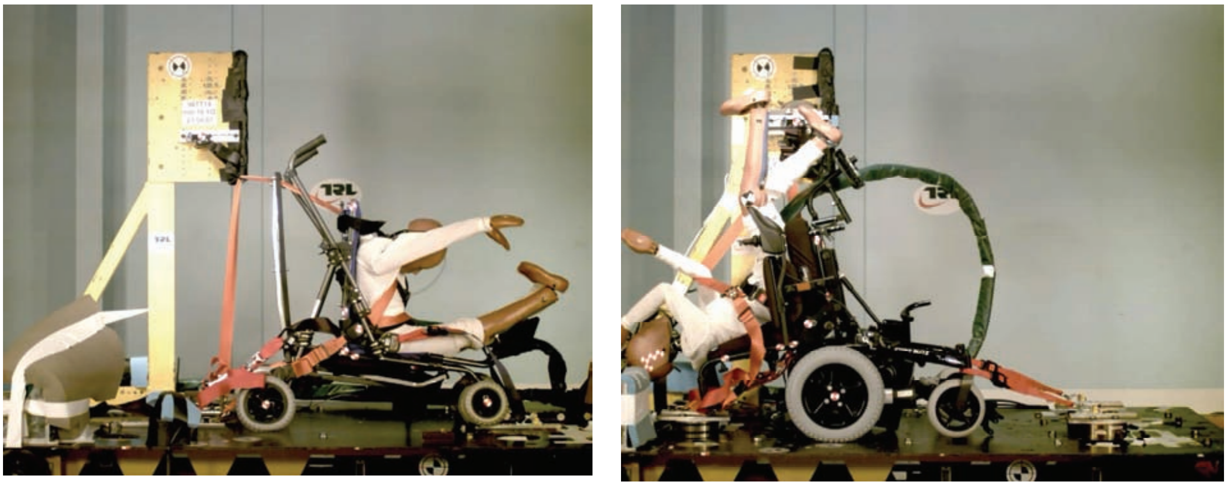


**Figure 18** Wheelchair stiffness in selected tests with ten year old dummy

Most wheelchairs in the test programme deformed to some extent, resulting in additional loading to the dummy. The effects varied by wheelchair type, but typically led to greater dummy accelerations and forces or greater loading to vulnerable body regions such as the abdomen. Children's wheelchairs derived from adults' wheelchairs seemed to be stronger than those devices developed specifically for children. This was probably because adult versions had been designed to withstand the loads with a 50$^{th}$ percentile dummy.

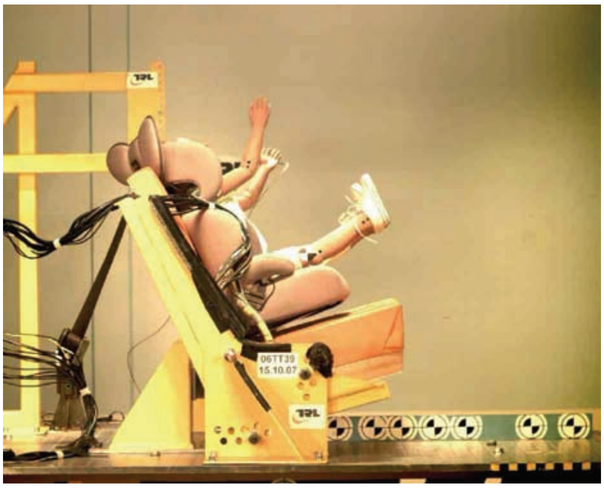
### *3.4.4 Effect of head and back restraint*

Few vehicles provide a head and back restraint for wheelchair users. The wheelchair backrest (and headrest if one is fitted) is therefore the main support for the occupant during the rebound phase of an impact. The backrest must be capable of withstanding the forces from the occupant to reduce the risk of body contact with the interior of the vehicle. Backrest strength requirements can be derived from general requirements about the position of the dummy and signs of wheelchair failure following the dynamic test in ISO 7176-19:2001. There is also a limit placed on the rearward head displacement of the dummy during the test. However, this limit allows significant neck extension. A child in a wheelchair could therefore be at risk of injury even if their wheelchair backrest remains intact. This was examined in the test programme.

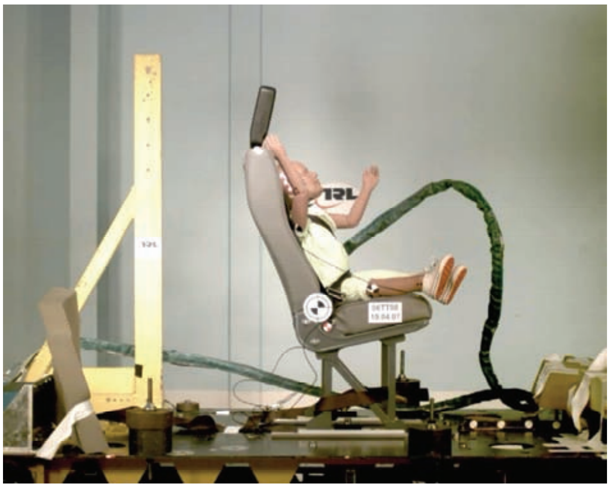
Figure 19 shows some examples with the three year old dummy. The image on the left of the top row shows the dummy seated on a booster seat on a standardised test seat that represents a modern passenger car. The image on the right of the top row shows the dummy seated directly on a minibus seat and the remaining images are selected wheelchair tests to illustrate the findings.

When the dummy was seated in a vehicle seat (with or without a booster), the head and neck were supported through the rebound phase. If a child was travelling in this way, there would be no possibility of contact with the vehicle (or other occupants) behind the seating position and minimal neck extension. When the dummy was seated in the modular seating system with a tilt-in-space wheelchair, the head rose above the top of the head- and backrest and the neck extended rearwards. This was due to the poor belt geometry combined with the angle of the seat, which led to the dummy ramping up the backrest. The dummy head remained within the footprint of the wheelchair. Nevertheless, a child would be exposed to the risk of contact with the vehicle interior. This risk could be mitigated by the provision of adequate space around the wheelchair, but that would not address the neck extension. Although the neck forces and extension moments were low during this part of the impact, the neck was bending below the level of the load cell. It is possible, therefore, that there is a further injury mechanism that the dummy is not able to predict.

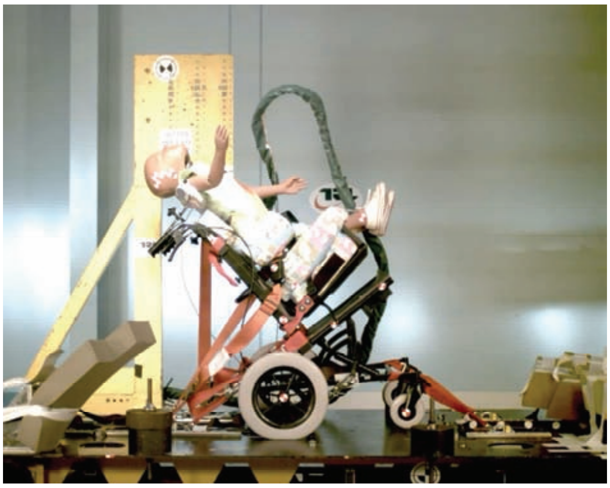
When the three year old dummy was seated in the manual wheelchair, the push handle folding mechanism failed. As the figure shows, the dummy tended to move towards the left hand side of the sled during rebound, possibly because the upper anchorage point was on that side. As a result, the dummy loaded the left push handle to a greater extent than the right push handle. If this occurred in a real vehicle, a child would be at greater risk of striking the interior surfaces.



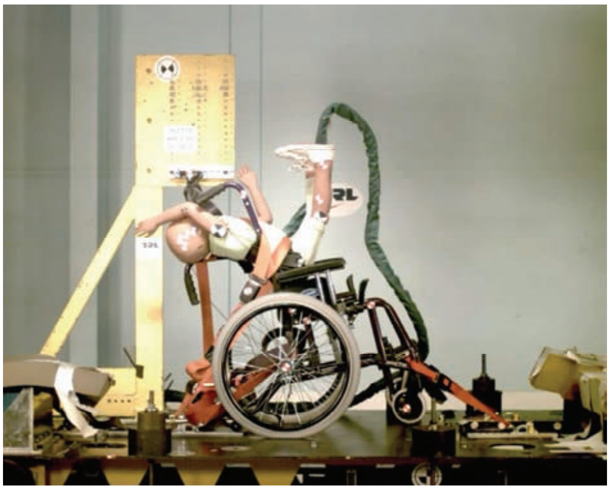
M1 vehicle seat and booster



M2 vehicle seat



Seating system – tilt-in-space



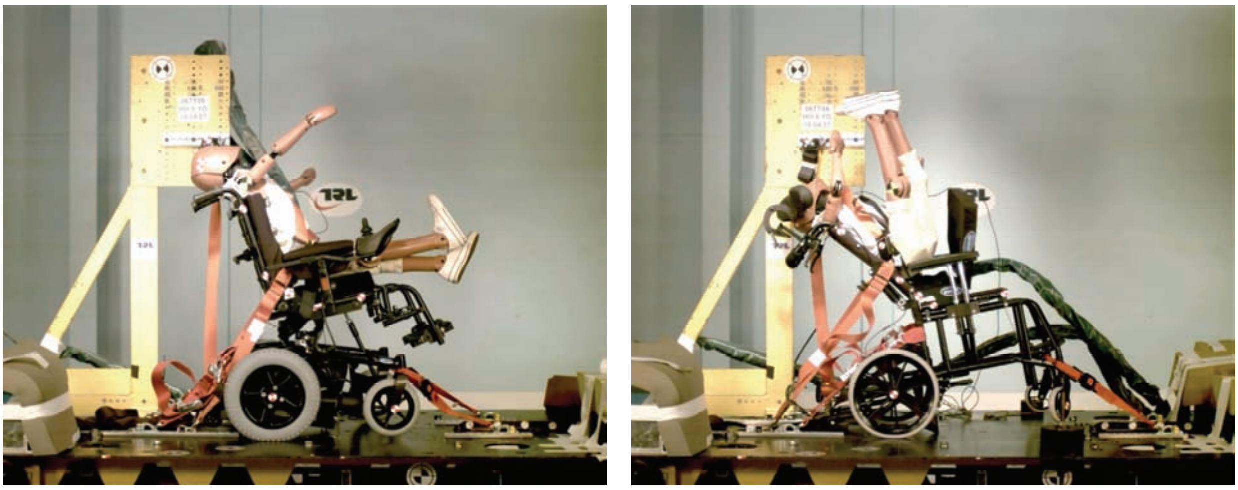
Basic manual wheelchair

**Figure 19** Head and back restraint in selected tests with three year old dummy

Some further examples are shown in Figure 20 with the six year old dummy. The vehicle seat supported the head and neck of the dummy, so the figure shows two examples with the dummy seated in a wheelchair. The image on the left shows a test with an electric wheelchair and the image on the right shows a test with a reclined manual wheelchair.

The backrest of the electric wheelchair withstood the loading from the six year old dummy, but the neck extended rearwards. The dummy head remained within the footprint of the wheelchair and restraint system, but a child travelling in this way would be placed at greater risk of head contact in some vehicles. Furthermore, the level of neck extension was considerably greater than the vehicle seated test.

The reclined wheelchair was fitted with a headrest, but this offered limited protection during the impact test. As the figure shows, the headrest was pushed away as the dummy ramped further up the backrest.



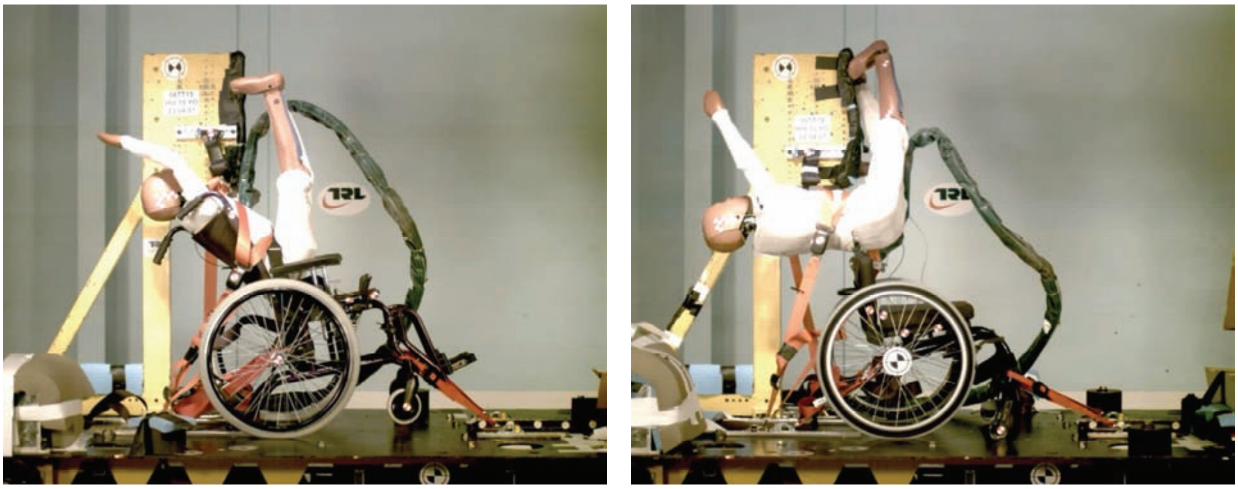
Electric wheelchair                Reclined manual wheelchair

**Figure 20** Head and back restraint in selected tests with six year old dummy

Figure 21 shows some tests with the ten year old dummy. Once again, the vehicle seat supported the head and neck of the dummy, so the figure shows two examples with the dummy seated in a wheelchair. The image on the left shows the dummy seated in a manual wheelchair and the image on the right shows the dummy seated in the active user wheelchair.

When the dummy was seated in the manual wheelchair, the push handle folding mechanism failed during the test, which was also observed with the three year old dummy. If this occurred in a real vehicle, the child might strike their head on the interior. Furthermore, their neck could extend rearwards, perhaps leading to injury.

The dummy was not contained during the rebound phase of the test with the active user wheelchair. This wheelchair was not designed to be used in a vehicle while occupied; however, it was included in the test programme to examine the issues. The test demonstrated that active wheelchairs can withstand the forces during a collision, but that the occupant is not protected by the wheelchair backrest during rebound. The low backrest is an important part of the design of active user wheelchairs and is likely to be appreciated by users.




Basic manual wheelchair　　Active user manual wheelchair

**Figure 21** Head and back restraint in selected tests with ten year old dummy

A child restraint system (or a vehicle seat) will support a child's head and neck during the rebound phase of a front impact. This reduces the risk of head contact with any vehicle structures behind the child and reduces the risk of neck injuries associated with extension. The buggies used in the test programme provided similar levels of support as the booster seat (and/or the vehicle seat), due to the height of their backrests. However, a number of issues emerged when the dummies were seated in other wheelchair types.

The strength of the backrest and any folding mechanism is critical. As the tests showed, if the backrest fails, the child could be thrown rearwards during a collision with the risk of head contact with the vehicle interior. It is very important to protect the head from contact because the bones in a child's skull are not developed fully, hence low levels of loading can result in relatively high deformations of the skull and brain.

When the backrest remains in position, the rearward head displacement and therefore the risk of head contact is reduced to some extent. However, the tests demonstrated that the head moves rearwards extending the entire neck. Uncontrolled movement of the head in this way is likely to result in soft tissue neck injuries. Although these injuries are sometimes classified as relatively minor, they can lead to long term problems.

Wheelchair headrests are not designed to be head restraints and did not perform that function in the impact tests. In some cases, the dummy ramped up the wheelchair backrest missing the headrest altogether, while in other cases the head pushed the headrest away.

The test programme has highlighted that children in some wheelchairs do not receive a comparable level of protection as children travelling in a child restraint or even a vehicle seat. This could be addressed by providing a head and back restraint for all wheelchair users in vehicles. A head and back restraint within the vehicle might be appropriate for manual and electric wheelchairs; however, there would need to be a wheelchair integrated solution for wheelchairs with supportive seating. This is because these wheelchairs may be fitted with a headrest for postural support which would prevent the child's head from being positioned against a head and back restraint in the vehicle.

### *3.4.5 Anchorage loading*

One of the tests described in Section 3.3.3 was used to investigate the loading on the vehicle anchorages. This test used the ten year old dummy restrained in the electric wheelchair.

The longitudinal forces (i.e. x axis) measured in the test were resolved to 45° to provide a consistent basis for a static strength test for a vehicle intended for children's wheelchairs only. The longitudinal component of the force was the largest in magnitude and therefore represents the worst case. Table 11 shows the resolved forces.

**Table 11 Restraint anchorage loads**

| | **Force (kN)** |
|---|---:|
| Wheelchair restraint – front | 2.65 |
| Combined wheelchair and occupant restraint – rear | 28.50 |
| Occupant restraint – upper anchorage | 7.30 |

The loads in Table 11 were derived from a dynamic test using a rigid sled platform. The floor of the sled did not flex or deform during the impact in the way that a vehicle floor might under this type of loading. However, Forinton and Glyn-Davies (2004) demonstrated that any load attenuation due to vehicle deformation is likely to be negligible.

### *3.4.6 Occupant space requirements*

The risk of injury resulting from body contact with the vehicle interior can be reduced if there is sufficient space for the wheelchair and occupant. Figure 22 shows the minimum space required for forward facing children in wheelchairs in M1 and M2 vehicles. The space was derived from head, knee and ankle excursion measurements with the Hybrid III ten year old dummy.

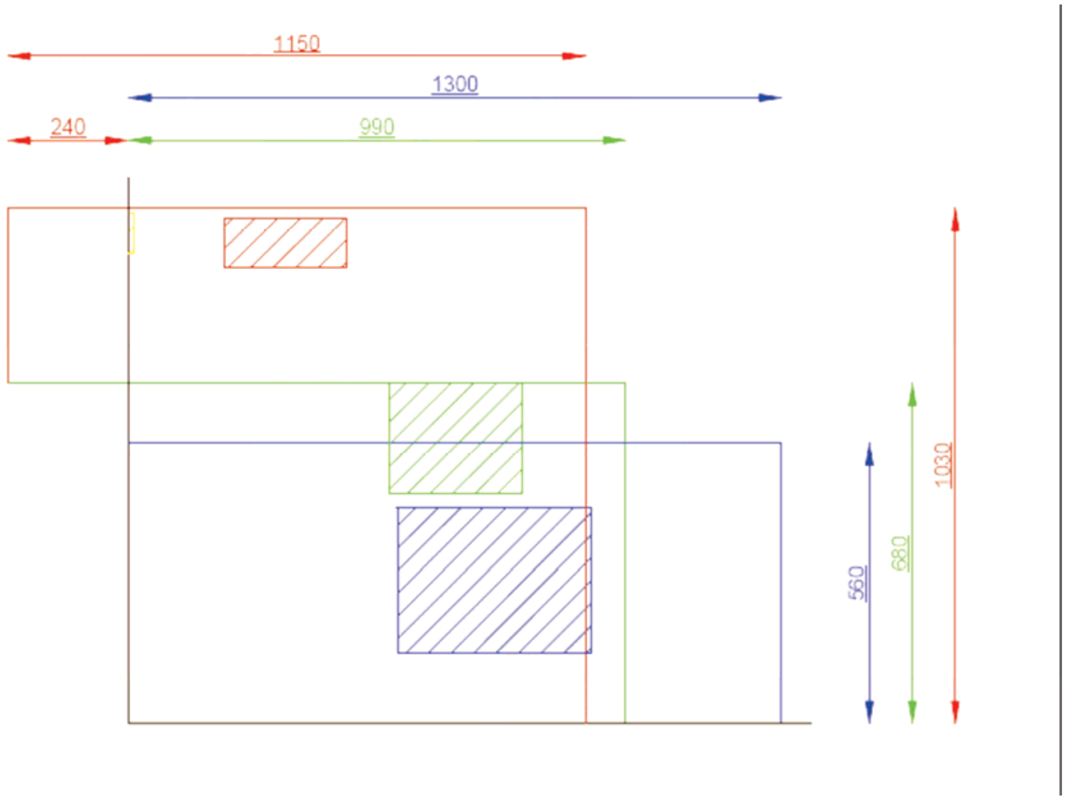



**Figure 22** Occupant space

The minimum space is the perimeter of the combined shape of the three sections in the figure. The red section represents the space required for the head, the green section represents the space required for the knee and the blue section represents the space required for the ankle. In each section, the shaded area denotes the initial position of each body part before the impact.

All vertical distances were taken from the floor of the sled, while the horizontal distances were taken from the upper anchorage position. These planes are represented by the black lines in the figure.

### 3.5 Test design – phase 2

Following the first phase of testing, it was clear that the test results could be used to make practical recommendations about the carriage of children in wheelchairs in M category vehicles. However, it was also clear that some further tests would be a useful means of supporting the recommendations, where necessary.

TRL and the DfT agreed that recommendations could be made to address the issues related to wheelchair stiffness, head and back restraint, anchorage loads and occupant space without further testing. Recommendations could also be made to address the issues related to occupant restraint geometry, but two proposals emerged that required further evaluation. The following sections describe these proposals in more detail and outline the process to develop the test matrix for the second phase of testing.

### *3.5.1 Key issues*

The first phase of the test programme highlighted that the geometry of the occupant restraint is an important issue for children who travel while seated in their wheelchairs. Although the occupant restraint was installed according to ISO 10542-1:2001 and to achieve the best fit possible around the dummy, the lap part of the belt loaded the abdomen in some tests. The capacity of the wheelchair to withstand the impact without deforming was important, but another factor was the initial position of the belt. The tests revealed that the belt was more likely to load the abdomen when the ideal path over the upper thighs was obstructed by the side of the wheelchair. The obstructions included side guards to prevent splashing from the wheelchair wheels and hip pads to position the child’s pelvis.

Side guards and hip support pads both have an important function. It would be inappropriate, therefore, to remove them from wheelchairs. However, it would be relatively straightforward to design the wheelchair to guide the seat belt more easily. Booster seats are an ideal example of what can be achieved. These often include a side structure, but incorporate guides that ensure that the lap part of the seat belt passes over the top of the thighs. These guides also keep the lower part of the diagonal belt adjacent to the pelvis. An additional guide ensures that the upper part of the diagonal belt lies flat on the centre of the shoulder and crosses the centre of the chest. The potential of seat belt guides to improve the path of the lap belt and therefore reduce the risk of abdomen loading was examined in the second phase of the test programme.

The first phase of the test programme also highlighted that the positioning harnesses and straps in some wheelchairs can complicate the fitment of the seat belt. In some cases, the positioning belts already occupied the ideal route for the seat belt. In other cases, the positioning straps and buckles were placed in an inappropriate place, resulting in additional loads being applied to the dummy.

It would be inappropriate to remove these harnesses and straps; however, they could be designed to provide restraint and distribute the forces in a collision. This would remove the need for an additional seat belt and might offer improved occupant protection by distributing the restraint forces more effectively. There would be a number of practical and technical issues to consider. Nevertheless, the potential benefits of a wheelchair integrated harness were examined in the second phase of the test programme.

### *3.5.2 Final test selection*

Two proposals were made for further investigation in the second phase of impact testing: a seat belt guide and an integrated crash tested harness. The intention was to repeat tests from the first phase of the test programme using wheelchairs that were modified to include a seat belt guide or an integrated harness. This would allow the results to be compared with the unmodified baseline test.

As a starting point, the wheelchairs that would benefit most from these proposals were included in a matrix. This is shown in Table 12. The matrix displays all the tests that could be carried out to evaluate each proposal fully. Buggies were excluded due to their structural performance in the first phase of testing. A number of other wheelchairs did not display sufficient strength in the first phase to be considered. These were highlighted by shading in the table. While it would be desirable to perform all the tests in the matrix, a number of priorities were identified. A tick meant that the test was selected for the final test matrix.

The greatest obstruction of the lap part of the seat belt was observed with the supportive seating system with tilt-in-space wheelchair base. The test with the three year old dummy was selected as the priority due to its small pelvis. It was anticipated that (in our sample) this combination of wheelchair type and occupant size would benefit most from the seat belt guide. In fact, the design of the seating system used with the tilt-in-space wheelchair was similar to buggies and other seating systems on the market. TRL was confident, therefore, that the findings could be applied to other wheelchairs.

The supportive seating system with tilt-in-space wheelchair base and three year old dummy were selected to investigate the potential of an integrated harness. The three year old dummy was expected to benefit most from a wheelchair integrated harness. A test with the ten year old dummy was also selected to examine a potential worst case in terms of the additional loads applied to the wheelchair.

**Table 12 Phase 2 – test selection**

| Proposal | Wheelchair | Backrest or tilt angle | Dummy | Priorities |
|---|---|---|---|---|
| Seat belt guide | Seating system – modular | Upright | 3 year old | |
| | | | 10 year old | |
| | | Tilted | 3 year old | ✓ |
| | | | 10 year old | |
| | Manual – basic | Upright | 3 year old | |
| | | | 10 year old | |
| Integrated harness | Seating system – modular | Upright | 3 year old | |
| | | | 10 year old | ✓ |
| | | Tilted | 3 year old | ✓ |
| | | | 10 year old | |

*3.5.3 Test matrix*

The tests selected for the second phase of the impact test programme are shown in Table 13. The vehicle environment created on the impact sled was identical to that created for the first phase of the testing.

**Table 13 Test matrix – M1 or M2 forward facing phase 2**

| Wheelchair | Backrest or tilt angle | Dummy |
|---|---|---|
| Seating system | Upright | 10 year old |
| | Tilted | 3 year old |
| | | 3 year old |

*3.5.4 Test set up*

Figure 23 shows the set up for the tests in the second phase of the impact test programme. The image on the left shows the three year old dummy in the supportive seating system with a tilt-in-space wheelchair base. The seating system was modified to guide the lap and diagonal parts of the seat belt. The image in the centre also shows the three year old dummy in the supportive seating system with a tilt-in-space wheelchair base. However, this time the seating system was modified to include a five point harness. The image on the right shows the ten year old dummy in the supportive seating system with an upright base. This seating system was also modified to include a five point harness.

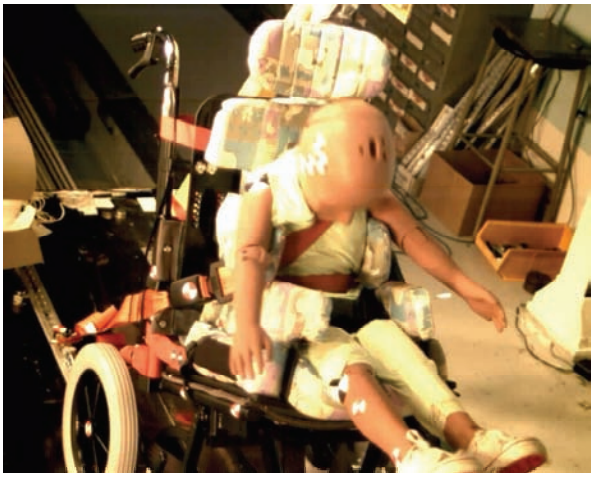
**Figure 23** Wheelchair modifications and set up for phase 2 of impact testing

The wheelchairs were restrained by the same production model four point webbing system described in Section 3.3.4. The dummy was restrained by the surrogate seat belt described in Section 3.3.4 during the test to investigate seat belt guides. The integrated harnesses were provided by a child restraint system manufacturer in consultation with a supportive seating manufacturer.

## 3.6 Findings – phase 2

### *3.6.1 Effect of restraint geometry*

Figure 24 shows a comparison between the lap belt path over the dummy in a supportive seating system and a seating system modified with a seat belt guide. The seating system was attached to an identical tilt-in-space wheelchair base in each test. As the figure shows, the path of the lap belt was improved in the modified wheelchair. This was due to the lap belt being positioned lower on the dummy, thus reducing the loading on the abdomen.



Without seat belt guides With seat belt guides

**Figure 24** Seat belt geometry in tests with three year old dummy in a seating system and tilt-in-space wheelchair

A clear improvement in belt path and abdomen loading was achieved when seat belt guides were added to the seating system. However, the advantage was limited by the design of the tilt-in-space wheelchair base in this restraint system configuration. This was because it was necessary to locate the anchorages further rearwards (with respect to the wheelchair) than would usually be the case. This was done to prevent the straps from fouling against the tipping levers on the wheelchair. The resulting side view angle of the lap belt was therefore lower than desirable (at around 40˚ from the horizontal) and affected the capacity of the belt to engage with the pelvis of the dummy.

The position of the diagonal belt path was also improved throughout the impact, as the upper belt guide maintained the favourable routing across the dummy's torso. These factors also assisted in reducing the dummy rearward excursion. This is shown in Figure 25. Reducing the occupant rearward excursion reduces the risk of the occupant's head striking an object behind the wheelchair, e.g. part of the vehicle interior. The maximum rearward head excursion for the unmodified version was 347 mm. The maximum rearward head excursion for the version with the seat belt guide was 218 mm. This is a decrease in rearward head excursion of 37 percent.

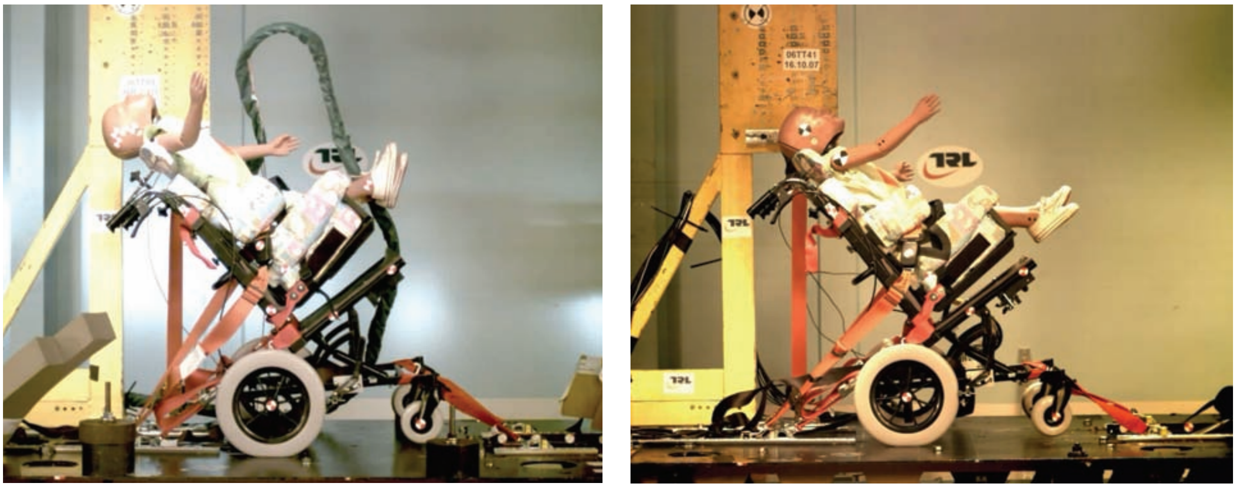
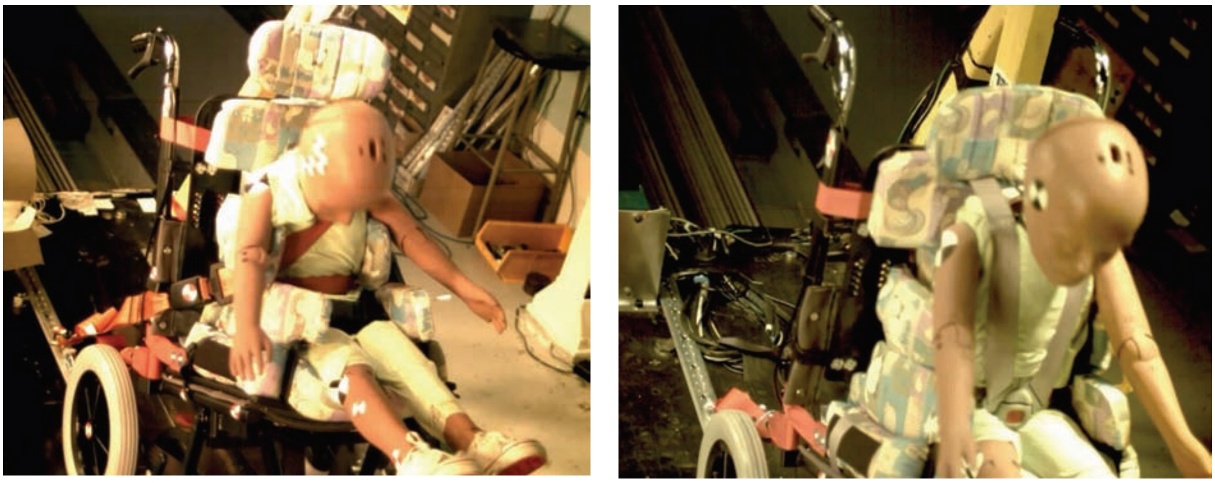


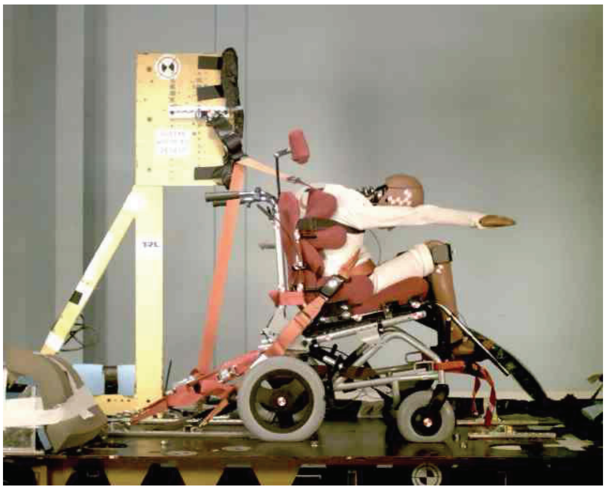
**Figure 25** Rearward head excursion in tests with three year old dummy in a seating system and tilt-in-space wheelchair

Figure 26 shows a comparison between the lap belt path over the three year old dummy in a seating system and a seating system modified to incorporate an integrated five point harness. The seating system was attached to an identical tilt-in-space wheelchair base in each test. Figure 27 shows a comparison between the lap belt path over the ten year old dummy in a seating system and a seating system modified to incorporate an integrated five point harness. The seating system was attached to an identical base in each test. As the figure shows, the five point harness provides preferable restraint routing as the loads are distributed more evenly over the strongest areas of the child's anatomy.

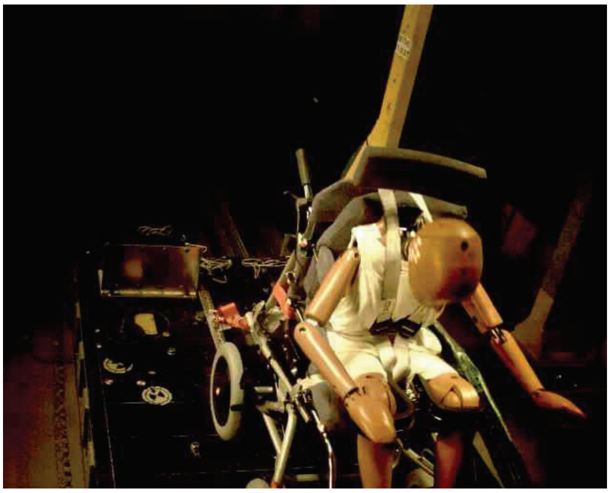


Three point seat belt | Integrated five point harness

**Figure 26** Comparison of three point seat belt and five point harness in a seating system and tilt-in-space wheelchair (three year old dummy)



Three point seat belt



Integrated five point harness

**Figure 27** Comparison of three point seat belt and five point harness in a seating system (ten year old dummy)

The use of a harness also reduced the level of rearward occupant excursion. The rearward head excursion of the three year old dummy in the seating system with a tilt-in-space wheelchair base was reduced by 98 percent when the harness was used in place of the seat belt. The corresponding figure for the ten year old dummy in the seating system with an upright base was 90 percent.

The resultant chest acceleration (3 ms exceedance) and the chest compression of the three year old dummy in the seating system with a tilt-in-space wheelchair base were reduced by 27 percent and 70 percent respectively when the harness was used in place of the seat belt. The corresponding figures for the ten year old dummy in the seating system with an upright base were 21 percent and 39 percent.

However, care must be used when drawing conclusions from the dummy loads or head excursions for these tests, as both wheelchairs with integrated harnesses sustained damage due to the loads placed on the wheelchair structure by the harness system. These loads were not present when the unmodified wheelchairs were tested, as the relevant loads were placed through the surrogate three point restraint system. Therefore, a certain amount of the impact energy was absorbed in damaging the wheelchair. Whereas deforming wheelchair structures can sometimes reduce the loads on an occupant, it is also the case that very high loads can result when the maximum deformation occurs. There is also a greater risk of contact with the interior of the vehicle because occupant excursion is usually greater when a wheelchair deforms.

The testing has shown that although the addition of a five point restraint harness to a wheelchair was a very simple solution, it requires further development. The ability of current wheelchairs to withstand the loads induced by an integrated harness system is poor as the wheelchair structure has not been designed for this purpose. However, if wheelchairs were designed with an integrated harness from the outset, and thus with a strong enough structure, the intention of the integrated system could be achieved.

## 3.7 Conclusions

- The path of the seat belt is important for the protection of the abdomen.
- Film analysis suggested that a child in a wheelchair might be placed at a higher risk of receiving an abdomen injury through belt loading than a child in a child restraint or even a vehicle seat.
- The lap part of the belt is more likely to load the abdomen when the wheelchair obstructed the ideal path of the belt.
- Wheelchair manufacturers should be encouraged to manage positively the path of the lap and diagonal parts of the seat belt.
- Measures to manage the path of the seat belt have the potential to reduce the risk of abdomen loading and vertical and rearward head excursion.
- Some positioning harnesses can complicate the fitment of a seat belt and may result in additional loads being applied to the abdomen if the harness buckle rests under the seat belt.
- A wheelchair integrated restraint harness is one way to reduce the risk of abdomen loading and to distribute the restraint forces over a wider area.
- A wheelchair intended for use in a vehicle would need to be designed to accommodate an integrated restraint harness from the outset due to the additional loads on the backrest.
- A wheelchair fitted with an integrated harness could potentially increase the loads on the wheelchair tie-downs and associated anchorages.

- The lap part of the seat belt is more likely to load the abdomen when the wheelchair compresses or deforms.

- Manufacturers who design wheelchairs for use in a vehicle should be encouraged to design anti-submarining features into their products.

- A performance criterion for abdomen loading should be included in the dynamic test for wheelchairs to encourage the development of occupant protection solutions.

- Some wheelchairs are unable to withstand the forces in an impact when they are used forward facing.

- In some cases, the maximum deformation or compression of the wheelchair coincides with periods of increased loading in the dummy.

- A crash tested supportive seating system and a crash tested base may not perform well together.

- The head and neck of a child in a wheelchair are not protected during the rebound phase of an impact.

- Wheelchair headrests (where fitted) are not intended to protect the user in a vehicle collision and are inadequate for that function.

- A child in a wheelchair will be exposed to a higher risk of head contact with the vehicle structure behind their seating position than a child in a child restraint or a vehicle seat.

- A child in a wheelchair might be exposed to a higher risk of receiving a soft tissue neck injury (due to the motion of their head relative to their torso) than a child in a child restraint or a vehicle seat.

- A head and back restraint would reduce the risk of head contact or soft tissue neck injury.

- A head and back restraint within the vehicle would be appropriate for some wheelchairs; however, it would be difficult to accommodate wheelchairs fitted with positioning headrests with a vehicle based solution. Instead, these wheelchairs would benefit from a wheelchair integrated solution.

# 4 M1 and M2 rear facing

## 4.1 Field study

No M2 vehicles were found in which a wheelchair user regularly travels rear facing. The vehicles examined in the field study were all M1 vehicles that were either purpose built or specially adapted to function as a taxi. In each vehicle, the wheelchair user travels rear facing against the bulkhead that separates the driver and passenger compartments. During the study, dummies representing children aged three, six and ten years old were seated and restrained in a range of wheelchairs. An overview of the methods was given in Section 2.2 and the results of the study are described in detail in Appendix B.

The study highlighted three main areas of concern: the protection that a child’s head and neck would receive during a collision, the protection that a child’s torso would receive during a secondary collision with the taxi bulkhead and the geometry of the occupant restraint system.

None of the vehicles examined in the field study provided a head and back restraint. In one vehicle, an 80 mm thick foam head support was attached to the clear centre division, but it was unlikely to afford any protection in a crash. When the dummy was seated in a wheelchair, the head was adjacent to a range of surfaces and structures. The distance between the head and these surfaces varied quite markedly in each vehicle and for each wheelchair. It seemed likely that a child’s head would strike one of these surfaces during a collision, which could result in serious head and neck injuries. It was also likely that the neck would bend significantly, possibly leading to extension injury to the cervical spine.

The wheelchair push handles or rear wheels prevented contact between the rear of the wheelchair backrest and the taxi bulkhead. The width of the gap between the backrest and the bulkhead depended on the vehicle and the type of wheelchair. It seemed likely that the wheelchair backrest would fail if it was unsupported or the wheelchair would rotate about the rear wheels. In either event, the child would be thrown against the bulkhead with considerable force, which could result in multiple injuries.

When a wheelchair user is travelling rear facing, the main function of the occupant restraint is to prevent them from riding up the back of the wheelchair and to hold them in place during rebound. Although the effects of poor seat belt geometry may be less significant for rear facing children compared with forward facing children, it might lead to greater vertical excursion and less favourable belt paths. A child would therefore be at greater risk of head and neck injury due to head contact and at greater risk of soft tissue injuries from the seat belt.

### 4.2 Scope of testing

The aim of the test programme was to examine whether children in wheelchairs and children in vehicle seats are likely to receive a comparable level of protection in a collision. When children travel rear facing, their protection is influenced mainly by their wheelchair and the vehicle they are travelling in, but also by their restraint system.

A wheelchair takes the place of a vehicle seat when it is used in transport. It must, therefore, be able to withstand the forces in a crash without transferring excessive forces to the child. A rear facing front impact test is not included in ISO 7176-19:2001, and hence the literature that accompanies a new wheelchair usually states that it should be used forward facing only in a vehicle. Nevertheless, wheelchair users are asked to travel rear facing in purpose built or adapted taxis. However, children use a range of different wheelchairs, as highlighted in Section 2.3.4, and each type of wheelchair has various features and adjustments that could affect the risk of injury in a crash. Furthermore, most of these wheelchairs result in there being a gap between the wheelchair and the bulkhead. As a result, it seems unlikely that the bulkhead will afford the necessary support to the rear of the wheelchair. It also seems unlikely that the head and neck of the child will be supported during a collision. With these points in mind, it was considered important for the project to include all types of wheelchairs in common use by children. It was also considered important to investigate the effect of the features and adjustments that were most relevant for transport.

Assuming that the vehicle is crashworthy and there is no passenger compartment intrusion, the layout of the interior is the main way that the vehicle can influence the risk of injury. The environment must be compatible with children's needs during a collision. However, the field study revealed that aspects of the interior might cause injury when children travel rear facing.

The restraint system comprises a wheelchair restraint to hold the wheelchair in place during rebound and an occupant restraint to prevent ejection and reduce the risk of contact with the interior. It is also important for the occupant restraint to distribute the restraint forces over the strongest parts of the child's anatomy. Although these forces may be relatively low compared with the front impact situation, they may nevertheless cause soft tissue injuries if the belt route is poor. The performance of wheelchair and occupant restraints for rear facing wheelchair users is not currently assessed dynamically. Most vehicles are fitted with similar equipment: a two point wheelchair restraint integrated into the bulkhead and a three point inertia reel seat belt, which is sometimes shared with the rear facing tip-up seat.

It was not considered worthwhile to make a detailed investigation of the restraint system issues for rear facing children in wheelchairs, since the devices currently in use are relatively similar in design and probable performance. Nevertheless, a very large test programme would be required to examine every combination of wheelchair and other vehicle issues, particularly when all the various types and adjustments are considered. TRL and the DfT agreed a more pragmatic approach, which was to test a series of common worst cases. This approach was used for the wheelchair and vehicle issues.

In summary, a worst case approach was adopted when selecting the wheelchair and vehicle issues to examine in the test programme. In each test, the wheelchair was restrained by a two point webbing system while the occupant was restrained by a surrogate lap and diagonal inertia reel seat belt with an upper anchorage. The seat belt was installed to achieve the best fit possible for the particular wheelchair.

## 4.3 Test design

As a starting point, the key wheelchair and vehicle design issues were combined in order to determine which issues should be examined in more depth. The next step was to take these issues and construct a matrix for each type of wheelchair. Each matrix displayed all the tests that would be required to complete the picture for the particular wheelchair when it was used rear facing in an M1 or M2 vehicle. The final step was to apply our expertise in impact biomechanics and our knowledge of injury mechanisms to identify priorities within each matrix. These priorities would be used to develop solutions for all combinations of wheelchair type, adjustment and child occupant size, etc. The following sections outline this process.

### *4.3.1 Key issues*

Tables 14 to 17 each represent a type of wheelchair. The first row in each table lists the key issues for that device when it is used rear facing in an M1 or M2 vehicle. There were a number of different options or adjustments for each issue that might affect a child's risk of injury in a crash. The most important issues for a particular wheelchair were selected on the basis of their frequency and likely influence on injury. In each table, a tick means that the issue was examined in the test programme and a square means that the most common or worst case was adopted during the test set up, as appropriate. A shaded cell means that no option or adjustment was possible for that wheelchair.

Table 14 summarises the key issues for buggies when children travel rear facing in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in a buggy and were therefore considered for the test programme.

Buggies are not intended to be used rear facing in a vehicle and are not tested in that condition. Nevertheless, the reality is that they will travel that way in a purpose built or adapted taxi. It is possible that the backrest of a buggy will collapse when loaded by a child during an impact. However, assuming that the strength of the backrest is sufficient, the child's injury mechanisms could be affected by the backrest angle. When a backrest is reclined, there is a risk that the child would ride up the surface of the backrest, increasing vertical head excursion and the risk of head and neck injury through head contact with the vehicle interior. When a backrest is upright, a child is less likely to ride up the backrest, but there is a risk of neck injury due to overextension. Some buggies provide a headrest or a backrest tall enough to support the head; however, this would not have been designed or tested as a head restraint for a rear facing system. When the seat and backrest are fixed but tilted rearwards, there is also a risk that the child would ride up the surface of the backrest. Occupant size was included because the size of the child affects the way they load the wheelchair backrest and also their sitting height with respect to the bulkhead.

Most children using a buggy will have a positioning harness. This type of harness is not usually crash tested and is not, therefore, intended to take the place of a seat belt. It is possible that the harness might interfere with the path of the seat belt during a crash. An investigation of different harness designs and their potential to affect the performance of the seat belt was not carried out. Instead, a typical positioning harness was fitted in all tests with a buggy.

Buggies can be found with a range of different push handle styles and some can be deployed or folded away. The style and position of the push handles would affect the way the buggy interacts with the vehicle; however, a large number of tests would be required to investigate each combination. Buggies with fairly typical push handles were used in the test programme and they were adjusted to reflect the most likely scenario of use.

The seat is usually forward facing in a buggy, but some models have rear facing seats while others have dual facing seats. Although the effect of the seat orientation could be significant, only a few products display this feature and it seemed likely that most buggies would be used with the seat installed forward facing. Seat orientation was not, therefore, investigated in the test programme.

**Table 14 Buggies – key issues**

| Seating type | Backrest angle | Tilt angle | Postural belts | Push handles | Seat direction | Occupant size |
|---|---|---|---|---|---|---|
| **Basic** | ✓ | ✓ | □ | □ | | ✓ |
| **Supportive** | ✓ | ✓ | □ | □ | □ | ✓ |

Table 15 describes the key issues for manual wheelchairs when children travel rear facing in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in a manual wheelchair and were therefore considered for the test programme. As discussed above, backrest angle can affect the likelihood of the occupant riding up the wheelchair backrest and the likelihood of neck extension. Occupant size can affect the wheelchair loads and the position of the head with respect to the bulkhead.

Although tilt angle may affect the way the child rides up the wheelchair backrest, manual wheelchairs with a tilt-in-space facility (i.e. comfort wheelchairs) are not used widely by children. This issue was not investigated in the test programme.

Most manual wheelchairs are fitted with side guards to protect the child's clothes from spray from the wheelchair wheels. Although they perform an important function, they can complicate the fitment of the occupant restraint in a vehicle. Side guards were fitted in all tests with a manual wheelchair to give a feel for their effect.

The style of the push handles fitted to manual wheelchairs can vary and sometimes they are removed. Push handles would affect the way the wheelchair interacts with the vehicle; however, the majority of basic manual wheelchairs are likely to have fairly typical push handles fitted. Active user wheelchairs are unlikely to have push handles. For these reasons, this issue was not considered for the test programme.

**Table 15 Manual wheelchairs – key issues**

| Frame type | Backrest angle | Tilt angle | Side guards | Push handles | Occupant size |
|---|---|---|---|---|---|
| **Basic** | ✓ | □ | □ | □ | ✓ |
| **Active user** | | | □ | | ✓ |

Table 16 summarises the key issues for electric wheelchairs when they travel rear facing in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in an electric wheelchair. As a result, these issues were considered for the test programme.

**Table 16 Electric wheelchairs – key issues**

| | Backrest angle | Tilt angle | Occupant size |
|---|---|---|---|
| **Electric** | ✓ | ✓ | ✓ |

Table 17 summarises the key issues for supportive seating systems when they travel rear facing in M1 or M2 vehicles. Moulded seating systems were not investigated in the test programme. A child in a moulded seat would not be accommodated easily using the restraint system in a purpose built or adapted taxi. Furthermore, current test dummies would not permit a full investigation of the situation. Although a seat could be moulded to a dummy, it could not reproduce the physical characteristics and issues associated with certain medical conditions. As such, the restraint of a child in a moulded seat may require a bespoke solution to meet their particular needs. However, it was impossible to examine individual cases in the project.

Tilt angle and occupant size were identified as having the greatest potential to affect the injury mechanisms in a modular seating system and were therefore considered for the test programme. As discussed above, tilt angle can affect the likelihood of the occupant riding up the backrest and occupant size can affect the loads applied to the wheelchair and the position of the head with respect to the bulkhead.

There are several different types and levels of support cushions and pads used within supportive seating units. Although it would be desirable to understand the effects of the different levels of support that are available, this type of assessment was impossible within this project. This issue was not examined in detail in the test programme, but a modular seat was used with the full range of support equipment fitted.

Children in supportive seats are likely to use a positioning harness. As discussed above, this harness might interfere with the path of the occupant restraint system in the vehicle. However, this issue was not considered for the test programme and a typical harness was used.

**Table 17 Supportive seating systems – key issues**

| Seating system | Tilt angle | Supports | Postural belts | Occupant size |
|---|---|---|---|---|
| **Modular** | ✓ | □ | □ | ✓ |
| **Moulded** | | | | |

### 4.3.2 Final test selection

Having identified the key issues for further investigation, the next step was to take these issues and construct a matrix for each type of wheelchair. These are shown in Tables 18 to 21. Each matrix displays all the tests that would be required to complete the picture for the wheelchair when it is used rear facing in an M1 or M2 vehicle. While it would be desirable to perform all the tests in each table, a number of priorities were identified, which could be used to investigate the issues and develop solutions for all combinations. A tick means that a test was selected for the final test matrix.

Table 18 shows all the tests that would complete the picture for children travelling rear facing in buggies in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as key issues for both types of buggy. When the backrest is upright, the child is at risk of overextension injury to the neck and applies greater loads to the backrest. When it is reclined, the child is more likely to ride up the backrest and strike their head on the vehicle interior. Buggies are usually available with a range of seat sizes. These were compared with the dimensions of child dummies, which revealed that the six year old dummy matched the smallest seat size for a basic buggy while the ten year old matched the largest seat size. Similarly, the three year old dummy matched the smallest seat size for a supportive buggy while the six year old matched the largest seat size.

If a basic buggy was used upright during a collision, a larger child would apply greater loads to the backrest than a smaller child. It is also possible that the head of a larger child would be more likely to be exposed above the top of the backrest. This could result in head injury due to impact with the vehicle structure and/or neck injury due to extension. The ‘upright’ test with the ten year old dummy was therefore selected as a priority.

If a basic buggy was reclined during a collision, the head of a larger child would be more likely to strike the interior of the vehicle after riding up the backrest. The ‘reclined’ test with the ten year old dummy was therefore selected as a priority.

A similar approach was taken for supportive buggies. If the backrest was upright during a crash, a larger child would apply greater loads than a smaller child and they would be more likely to strike their head. The ‘upright’ test with the six year old dummy was therefore selected as a priority. If a backrest was reclined, the risk of head and neck injury due to ramping would be greater for a larger child. The ‘reclined’ test with the six year old dummy was therefore selected as a priority.

Although some buggies are available with a tilting seat, TRL concluded that the issues around tilt-in-space could be investigated better with another type of wheelchair. As a result, no ‘tilted’ tests were prioritised for either type of buggy.

**Table 18 Buggies – test selection**

| Seating type | Backrest or tile angle | Dummy | Priorities |
|---|---|---|---|
| Basic | Upright | 6 year old | |
| | | 10 year old | ✓ |
| | Reclined | 6 year old | |
| | | 10 year old | ✓ |
| | Tilted | 6 year old | |
| | | 10 year old | |
| Supportive | Upright | 3 year old | |
| | | 6 year old | ✓ |
| | Reclined | 3 year old | |
| | | 6 year old | ✓ |
| | Tilted | 3 year old | |
| | | 6 year old | |

Table 19 shows all the tests that would complete the picture for children travelling rear facing in manual wheelchairs in M1 or M2 vehicles. Backrest angle and occupant size were identified as key issues for manual wheelchairs. Basic manual wheelchairs are available with an upright or a reclined backrest, but active user wheelchairs have a small upright backrest only.

Both types are usually available with different seating dimensions and active user wheelchairs can sometimes be adjusted. The smallest seat in a typical basic wheelchair with an upright backrest would accommodate a child similar in size to a three year old dummy. The largest seat would accommodate a child similar in size to a ten year old dummy. The smallest seat in a typical basic wheelchair with a reclining backrest would accommodate a child similar in size to a six year old dummy and the largest seat would accommodate a child similar to a ten year old dummy. The corresponding dummies for a typical active user wheelchair are a six year old and a ten year old.

Children travelling in a basic manual wheelchair with an upright backrest are at risk of head and neck injury due to head contact with the interior. They are also at risk of extension injury to the neck with or without head contact. Furthermore, the wheelchair backrest might fail, which could result in multiple injuries if the child is thrown against the vehicle bulkhead. Very young children have a lower injury tolerance; however, older children apply greater loads to the backrest. In this instance, both the smallest and largest children needed to be considered because they were very different in terms of their level of development and could have different injury mechanisms. The three year old dummy and the ten year old dummy were therefore selected as priorities for basic manual wheelchairs with an upright backrest.

If a basic manual wheelchair with a reclined backrest was used in a crash, it is likely that the child would ride up the backrest and strike their head on the bulkhead. Taking into account the prevalence of reclining wheelchairs for children, it was concluded that the risks associated with travelling in this way would be examined with other wheelchair types.

The low backrest in active user wheelchairs places an additional risk on the back and spine due to the lack of support above the thoraco-lumbar region. The risk of injury is similar irrespective of occupant size; however, a larger child would apply greater loads to the wheelchair. The test with the ten year old dummy was therefore selected as a priority.

**Table 19 Manual wheelchairs – test selection**

| Frame type | Backrest angle | Dummy | Priorities |
|---|---|---|---|
| Basic | Upright | 3 year old | ✓ |
| | | 6 year old | |
| | | 10 year old | ✓ |
| | Reclined | 6 year old | |
| | | 10 year old | |
| Active user | Upright | 6 year old | |
| | | 10 year old | ✓ |

Table 20 shows all the tests that would complete the picture for children travelling rear facing in electric wheelchairs in M1 or M2 vehicles. Backrest angle, tilt angle and occupant size were identified as key issues for electric wheelchairs. Based on the dimensions of the seat, electric wheelchairs are used by children that range in size between the six year old and ten year old child dummies.

During a collision, a child travelling in an electric wheelchair with an upright backrest would be at risk of head and neck injury from head contact and neck injury from extension.  It is also possible that the wheelchair backrest might fail, which could result in multiple injuries if the child is thrown against the vehicle bulkhead.  Younger children would be most at risk from the added danger of wheelchair movement, while older children apply greater loads to their backrest and may find their head closer to the vehicle interior.  The level or risk meant that it was necessary to consider both the youngest and oldest children.  The six year old dummy and the ten year old dummy were therefore selected as priorities for electric wheelchairs with an upright backrest.  Taking their prevalence for children into account, it was decided not to include electric wheelchairs with a reclining backrest or a tilt-in-space facility.

**Table 20 Electric wheelchairs – test selection**

| | Backrest or tilt angle | Dummy | Priorities |
|---|---|---|---|
| Electric | Upright | 6 year old | ✓ |
| | | 10 year old | ✓ |
| | Reclined | 6 year old | |
| | | 10 year old | |
| | Tilted | 6 year old | |
| | | 10 year old | |

Table 21 shows all the tests that would complete the picture for children travelling rear facing in supportive seating systems in M1 or M2 vehicles. Tilt angle and occupant size were identified as the key issues for supportive seats.  Based on the dimensions of the seat, these are used by children that correspond in size with a range of child dummies from the three year old up to the ten year old.

If a supportive seating system was used with an upright backrest during a collision, a child would risk head and neck injury due to head contact and neck injury due to extension.  It is also possible that the backrest might fail, which could result in multiple injuries if the child is thrown against the vehicle bulkhead.

Younger children have a lower injury tolerance than older children; however, older children apply greater loads to the backrest and their head is more likely to be closer to the interior surfaces of the vehicle.  In this instance, both the smallest and largest children needed to be considered because they are very different in terms of their level of development and have different injury mechanisms. The three year old dummy and the ten year old dummy were therefore selected as priorities to examine the possible injury mechanisms for children in supportive seating units with an upright backrest.

If a supportive seating system was used with a tilt-in-space wheelchair base during a collision, a child would be at risk of riding up the backrest and striking their head on the vehicle interior. The largest tilt angle represents the greatest risk. When the wheelchair is used in this way, children travelling rear facing in an M1 or M2 vehicle could be at a significant risk of injury. Their head would be positioned very close to the bulkhead and the potential for ramping up would be great. The perceived level of risk necessitated tests with both dummy sizes. The three year old and the ten year old dummies in a fully tilted wheelchair were therefore selected as priorities for seating units with a tilt-in-space base.

**Table 21 Supportive seating systems – test selection**

| Seating system | Tilt angle | Dummy | Priorities |
|---|---|---|---|
| Modular | Upright | 3 year old | ✓ |
| | | 6 year old | |
| | | 10 year old | ✓ |
| | Tilted | 3 year old | ✓ |
| | | 6 year old | |
| | | 10 year old | ✓ |

### *4.3.3 Test matrix*

The final step was to compile the tests identified as priorities from Tables 18 to 21. These are shown in Table 22, along with three baseline tests with the dummies restrained in a typical vehicle based restraint system.

This vehicle scenario was intended to represent purpose built or adapted taxis where wheelchair users travel rear facing against the bulkhead that separates the driver and passenger compartments. Whereas a full body shell would represent the complex interaction between the wheelchair, the occupant and the bulkhead, it was important to represent the range of different vehicle makes and models. It was felt that a generic mock up would provide information that could lead to more robust recommendations for this vehicle type. A mock up was created to reproduce the essential interactions without being linked to a specific vehicle.

**Table 22 Test matrix – M1 or M2 rear facing**

| **Wheelchair** | **Backrest or tilt angle** | **Dummy** |
|---|---|---|
| Buggy – basic | Upright | 10 year old |
| | Reclined | 10 year old |
| Buggy – supportive | Upright | 6 year old |
| | Reclined | 6 year old |
| Manual – basic | Upright | 3 year old |
| | | 10 year old |
| Manual – active user | Upright | 10 year old |
| Electric | Upright | 6 year old |
| | | 10 year old |
| Supportive seating system – modular | Upright | 3 year old |
| | | 10 year old |
| | Tilted | 3 year old |
| | | 10 year old |
| Vehicle seat | | 3 year old |
| | | 6 year old |
| | | 10 year old |

### *4.3.4 Test set up*

Figure 28 shows the set up in typical tests with rear facing wheelchairs. The image on the left shows a baseline test with the ten year old dummy, while the image on the right shows a corresponding wheelchair test. A two point webbing restraint was used to restrain the wheelchair in rebound and a three point seat belt held the dummy in place.

The wheelchairs were restrained by the two rear straps from a production model four point webbing system that was secured to the floor by aluminium track fittings. The wheelchair restraints were not designed for use in this orientation. However, it was considered that the loads in the restraints during the later phase of the impact, when the wheelchair moves away from the bulkhead, would be much lower than the loads that the restraints were designed and tested to withstand.

The dummy was restrained independently by a three point seat belt. The seat belt included an inertia reel and an upper anchorage point on the B pillar. The seat belt was a surrogate model developed for the test programme by a manufacturer of commercial wheelchair tie-downs and occupant restraint systems through consultation with another wheelchair and occupant restraint manufacturer. The performance of the surrogate seat belt was verified with the four point webbing restraint during a dynamic test according to ISO 10542-1:2001.

All test pieces were installed according to the manufacturer's instructions and to the ISO Standards, unless there was a strong reason for not doing so. Any deviations from the Standards were documented. In particular, the occupant restraint was installed to achieve the best possible belt path for the child dummy, although it was recognised that this was not always the case in the real world. However, it was not within the scope of the project to investigate potentially unfavourable belt routes and misuse.

The main aim of the tests was to investigate occupant loading in a range of common children's wheelchairs and compare these loads with a vehicle seated baseline.

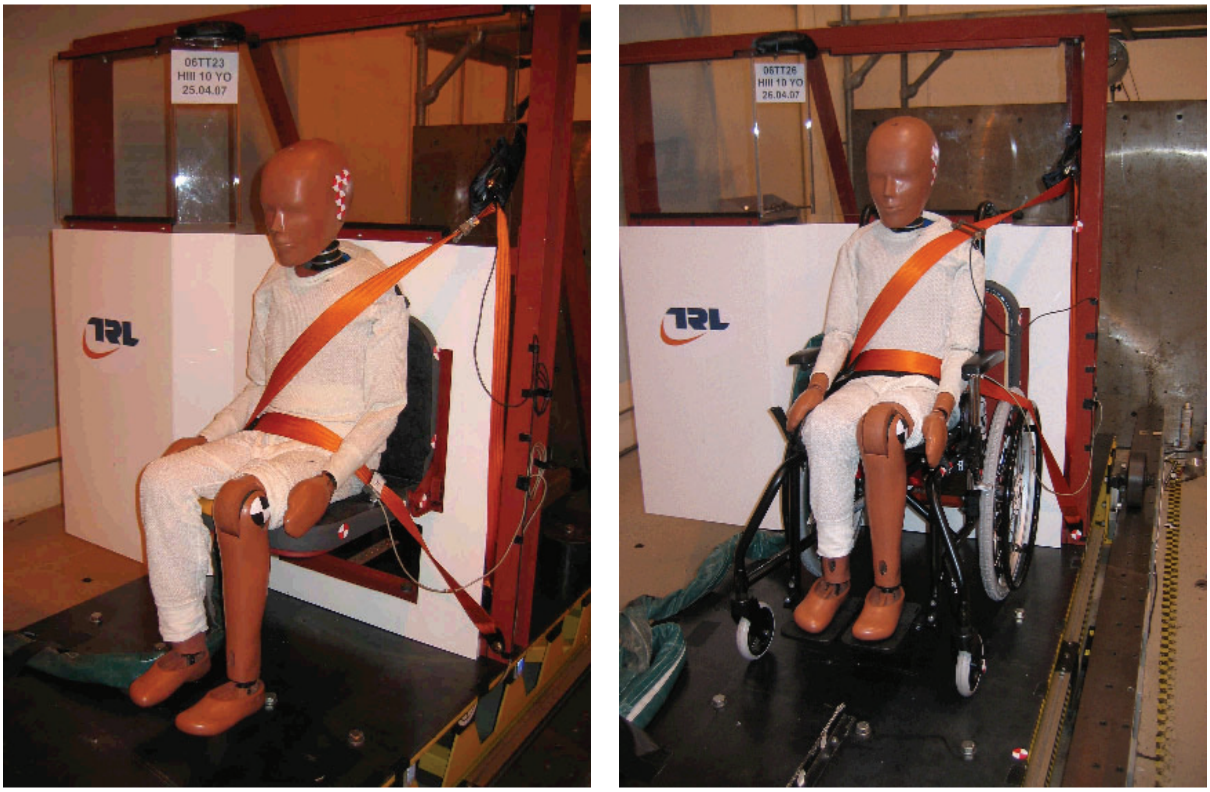


**Figure 28** Rear facing ten year old dummy restrained in a vehicle seat (left) and a basic manual wheelchair (right)

## 4.4 Findings

### *4.4.1 Relative safety of current situation*

The test programme highlighted a number of issues for children travelling rear facing in a wheelchair in an M1 or an M2 vehicle. These issues related to the stiffness of the wheelchair and to the environment within the vehicle.

The stiffness of the wheelchair affected its capacity to withstand the forces of the impact. When the wheelchair deformed excessively, the rear of the backrest struck the vehicle bulkhead and the dummy tended to record high chest acceleration. It seemed likely that a real child would be at risk of serious injury in these circumstances. When the dummy was seated on the rear facing vehicle seat, the impact forces were applied very early in the impact and over a wide area. As a result, the chest acceleration tended to be lower than the wheelchair tests and within the limit in FMVSS 213.

The environment within the vehicle did not afford any protection of the head and neck (of the dummy in a wheelchair) during the impact and did not protect the chest during secondary impact with the bulkhead. For instance, the dummy head extended rearwards and struck the bulkhead or the clear plastic division. Head and neck loads were high when this occurred, although the neck bending occurred below the level of the instrumentation. A child would be at risk of serious head and neck injuries in these circumstances. A similar issue was observed with the rear facing vehicle seat; however, the head tended to be closer to the bulkhead or plastic division. This seemed to mitigate some of the loads in certain circumstances. A secondary impact with the bulkhead occurred when the wheelchair rotated or deformed. This usually resulted in high chest accelerations in the dummy and hence an increased risk of injury for a child. A child in a vehicle seat would not be exposed to this risk, because they would be supported by their backrest during the collision.

The following sections examine the effects of wheelchair stiffness and of head and back restraint in more depth.

### *4.4.2 Effect of wheelchair stiffness*

ISO 7176-19:2001 does not include a rear facing front impact test. Since wheelchairs are not usually tested in that condition, most manufacturers will say that their wheelchair should be used forward facing only. It was not surprising, therefore, that wheelchair stiffness varied significantly during the test programme and some wheelchairs were unable to withstand the impact forces.  An example with the three year old dummy is shown in Figure 29.  The image on the left shows the dummy and the wheelchair just before the impact and the image on the right illustrates how wheelchair deformation can result in additional loading to the child.  The wheelchair was a common supportive seating system with a base supplied by a different manufacturer.  The seating attachments withstood the impact, but the base compressed and the rear of the backrest struck the bulkhead.  The chest acceleration exceeded the baseline test by 184 percent and exceeded the limit in FMVSS 213 by 164 percent.

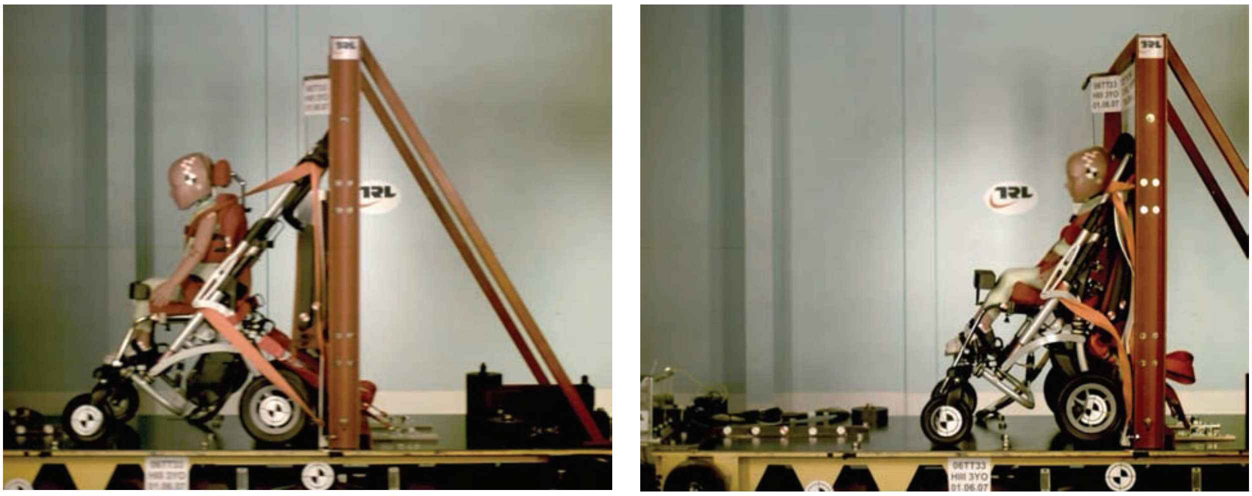


**Figure 29** Wheelchair stiffness in selected tests with three year old dummy

An example with the ten year old dummy is shown in Figure 30.  Once again, the image on the left shows the dummy and the wheelchair just before the impact and the image on the right shows the wheelchair deformation.  The wheelchair was a basic buggy.  The frame of the buggy failed during the impact and the rear of the backrest struck the bulkhead.  The chest acceleration exceeded the baseline test by 27 percent and exceeded the limit proposed by the NHTSA by 32 percent.

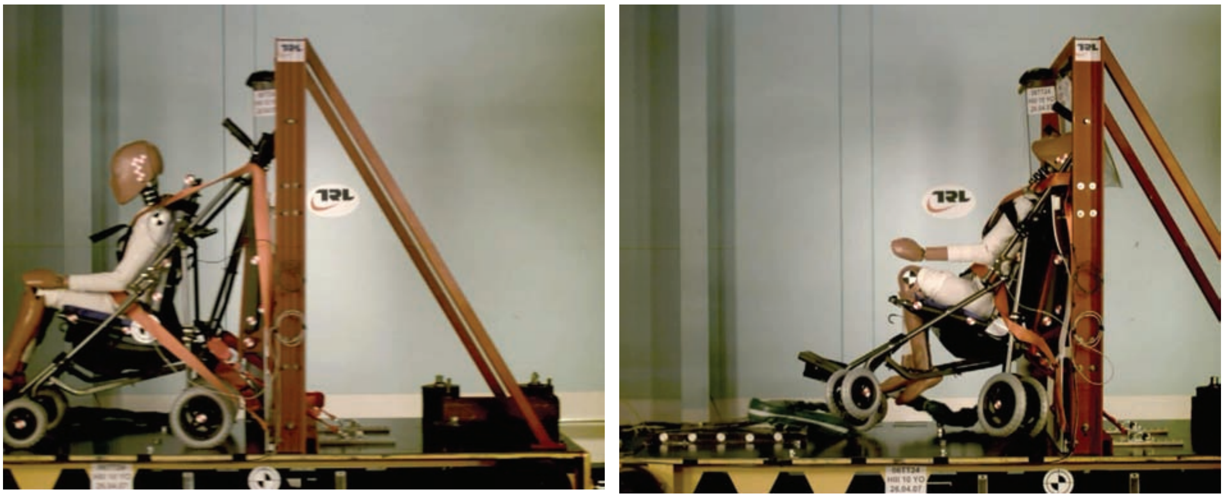


**Figure 30** Wheelchair stiffness in selected tests with ten year old dummy

These two examples were selected to illustrate the importance of wheelchair stiffness, but the same outcome was observed in all tests with buggies (basic and supportive). In fact, wheelchairs tended to deform in this way when the push handles were pressed against the bulkhead, thereby preventing rotation about the rear wheels. It seems likely that other wheelchairs that are similar in design will also be unable to withstand the forces in a front impact crash when they are used rear facing in a vehicle.

### *4.4.3 Effect of head and back restraint*

Current vehicles in which a wheelchair user travels rear facing do not provide a head and back restraint. The test programme examined the implications for children when their head and neck are not protected during a collision.

Figure 31 shows an example with the three year old dummy. The image on the left shows the baseline test with the dummy seated on the vehicle seat. The image on the right shows the dummy seated in a basic manual wheelchair. The vehicle seat included a backrest but there was no head restraint. During the impact, the head of the dummy struck the bulkhead, as shown in the figure. When the dummy was seated in the manual wheelchair, the wheelchair rotated about the rear wheels. The backrest made contact with the bulkhead and the head of the dummy extended rearwards until it struck the top of the bulkhead, in a similar place as the vehicle seated test. In the case of the manual wheelchair, the sled had come to rest when head contact occurred. As a result, very high head acceleration and HIC were recorded. The HIC value exceeded the vehicle seat test by 212 percent and the limit used in

FMVSS 213 by 124 percent.  Neck loads also tended to be greater than the baseline test.

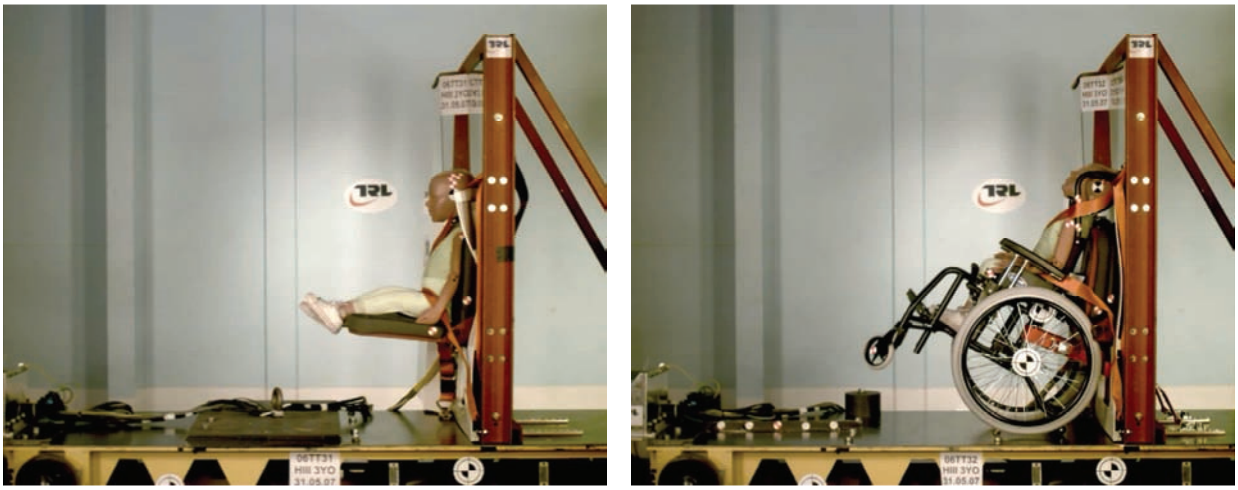


**Figure 31** Neck extension in selected tests with three year old dummy

An example with the six year old dummy is shown in Figure 32.  The image on the left shows the baseline test with the dummy seated on the vehicle seat.  The image on the right shows the dummy seated in an electric wheelchair.  When the dummy was seated on the vehicle seat, the head struck the clear plastic division above the bulkhead before any significant neck extension.  When the dummy was seated in the electric wheelchair, the push handles displaced the clear plastic division and hence the neck was able to extend.  As a result, very high bending moments in extension were recorded in the neck.  The extension moment exceeded the vehicle seat test by 780 percent and the limit proposed by Mertz *et al.* (2003) by 193 percent.

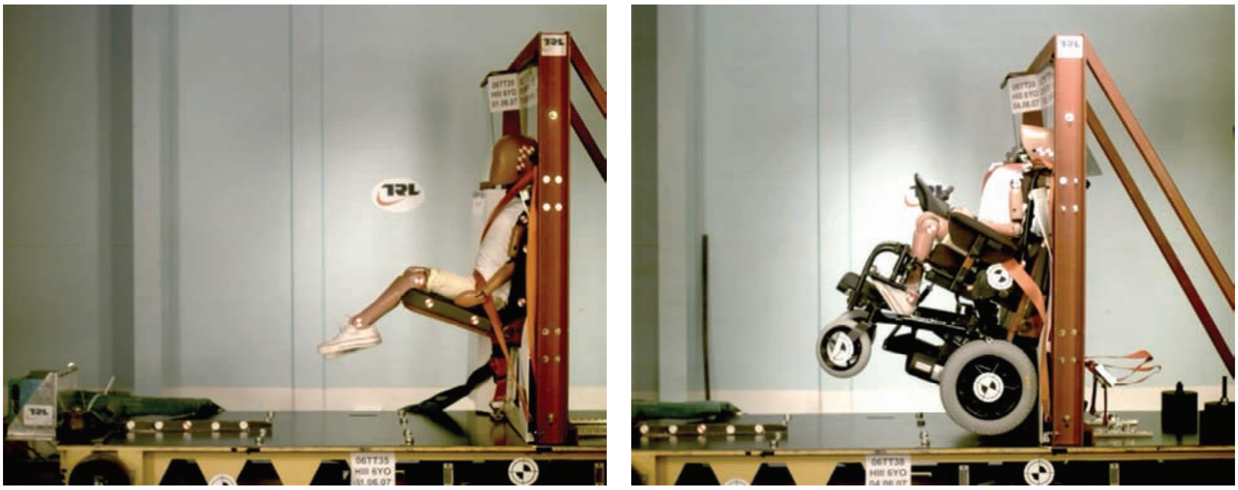


**Figure 32** Neck extension in selected tests with six year old dummy

Figure 33 shows an example with the ten year old dummy. The image on the left shows the baseline test with the dummy seated on the vehicle seat.  The image on the right shows the dummy seated in a supportive seating unit. When the dummy was seated on the vehicle seat, the head struck the clear plastic division above the bulkhead and displaced it from its mounting attachments. This allowed some bending of the neck to occur, although the head was supported to some extent by the displaced plastic surface.

When the dummy was seated in the supportive seating unit, the push handles displaced the clear plastic division to a much greater extent. As a result, the neck was able to extend significantly despite the presence of a headrest on the seating unit. The dummy recorded high bending moments in extension in the neck. The extension moment exceeded the vehicle seat test by 21 percent but it did not exceed the limit proposed by Mertz *et al.* (2003). In general, the dummy loads in this test were not as high as the kinematics suggested, which may have been a function of the location of the instrumentation.

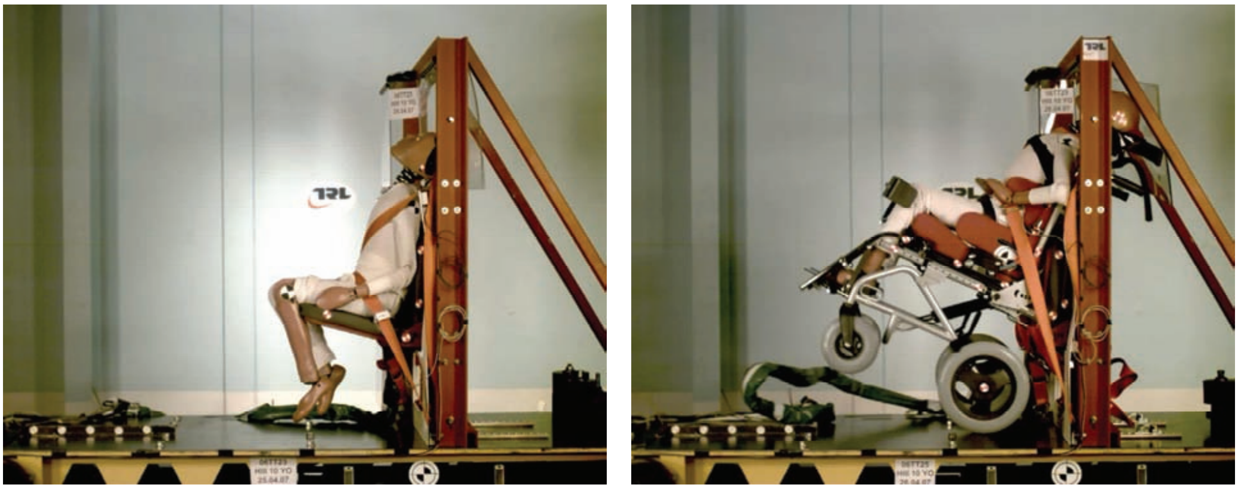


**Figure 33** Neck extension in selected tests with ten year old dummy

A few examples were presented here, but the protection of the head and neck was an important issue when the dummy was seated in every type of wheelchair that was used in the test programme. The headrests provided on some wheelchairs were not intended to be vehicle head restraints and were inadequate for that purpose in these tests.

The test programme also examined the implications for children when their chest is not protected during a secondary impact with the vehicle bulkhead. This issue is illustrated in Figure 34 with the ten year old dummy. The image on the left shows the dummy and the wheelchair just before the impact and the image on the right shows the wheelchair in contact with the bulkhead. The wheelchair was a basic manual wheelchair. Before the impact, there was a gap between the wheelchair backrest caused by the rear wheels and push handles. However, during the impact, the wheelchair rotated about the rear wheels and the backrest struck the bulkhead. This secondary impact occurred when the sled had come to rest; hence the loads on the dummy were high. The chest acceleration was 85 percent higher than the baseline test and 92 percent higher than the limit proposed by the NHTSA.

**Figure 34** Chest loading in selected tests with ten year old dummy

A secondary impact with the bulkhead can occur when the wheelchair rotates or when the wheelchair fails as shown in Section 4.4.2. Wheelchair rotation could be prevented by an additional wheelchair restraint, but that would increase the loads on the wheelchair backrest and occupant neck extension. The effects of the secondary impact could be mitigated by specifying performance requirements for the bulkhead surfaces.

A vehicle based head and back restraint compatible with children's wheelchairs would address the protection of the head and neck during the impact and the protection of the chest from secondary impacts within the vehicle. While this would be a relatively straightforward solution for manual and electric wheelchairs, the design of buggies and supportive seating systems would be difficult to accommodate with a vehicle based solution. For these devices, it may be necessary for the wheelchair to protect these body regions.

The results of this study will have been influenced by the surface characteristics and dimensions of the vehicle mock up and by the way the clear plastic division was attached. However, every effort was made to ensure that these aspects of the bulkhead were representative of real vehicles. It follows, therefore, that the issues highlighted by the test programme would also apply to the real world.

## 4.5 Conclusions

- Some wheelchairs were unable to withstand the forces in an impact when they were used rear facing.

- When a wheelchair deformed or failed, the dummy struck the vehicle bulkhead after it had come to rest. This resulted in high accelerations and forces, which suggested that a child would be at risk of injury.

- A rear facing front impact test would address the wheelchair strength issues.

- The head and neck of the dummy were not protected by the vehicle or by the wheelchair. The head struck the bulkhead or the clear plastic division and the neck extended rearwards. A child would be at risk of head and neck injuries in these circumstances.

- Wheelchair headrests are not intended to protect the user in a collision and were inadequate for that function.

- The chest of the dummy was not protected during secondary impacts with the bulkhead.

- A head and back restraint would address the protection of the child’s head and neck and would prevent secondary impacts with the bulkhead.

# 5 M3 forward facing

## 5.1 Field study

The field study included M3 vehicles in which a passenger in a wheelchair travels forward facing. In each vehicle, dummies representing children aged three, six and ten years old were seated and restrained in a range of wheelchairs. An overview of the methods was given in Section 2.2 and the results of the study were described in detail in Appendix B.

The study highlighted that the wheelchair space in an M3 vehicle is likely to be similar to that in other M category vehicles when the wheelchair is forward facing. As a result, the main observations for M1 and M2 vehicles with forward facing wheelchairs (summarised in Section 3.1) also applied to M3 vehicles. Although an M3 vehicle would experience a lower deceleration during a collision, the geometry of the occupant restraint system, the protection of the child's head and neck during rebound and the amount of clear space around the child remain important. This is because vulnerable parts of a child's anatomy are affected.

The occupant restraint system was installed according to ISO 10542-1:2001 and to achieve the best fit. The vehicles examined did not provide an upper anchorage point for the occupant restraint. The lap belt anchorages and consequently the seat belt buckle were attached to floor tracking behind the wheelchair. This meant that the diagonal part of the seat belt passed around the ribs before joining the lap belt at the buckle. In some cases, the wheelchair obstructed the ideal path of the lap part of the seat belt. These obstructions were caused by side guards to prevent splash from the wheelchair wheels and by hip support pads to position the child's pelvis within the wheelchair.

The vehicles did not provide a head and back restraint for the wheelchair user. Although there is no requirement to fit a head and back restraint, some coaches on scheduled interurban services are equipped with them. The vehicles examined in the field study therefore represent the worst case. In a collision, a child's neck would extend rearwards during the rebound phase. This would increase the risk of head contact behind the seating position and could lead to soft tissue neck injuries. This was thought to represent a greater risk of injury to a child than positioning their wheelchair with a gap between their backrest and the head and back restraint.

The amount of space in front of the wheelchair user was also important, although the current requirements would seem to be adequate to reduce the risk of head contact for children.

## 5.2 Approach

The field study highlighted some similarities with other M category vehicles that carry wheelchair users forward facing. As a consequence, the main observations were the same for M3 vehicles as they were for M1 and M2 vehicles. The study revealed that vulnerable parts of a child's body were affected, such as the head, neck or abdomen. These body regions can be injured with relatively low rates of loading, due to the way the human body develops through childhood. Nevertheless, the risk of injury is likely to be lower in an M3 vehicle compared with an M1 or M2 vehicle. This was the case for adults in a previous research project for the DfT (UG327).

During the course of the project, it became clear that there were a number of important issues to consider for children in wheelchairs. A comprehensive investigation of all the issues for every vehicle category and wheelchair direction would require a very high number of sled tests. Since M1 and M2 vehicles represented the main priority in terms of the risk of injury to children, the DfT agreed that M3 vehicles with forward facing wheelchairs would not be included in the test programme. However, given the similarities mentioned above, it was anticipated that conclusions and recommendations could be made for M3 vehicles with forward facing wheelchairs based on the results of the sled tests representing M1 and M2 vehicles with forward facing wheelchairs.

## 5.3 Conclusions

- The path of the seat belt could be improved for children in wheelchairs.

- Although the vehicle deceleration pulse would be relatively low in an M3 vehicle, a child in a wheelchair might be placed at a higher risk of receiving an abdomen injury through belt loading than a child in a vehicle seat.

- The greatest improvements would be made if wheelchair manufacturers were encouraged to manage positively the path of the seat belt.

- It is likely that children’s wheelchairs will be able to withstand the forces in a collision when they are used forward facing in an M3 vehicle.

- The head and neck of a child are unlikely to be protected during the rebound phase of a front impact.

- A child in a wheelchair should be provided with a head and back restraint if it is intended that they should receive a level of protection that is comparable to that for a child travelling in a vehicle seat.

- A head and back restraint within the vehicle would be appropriate for some wheelchairs; however, it would be difficult to accommodate wheelchairs fitted with positioning headrests with a vehicle based solution.  Instead, these wheelchairs would benefit from a wheelchair integrated solution.

# 6 M3 rear facing

## 6.1 Field study

The field study included M3 vehicles in which a passenger in a wheelchair travels rear facing (i.e. usually low floor buses). In each vehicle, dummies representing children aged three, six and ten years old were seated in a range of wheelchairs. The wheelchairs were positioned in the wheelchair space, which is a protected area fitted with a padded backrest. An overview of the methods was given in Section 2.2 and the results of the study are described in detail in Appendix B.

In this section, any references to locations or directions within the wheelchair space are made with respect to the bus. For example, the front end of the wheelchair space is towards the front end of the bus and the rear end of the space is towards the rear of the bus. However, any references to locations or directions on the wheelchair are made with respect to the wheelchair, irrespective of the direction that it faces.

The study highlighted some potential issues of compatibility between children's wheelchairs and the padded backrest in low floor buses. For example, the backrest was wider than the distance between the handles on the manual wheelchair used in the study. This meant that the handles were unable to pass either side of the backrest. Instead, they rested against the padded surface, resulting in a gap between the backrest and the dummy. The head of a child travelling in this way would extend rearwards (i.e. towards the front of the bus) in the event of heavy braking or a collision. This motion might result in a soft tissue neck injury. It was also noted that the wheelchair was not as far forwards in the wheelchair space when the handles rested against the backrest. This meant that the wheelchair was positioned differently with respect to the vertical stanchion or the retractable rail than it would have been if the handles passed either side of the backrest. This might increase the risk of the wheelchair moving sideways into the gangway during normal driving manoeuvres. This will be examined in Section 7.

The Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended) include dimensions for a backrest to be fitted when wheelchair users travel rear facing. The width of the backrest must fall between 270 mm and 300 mm at a height exceeding 830 mm from the floor. Below this height, the width of the backrest must fall between 270 mm and 420 mm. The DfT commissioned a survey of occupied wheelchairs and scooters to determine their overall mass and dimensions.  The findings of the survey were reported by Hitchcock *et al.* (2006).  The average distance between the handles of the children's wheelchairs in the survey was 292 mm.  A child was defined as a person under the age of 16 years and the average age of the children was ten years.

Another compatibility issue was found when the electric wheelchair was positioned against the padded backrest in each vehicle.  The electric wheelchair used in the study included a large base that extended rearwards behind the wheelchair seat.  This pressed against the mounting structure below the bottom edge of the padded surface and introduced a gap between the backrest and the dummy.  Once again, a child travelling in this way might be at risk of soft tissue neck injury in the event of heavy braking or a collision and their wheelchair would be positioned differently with respect to the stanchion or rail.

Hitchcock *et al.* (2006) assessed whether the wheelchairs in their survey would be likely to fit against the backrest defined in the Regulations. This revealed that 71 percent of the electric wheelchairs used by children would not fit.  The reasons included the handles being too close together, a continuous bar handle preventing the backrest from locating against the body of the wheelchair, narrow wheels and the battery or other items obstructing the backrest. While this gives an indication of the compatibility of children's wheelchairs with the backrest in buses, dimensions of the area around the base of electric wheelchairs were not included.

In order to understand further the influence of the base or battery of electric wheelchairs on the interaction with the backrest, Hitchcock (2008) provided some additional measurements.  These included the distance from the rear surface of the wheelchair backrest to the rear edge of the base and the height of the base from the floor.  Of the 59 electric wheelchairs examined, 51 (86 percent) were found where the base extended further rearwards than the rear surface of the wheelchair backrest.  The implication is that these wheelchairs might not fit against the backrest.  The measurements are summarised in Table 23.

In addition, Hitchcock (2008) provided similar measurements for manual wheelchairs. The manual wheelchair used in the field study was incompatible with the backrest because the push handles were too narrow to pass by the sides. Other manual wheelchairs may have push handles that are further apart, but instead, the anti-tip devices may prevent the wheelchair from achieving the correct position against the backrest. The measurements provided by Hitchcock included the distance from the rear surface of the wheelchair backrest to the rear edge of the anti-tip devices and the height of the anti-tip devices from the floor. Of the 151 manual wheelchairs examined, 125 (83 percent) were found with anti-tip devices that extended further rearwards than the rear surface of the wheelchair backrest. The data from these wheelchairs are summarised in Table 24.

**Table 23 Electric wheelchair measurements (Hitchcock, 2008)**

| Measurement | Function | Value (mm) |
|---|---|---|
| Backrest to base | Mean | 111 |
| | 95th percentile | 263 |
| | 50th percentile | 102 |
| | 5th percentile | 7 |
| Height of base | Mean | 365 |
| | 95th percentile | 449 |
| | 50th percentile | 369 |
| | 5th percentile | 293 |

**Table 24 Manual wheelchair measurements (Hitchcock, 2008)**

| Measurement | Function | Value (mm) |
|---|---|---|
| Backrest to anti-tip devices | Mean | 112 |
| | 95th percentile | 216 |
| | 50th percentile | 115 |
| | 5th percentile | 15 |
| Height of anti-tip devices | Mean | 263 |
| | 95th percentile | 426 |
| | 50th percentile | 261 |
| | 5th percentile | 125 |

## 6.2 Approach

The field study raised some questions about the interaction between children's wheelchairs and the equipment in the wheelchair space in low floor buses. A backrest is required to support the back of the wheelchair (and the user) and to prevent the wheelchair from tipping rearwards when the vehicle is in motion. A means of restricting movement of the wheelchair into the gangway is required to maintain the wheelchair within the wheelchair space. It is likely that this equipment will afford a degree of protection in the event of a collision as well as in normal driving manoeuvres.

Other vehicle occupants, and in particular standing passengers, are afforded little protection in the event of a collision. The Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended) specify requirements for the strength of the backrest, although this may only address loads in normal travel. The management of the occupant's loads is not considered for vehicle seated passengers or for wheelchair seated passengers. It could be argued, therefore, that a comparable level of protection is afforded. Nevertheless, children in wheelchairs may be more vulnerable, particularly due to the issues highlighted in the field study.

During the course of the project, it became clear that there were a number of important issues to consider for children in wheelchairs. A comprehensive investigation of all the issues for every vehicle category and wheelchair direction would require a very high number of sled tests. Since M1 and M2 vehicles represented the main priority in terms of the risk of injury to children, the DfT agreed that M3 vehicles with rearward facing wheelchairs would not be included in the test programme. However, it was anticipated that conclusions and recommendations could be made for M3 vehicles with rearward facing wheelchairs based on the results of the field study. Furthermore, a study was carried out to examine whether the backrest or methods for restricting lateral movement of wheelchairs described in the Regulations are adequate for children's wheelchairs. This study will be reported in Section 7.

## 6.3 Conclusions

- M3 vehicles in which a passenger in a wheelchair travels rear facing (i.e. low floor buses) also carry standing passengers and do not, therefore, offer crash protection above that provided by the vehicle structure.

- Although it is not its intended function, the backrest that supports the wheelchair user, and the stanchion or other means of restricting movement into the gangway, are likely to provide a degree of protection for a child in the event of a collision.

- The gap between the handles of some children's wheelchairs is likely to be too small for the handles to pass on either side of the backrest.

- The base of some electric wheelchairs might extend further rearwards than the space below the backrest in vehicles.

- A gap between a child in a wheelchair and a backrest in the vehicle might result in the child being placed at an increased risk of soft tissue neck injury.

# 7 M3 non-impact protection

## 7.1 Scope

The requirements of the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended), being the relevant legislation in the UK, are the focus for this section; however, it is recognised that requirements for M3 vehicles are also made in European Commission Directive 2001/85/EC and in UNECE Regulation 107 and that these requirements may differ slightly from the UK Regulations.

The Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended) allow a wheelchair user in a bus to travel facing rearwards, in a protected area fitted with a backrest. Earlier research carried out by TRL demonstrated that this configuration will prevent an adult in a wheelchair from tipping during normal transit (Le Claire *et al.*, 2003).

The Regulations also demand a method for restricting lateral movement of the wheelchair into a gangway. This lateral restraint can be a vertical stanchion situated at the front end of the wheelchair space and running continuously from the floor to the roof, or a retractable horizontal rail extending from the front of the wheelchair space. A range of positions for both these items within the wheelchair space is specified. Figure 35 summarises the requirements for the wheelchair space in buses.

Previous research carried out for the DfT by TRL (UG327) examined the extent of lateral movement of an adult wheelchair during normal driving conditions in a bus that was compliant with the Regulations. A 50$^{th}$ percentile male Hybrid II dummy was seated in the Disability Discrimination Act Reference Wheelchair, while a bus was driven through a manoeuvre that generated levels of lateral movement recorded on real bus routes. Wheelchair displacement was observed, but it was restricted by the vertical stanchion on the edge of the wheelchair space. Performance of the horizontal rail was dependent on height, as it restricted lateral movement of the wheelchair at lower positions but did not at higher positions that were allowable within the Regulations.

Children’s wheelchairs are narrower than those for adults and some have pushchair style handles. It was not clear whether the backrest or the methods for restricting lateral movement (namely the vertical stanchion or horizontal rail) that are described in the Regulations are adequate to restrict movement of children's wheelchairs.

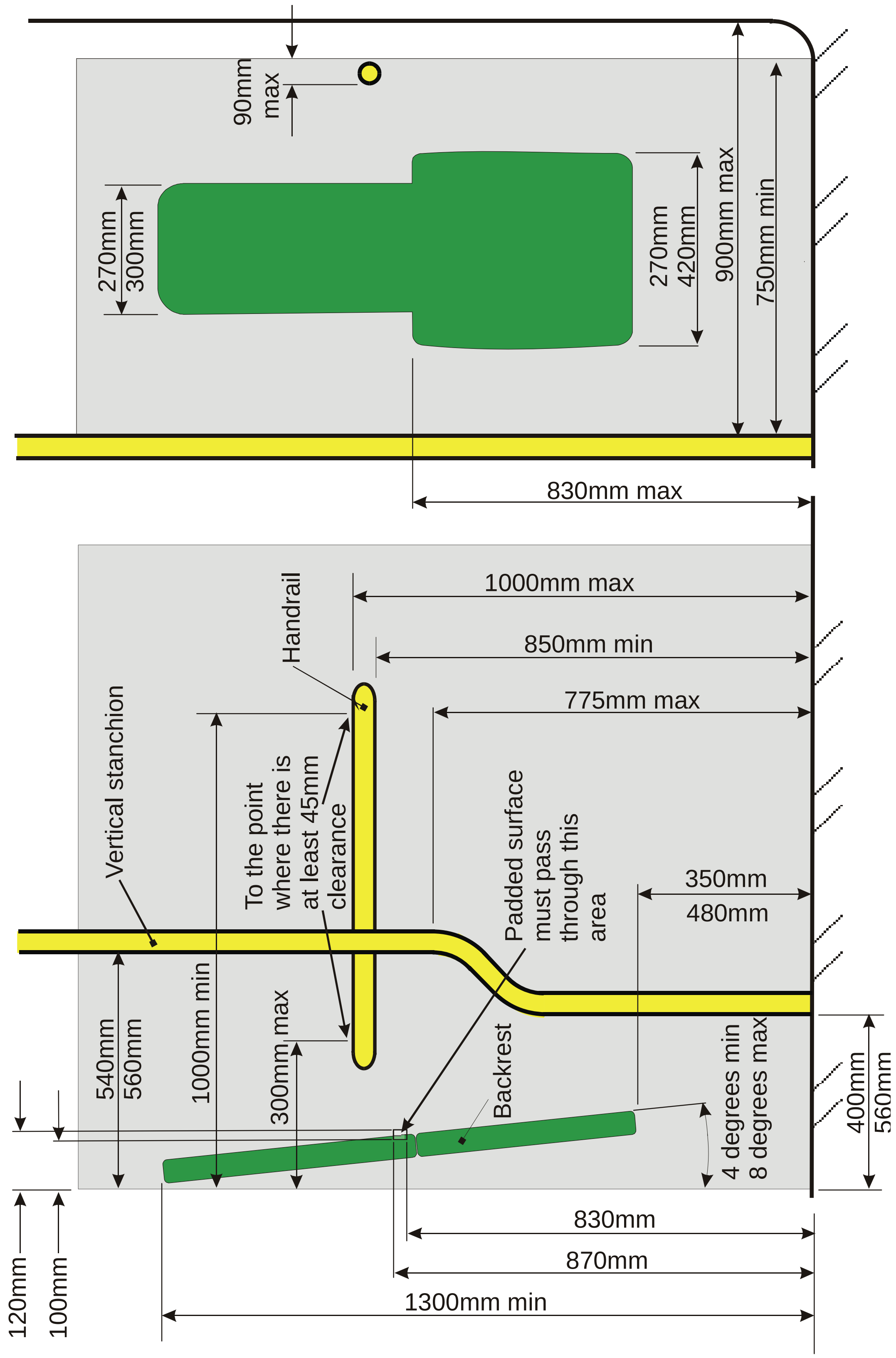



**Figure 35** Wheelchair space in buses

The main objective of the work reported here was to investigate paediatric wheelchair displacement during normal driving conditions in a bus that is compliant with the Regulations.  A series of trials was undertaken to repeat the adult study described above, this time using children's wheelchairs and child dummies.  A number of combinations of wheelchairs and child dummy sizes were used in order to check the effect of different styles of child wheelchair and occupant size and weight.

## 7.2 Testing methodology

Previous research at TRL has demonstrated that lateral accelerations on low floor buses can reach 0.4 g on bus routes selected as being difficult to negotiate (Stone, 1999; unpublished Project Report).  The study using adult wheelchairs described a test procedure to achieve this level of lateral acceleration where a low floor bus was driven around a bend of 20 metres constant radius at a constant speed of approximately 24 mph. The procedure was replicated for this testing (Figure 36).  However, it was found that a speed of 21 to 23 mph was sufficient to achieve the required lateral acceleration. The speed and lateral acceleration of the bus was measured using global positioning system technology.

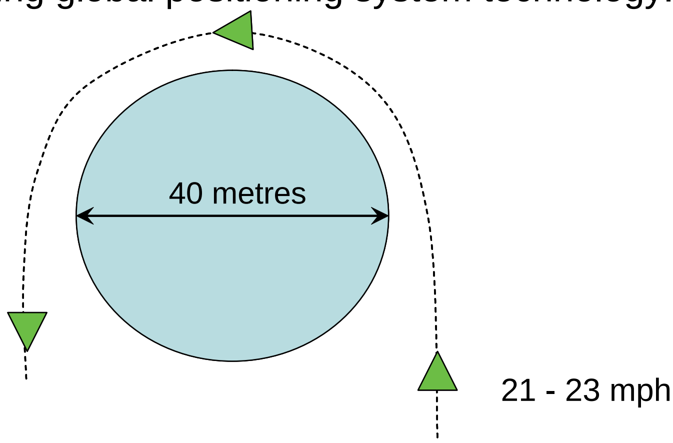



**Figure 36** Diagram showing test procedure

Two low floor buses were used for the testing, one with each type of lateral restraint fitted.  The vertical stanchion was fitted in Bus 1, and the horizontal retractable rail was fitted in Bus 2 (Figure 37).  Both buses were in current use on scheduled services and had been certified according to the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended).

In the remainder of this section, any references to locations or directions within the wheelchair space are made with respect to the bus.  For example, the front end of the wheelchair space is towards the front of the bus and the rear end of the space is towards the rear of the bus.


Bus 1 (vertical stanchion) Bus 2 (retractable rail)

**Figure 37** Buses used in study

Bus 1 had the wheelchair space on the right side of the bus, and therefore was driven around the bend in a clockwise direction (right hand turn) to ensure that the lateral acceleration on the wheelchair acted towards the opposite side of the bus. The wheelchair space in Bus 2 was on the left side of the bus, so it was driven around the bend in an anti-clockwise direction (left hand turn).

The cranked vertical stanchion and backrest in Bus 1 are shown in Figure 38.


**Figure 38** Vertical stanchion and back restraint in Bus 1

The horizontal retractable rail in Bus 2 in both the raised and lowered positions is shown in Figure 39.

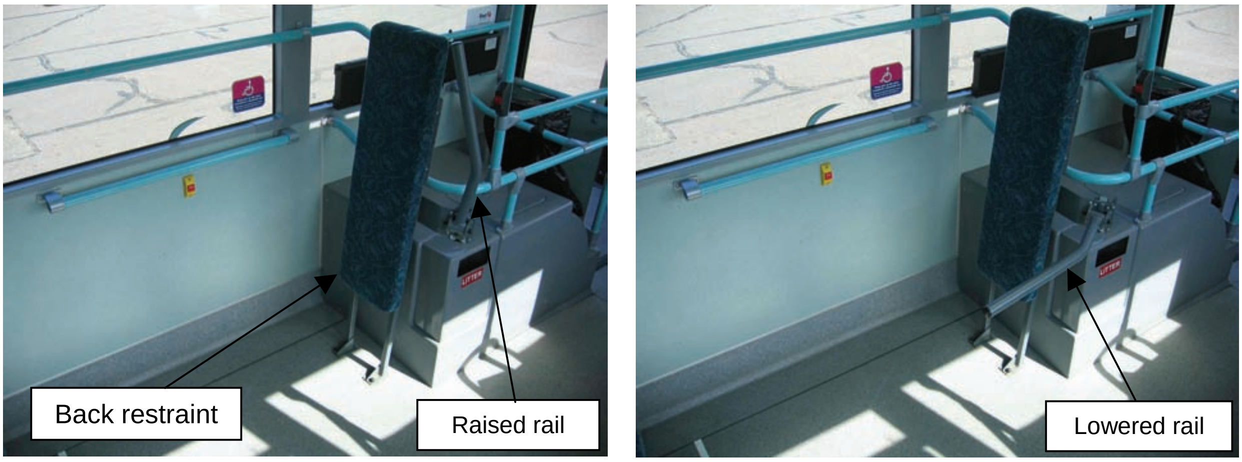



**Figure 39** Retractable rail and backrest in Bus 2, showing rail raised (left) and lowered for use (right)

Three different-sized child dummies and three different wheelchairs were used in the study. The dummies used were a Q3 (three year old), a Hybrid III six year old and a P10 (ten year old). The wheelchairs used were a supportive buggy, an electric wheelchair and a manual wheelchair. These wheelchairs were described in detail in Section 2.2.3. The six year old and ten year old dummies were tested in both the electric and manual wheelchairs, while the three year old was only tested in the supportive buggy. The three year old dummy was seated in the supportive buggy using the integral harness provided. The dummies and wheelchairs are shown in Figure 40.

| Three year old dummy in supportive buggy | Six year old dummy in electric wheelchair | Ten year old dummy in manual wheelchair |
|---|---|---|

**Figure 40** Dummies and wheelchairs used in study

The wheelchairs were positioned in the wheelchair spaces such that the centreline of the wheelchair aligned with the centreline of the backrest. The wheelchair was moved as far forwards in the wheelchair space as possible, so that the wheelchair was in contact with the backrest. All the wheels on the wheelchair were aligned in the fore/aft direction, with the brakes applied where fitted. Two video cameras were mounted in the bus to film the movement of the wheelchairs and dummies during the test runs.

## 7.3 Results

Both the vertical stanchion and the horizontal retractable rail are designed to prevent movement of a wheelchair into the gangway of a bus, as this could be hazardous for both the wheelchair occupant and other bus users, especially those standing in the vicinity. In this study, a wheelchair was considered to be restrained effectively if all parts of it remained inside the wheelchair space during the manoeuvre and the occupant remained in the wheelchair at the end of the manoeuvre.

### *7.3.1 Observations before testing*

A number of observations were made before testing regarding the position of the wheelchairs within the wheelchair spaces. One of the main observations was that there were compatibility issues between the wheelchairs and the backrests in each bus. This is illustrated in Figure 41.

The first incompatibility issue was that the backrests on both buses were wider than the gap between the handles on the manual wheelchair, meaning that the wheelchair occupant was not in contact with the backrest. This meant that there was no restraint to support the head of the dummy, which could lead to potential injury to the neck in the event of heavy braking or a front impact.

The second issue that was identified was an incompatibility between the battery pack and motor on the electric wheelchair with the base of the backrest, which also resulted in the wheelchair occupant not being in contact with the backrest. This, again, could lead to potential neck injury as mentioned above.

Both of the compatibility issues discussed above also meant that the wheelchair occupant was positioned further rearwards in the wheelchair space on the bus in relation to the lateral restraint.

**Figure 41** Examples of compatibility between children's wheelchairs and the backrests in typical buses

One of the other observations was that the wheelchair space was wider than the children's wheelchairs, resulting in there being a gap between the wheelchair and the vertical stanchion or horizontal rail (Figure 42). This would potentially allow more movement of a paediatric wheelchair in the wheelchair space before contact with the lateral restraint than an adult wheelchair.

**Figure 42** Example of the distance between a typical children's wheelchair and the method of restricting lateral movement in a bus

In the bus fitted with the retractable rail, it was observed that the rail did not align with any of the side structures of the manual or electric wheelchairs (with the exception of the backrest of the chair) as it was too high. This can be seen in Figure 41, shown previously.

### *7.3.2 Wheelchair space fitted with stanchion*

The stanchion in Bus 1 was tested at three different positions in the fore/aft direction within the allowable range in the Regulations (400 mm to 560 mm rearwards of the front of the wheelchair space). These were the furthest forward position (400 mm), mid position (480 mm) and furthest rearward position (560 mm). Each wheelchair and occupant combination was tested with each stanchion position. The stanchion was located 875 mm from the side of the bus in the lateral direction, and this was kept constant for all the tests.

The stanchion did not restrain the manual wheelchair effectively when in the 400 mm or 480 mm positions. As the bus performed the manoeuvre, the front castor wheels on the manual wheelchair turned and the front of the wheelchair rotated around the stanchion. This led to the ejection of both the six year old and ten year old dummies during the test (Figure 43). The brakes on the rear wheels remained engaged during the tests, and the rear wheels were observed to skid over the floor of the bus while the manual wheelchair rotated, with no rolling of the rear wheels being observed.

**Figure 43** Ejection of six year old dummy from manual wheelchair after rotation of seat around stanchion (400 mm position)

The manual wheelchair was only restrained by the stanchion in the 560 mm position as the front of the large rear wheel contacted the stanchion as the chair rotated. This prevented the full rotation of the chair as seen in the tests with the stanchion in the 400 mm and 480 mm positions. However, the chair started to tip over sideways and the occupant was almost ejected out of the chair sideways, but was prevented from doing so by the stanchion.

The electric wheelchair was restrained by the stanchion in all three stanchion positions and the occupant remained seated, although rotation of the chair was observed before it contacted the stanchion. In the test with the stanchion in the 400 mm position, the front wheel of the wheelchair was outside the wheelchair space at the end of the test.

The supportive buggy was restrained by the stanchion in all stanchion positions. The front wheel of the supportive buggy was fixed in the fore/aft position, rather than being a rotating castor as in the manual and electric wheelchairs. This appeared to prevent any rotation of the supportive buggy during the manoeuvre. In the tests the supportive buggy started to tip over sideways, but was prevented from doing so as the side rail of the supportive buggy contacted the stanchion.

### *7.3.3 Wheelchair space fitted with horizontal retractable rail*

The horizontal retractable rail was tested in one position, as it was not possible to adjust the height of the rail on the bus tested. The front of the rail was approximately 725 mm above the floor of the bus in its deployed position. The Regulations allow a rail such as this to be in the range of 600 mm to 800 mm above the floor of the bus. As described previously, the rail did not align with the side structures of the manual or electric wheelchairs as it was too high. The front of the rail was approximately 770 mm from the side of the bus in the lateral direction.

Both the manual and electric wheelchairs rotated by 90˚ during the tests, as there was no structure on the bus to prevent this. The chairs were not restrained within the wheelchair space by the horizontal rail. The six year old and ten year old dummies were either ejected from the wheelchairs or trapped between the wheelchair and the rail (Figure 44).

**Figure 44** Ejection and entrapment of child dummies observed in testing with horizontal rail

In the bus tested, the horizontal rail did not lock in the deployed position, which meant that it was able to rise up when it was contacted by the dummy in the wheelchair. In some cases this resulted in the rail contacting the child dummy's chest, or even the neck as shown in Figure 45.

**Figure 45** Horizontal rail rose during testing, resulting in contact with child dummy's chest and neck

The supportive buggy did not rotate during the testing and remained within the wheelchair space. The supportive buggy started to tip over sideways during the manoeuvre but was restrained by the horizontal rail.

## 7.4 Discussion

The results indicated that there were several issues relating to the adequacy of the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended) with regard to the restraint of children's wheelchairs in buses. The main areas of concern were the incompatibility between the paediatric wheelchairs and the backrest and the potential for injury to children in wheelchairs and other bus users as a result of ejection from the wheelchairs and/or contact with the lateral restraint.

The incompatibility issue between the manual and electric wheelchairs and the backrest in the buses gave cause for concern. The handles on the manual wheelchair and the battery/motor on the electric wheelchair prevented the wheelchair occupant from being positioned close enough to the backrest, meaning that the wheelchair occupant's head would not be prevented from moving rearwards in the event of heavy braking or a frontal impact. This has the potential to result in occupant injury due to extension of the neck. A secondary result of this incompatibility issue is that it may result in the wheelchair being positioned further rearwards in the wheelchair space relative to the vertical stanchion or horizontal rail. This may reduce the ability of the lateral restraint to keep the wheelchair and occupant within the wheelchair space during normal driving conditions.

There are two general options for rectifying this incompatibility issue. The first is to change the wheelchair design and the second is to change the design of the wheelchair space. For example, potential solutions to the issue with incompatibility between the handles and back restraint are making the backrest narrower or modifying the wheelchair handles. Narrowing the backrest may lead to problems with adult wheelchair occupants not being adequately supported, so this may not be practical. However, modifying the handles to be slightly further apart, or perhaps able to fold out of the way of the back restraint, may be a potential solution. In terms of the battery and motor on the electric wheelchair, it may be more practical to change the design of the base of the backrest rather than the wheelchair, as changes to the wheelchair may affect its stability, for example.

The vertical stanchion in Bus 1 was not effective in restraining the manual wheelchair in the 400 mm or 480 mm positions. The wheelchair was able to rotate about the base of the stanchion during the manoeuvre, which led to the ejection of both the six year old and ten year old dummies. The stanchion only restrained the manual wheelchair when in the 560 mm position, the furthest rearward position in the wheelchair space allowable in the Regulations. The vertical stanchion did restrain the electric wheelchair in all positions, although rotation of the chair was still observed during the manoeuvre. However, these results do not mean that the 560 mm position is necessarily the most appropriate, as it is likely to be the relative position of the wheelchair and stanchion that is more important. In the event that the compatibility issues between the wheelchairs and the backrest are resolved, the wheelchairs and their occupants will be seated further towards the front of the wheelchair space.

The performance of the retractable rail in Bus 2 gave cause for concern. The rail did not align with any part of the side structure on the manual and electric wheelchairs due to its height above the floor and small contact area. If the wheelchairs rotated during the manoeuvre, the rail would most likely directly contact the wheelchair occupant. The rail appeared to pose an injury risk to child wheelchair occupants in the manual and electric wheelchairs as they were often contacted directly by the restraint and either ejected from the wheelchair or trapped between the chair and the rail. The single rail did not have any features that might mitigate injury in the event of direct contact between the rail and a wheelchair occupant, such as padding. The end of the rail trapped the dummy by the chest in some cases, and in one test the end of the rail rose up and contacted the dummy's neck. These appeared to be scenarios which could be potentially injurious to a child in a wheelchair.

In previous research with a 50$^{th}$ percentile adult dummy seated in the Disability Discrimination Act Reference Wheelchair, the horizontal rail was not effective at restraining the wheelchair in positions within the allowable height of 600 mm to 800 mm (Le Claire *et al.*, 2003). The rail was found to be more effective at a lower height (550 mm) where it contacted the handrims of the wheelchair and prevented movement of the wheelchair into the gangway. This indicated that the rail may also be more effective at restraining children's wheelchairs if it were positioned at a lower height. However, the reduced width of children's wheelchairs compared with adult wheelchairs may mean that children's wheelchairs are able to rotate in the wheelchair space before contacting the rail, even if the rail is positioned at a lower height.

The rotation of the wheelchairs in the tests appeared to be a significant contributory factor to the overall performance during the tests, especially in relation to ejection or entrapment of the wheelchair occupants. Both the manual and electric wheelchairs rotated in the tests with the vertical stanchion and the horizontal rail, and the occupants were ejected in several of these tests. The only wheelchair that was consistently restrained within the wheelchair space with both lateral restraints was the supportive buggy with the three year old dummy. There was no rotation of the supportive buggy in any of the tests performed with either lateral restraint, and this was considered to be a significant factor in the supportive buggy remaining within the wheelchair space. The supportive buggy had a fixed front wheel that could not rotate like the front wheels on the manual and electric wheelchairs, which appeared to be the main factor in the prevention of rotation of the supportive buggy.

Preventing the rotation of the wheelchairs could be achieved in several different ways. Locking the front wheels in the fore/aft direction when the wheelchair is in a wheelchair space in a bus is a potential solution, although it is not known how effective it would be on a manual wheelchair with much smaller front wheels than the supportive buggy. Alternatively, the use of an additional restraint to hold the wheelchair in place may be effective, but this could affect the ease of use of the vehicle and wheelchair space. Solutions such as these could be further explored through assessment.

### 7.5 Conclusions

- The backrest on both buses was wider than the gap between the handles on the manual wheelchair. This meant that the head of the dummy was not supported by the backrest.
- The battery pack on the electric wheelchair was obstructed by the supporting structure below the backrest in each vehicle. This meant that the head of the dummy was not supported by the backrest.
- A gap between a child's head and the surface of the backrest could lead to potential injury to the neck in the event of heavy braking or a frontal impact.
- The vertical stanchion did not restrain the manual wheelchair when it was positioned 400 mm or 480 mm rearwards of the front of the wheelchair space; however, the stanchion did restrain the manual wheelchair when it was 560 mm from the front of the space.
- The retractable horizontal rail appeared to pose an injury risk to children in wheelchairs as they could be ejected from the wheelchair or become trapped between the wheelchair and the rail.
- The rail was too high to interact with the side structure of the manual or electric wheelchairs. This resulted in direct contact between the rail and the dummies when the wheelchairs moved during the driving manoeuvre.
- The rotation of the wheelchairs in the wheelchair space during the cornering manoeuvre appeared to be a contributory factor to the ejection of the child dummies from the wheelchairs.

- The manual wheelchair rotated around the stanchion in both the 400 mm and 480 mm positions, resulting in the ejection of the child dummies.
- Both the manual and electric wheelchairs rotated in the wheelchair space with the retractable rail, leading to either ejection or entrapment of the child dummies.
- The supportive buggy, which had a fixed front wheel, did not rotate in either bus during testing and remained in the wheelchair space.

# 8 Cost analysis

## 8.1 Introduction

In conventional vehicle safety analyses of effectiveness, changes are evaluated in terms of the potential injuries that they would prevent. This provides a theoretical number of injuries saved by the safety intervention. The DfT has derived figures in order to value the benefit to society arising from such a reduction in injury numbers. These figures were developed based on the 'willingness to pay' approach. Essentially, this approach estimates the amount that society should be willing to pay in order to prevent an injury. It considers both human costs, such as pain, grief and suffering, as well as direct economic costs associated with hospital treatment and loss in earnings. The latest versions of these figures, for 2006, can be found in *Road Casualties Great Britain 2006* (DfT, 2007). It should be noted that these figures were developed to represent the average road traffic casualty and may not be appropriate for use exclusively with children or wheelchair users. For instance, the expected loss in earnings may not be accurate. However, they should provide indicative figures against which the costs of injury saving proposals can be evaluated.

The costs associated with design changes to wheelchairs and the vehicles that carry them also need to be derived. The costs used here have been developed with particular consideration of three main categories: economic and societal costs as well as environmental effects. The costs estimated by the authors have then been considered alongside those produced by Le Claire *et al.* (2003), and moderated if it seemed appropriate to do so.

It is very important to consider that these costs are initial estimates made by the authors. They are based on suggested changes which have been proposed for other similar cost analyses, but are supported by a limited knowledge of the wheelchair manufacturing processes and market conditions. The costs have been presented here to provoke consideration as to whether the suggested interventions would be beneficial from a cost perspective. As such, they should be treated with a level of caution before they have been validated by stakeholders in the industry.

It would be possible to increase the robustness of the cost estimates made here, through two key steps:

1. Wheelchair manufacturers should be consulted on the proposed changes to improve safety for children in wheelchairs. The manufacturers should be able to provide more accurate estimates of costs that they might incur.

2. The costs provided in this document should be reviewed by stakeholders in the industry and revised based on any feedback received.

These steps should be considered to improve the estimates of cost made in the following sections. However, it is TRL's experience that the costs provided by stakeholders can vary significantly from organisation to organisation. It would be necessary, therefore, to consult a wide range of organisations and to review the costs that are provided. While such a review was beyond the scope of this project, it could be important if the proposed options are taken forwards for legislation.

It is unlikely that any of the design changes suggested in this report would affect the environment significantly. Increases in the use of raw materials may have an environmental impact and vehicle fuel consumption might increase if significant weight is added to the vehicle. However, design solutions and the use of appropriate materials could minimise these effects.

## 8.2 Child wheelchair users and their involvement in collisions

The number of children in wheelchairs has now risen above 100,000 (www.wheelchairchildren.org.uk). This represents around 1.18 percent of the UK population of children less than 12 years of age[1]. It would be necessary to compare the travel patterns of children in wheelchairs with those for other children to confirm that they make up 1.18 percent of the child vehicle users in the UK. Unfortunately, there is insufficient information with which to do this at present. Neither is there sufficient information to identify the proportion of child wheelchair users that transfer to a vehicle based restraint system when travelling. Given that some children in wheelchairs will transfer for some journeys, it is assumed that child wheelchair users represent 1 percent of the exposure to the UK population of children from travel risks. It is suggested that this assumption is revised when sufficient information becomes available with which to do so.

[1] There are an estimated 8.45 million children under 12 according to National Statistics (2007).

*Road Casualties Great Britain 2006* (DfT, 2007) presents statistics about personal injury road accidents and their casualties. Detailed tables are included that cover a range of variables. One such table displays casualties by age band, road user type and severity[2]. Two of the road user type groups in the table are relevant for this research: the car passengers group and the bus and coach passengers group. Analysis by TRL revealed that the car passengers group included people travelling in cars, taxis and minibuses and hence both M1 and M2 vehicles. The bus and coach passengers group was more straightforward and referred to people travelling in M3 vehicles. Table 25 reproduces the data from *Road Casualties Great Britain 2006* (DfT, 2007) for children less than 12 years of age.

**Table 25 Child passenger casualties by severity and vehicle type during 2006 (DfT, 2007)**

| Severity | Car passengers including minibuses (M1 and M2 vehicles) | Bus or coach passengers (M3 vehicles) |
|---|---:|---:|
| Killed | 26 | 0 |
| Seriously injured | 277 | 15 |
| Slightly injured | 6,146 | 534 |

For the purposes of this study, it was desirable to separate the car passengers further by vehicle category. Unfortunately, the information was not presented in this way for children in *Road Casualties Great Britain 2006* (DfT, 2007). However, it was presented in this way for all casualties (i.e. including adults). Ratios were therefore used to estimate the number of children killed or injured in M1 vehicles only and in M2 vehicles only. This is shown in Table 26.

**Table 26 Child passenger casualties estimated by severity and vehicle type during 2006**

| Severity | M1 vehicles (estimated) | M2 vehicles (estimated) | M3 vehicles |
|---|---:|---:|---:|
| Killed | 25.76 | 0.24 | 0 |
| Seriously injured | 274.55 | 2.45 | 15 |
| Slightly injured | 6,072.92 | 73.08 | 534 |

It should be noted that there is evidence that an appreciable proportion of non-fatal injury accidents are not reported to the police and therefore

[2] See Table 30a in *Road Casualties Great Britain 2006* (DfT, 2007).

are not included in these figures (DfT, 2007). Nevertheless, the data reveal that relatively low numbers of children are killed or seriously injured in M2 vehicles and in M3 vehicles. Difficulties can arise when trying to analyse accident statistics where there are only a few occurrences of the situation being investigated. One of the most fundamental difficulties is in establishing how well each occurrence represents the risks for the population as a whole. These issues are emphasised when considering injuries to children in wheelchairs. This is highlighted in Table 27. The figures in Table 27 are based on the assumption that children in wheelchairs represent 1 percent of the exposure of all children.

**Table 27 Estimates of number of children in wheelchairs injured by severity and vehicle type during 2006 (based on exposure)**

| Severity | M1 vehicles | M2 vehicles | M3 vehicles |
|---|---:|---:|---:|
| Killed | 0.26 | 0.00[3] | 0 |
| Seriously injured | 2.75 | 0.02 | 0.15 |
| Slightly injured | 60.73 | 0.73 | 5.34 |

The research has shown that children in wheelchairs do not receive a level of protection that is comparable to that for children in vehicle based restraint systems. In addition, children in wheelchairs may have a lower injury tolerance than other children. These considerations lead to the assumption that children in wheelchairs are more likely to be injured in a collision than other children. Estimates of the number of children in wheelchairs that are injured based solely on exposure may not, therefore, be adequate. TRL estimated that children in wheelchairs are 50 percent more likely to be injured in a collision than other children. This figure was based on observations from the test programme and on our knowledge of child biomechanics. Nevertheless, it would be useful to revise this figure if more data becomes available in the future. Table 28 shows the estimates of the number of children in wheelchairs that are injured when both exposure and risk are considered. The estimated value of prevention of these casualties is shown in Table 29.

[3] This figure has been rounded to two decimal places.

**Table 28 Estimates of number of children in wheelchairs injured by severity and vehicle type during 2006 (based on exposure and risk)**

| Severity | M1 vehicles | M2 vehicles | M3 vehicles |
|---|---|---|---|
| Killed | 0.39 | 0.00[4] | 0 |
| Seriously injured | 4.12 | 0.04 | 0.23 |
| Slightly injured | 91.09 | 1.10 | 8.01 |

**Table 29 Estimates of total value of prevention of injuries to children in wheelchairs during 2006 (based on exposure and risk)**

| Severity | M1 vehicles (£) | M2 vehicles (£) | M3 vehicles (£) | Total (£) |
|---|---|---|---|---|
| Killed | 575,566 | 5,319 | 0 | 580,886 |
| Seriously injured | 689,221 | 6,159 | 37,656 | 733,037 |
| Slightly injured | 1,175,110 | 14,141 | 103,329 | 1,292,580 |
| **Total** | **2,439,897** | **25,620** | **140,985** | **2,606,502** |

TRL contacted the Medicines and Healthcare products Regulatory Agency (MHRA) to obtain additional information on child wheelchair user casualties in order to verify the figures in Table 27. The MHRA was unable to provide any pertinent accident records. In addition, a search of recent internet newspaper articles was carried out. Unfortunately, this search also found no additional accident cases in which it was stated that a child in a wheelchair had been injured.

It is surprising that no casualty records can be found for children in wheelchairs. As noted in Section 2.1, the number of children using wheelchairs seems to continue to increase due to improvements in healthcare provisions for children and vehicle accessibility. This should lead to an increase in the number of children travelling in wheelchairs on the roads and hence an increased exposure to the risk of injury for this group of the population. However, the accident statistics and records do not reflect such an increase in exposure. This leads to the hypothesis that either accident records are not reporting the involvement of children in wheelchairs adequately, or that the exposure to injury for children in wheelchairs is low and in line with the data in Table 27. It is not possible to judge accurately the extent to which these assumptions may be true.

[4] This figure has been rounded to two decimal places.

However, it is suggested that some children in wheelchairs are involved in UK road traffic accidents each year.

## 8.3 M1 vehicles (cars and taxis)

### *8.3.1 Vehicle design changes*

Wheelchair accessible M1 vehicles are already equipped with a means of transporting children who remain seated in their wheelchairs. Existing technical requirements for the strength of the anchorages in these vehicles and for the provision of space around the wheelchair are unlikely to require significant reappraisal for the carriage of children. The DfT may wish to relax the requirements for vehicles intended to be used exclusively by children, but it was assumed that this would not lead to increased engineering costs for vehicle manufacturers.

The provision of a head and back restraint is the most significant vehicle design change that is necessary. When a wheelchair is forward facing, a head and back restraint prevents the head and neck from extending rearwards when the occupant has moved back into their seated position following a collision. A head and back restraint is the only vehicle based means of ensuring that children in wheelchairs are provided with a level of protection from this type of loading that is comparable to that for children in child restraints (or vehicle seats). When a wheelchair is rear facing, a head and back restraint is the only means of reducing the risk of serious head and neck injury in a collision.

### *8.3.2 Annual production estimates*

Le Claire *et al.* (2003) estimated that there were 3,000 wheelchair accessible vehicles, of M1 class, produced each year in which wheelchair seated passengers travel forward facing. Additionally, Le Claire *et al.* (2003) estimated that there was the same number of M1 vehicles in which wheelchair seated passengers travel rear facing.

### *8.3.3 Cost estimates*

The estimated cost incurred to install a head and back restraint in an M1 vehicle is £ 500 per vehicle (Le Claire *et al.,* 2003). To install these features in 6,000 vehicles would cost £ 3,000,000.

## 8.4 M2 vehicles (minibuses)

### *8.4.1 Vehicle design changes*

Wheelchair accessible M2 vehicles are already equipped with a means of transporting children who remain seated in their wheelchairs. Existing technical requirements for the strength of the anchorages in these vehicles and for the provision of space around the wheelchair are unlikely to require significant reappraisal for the carriage of children. The DfT may wish to relax the requirements for vehicles intended to be used exclusively by children, but it was assumed that this would not lead to increased engineering costs for vehicle manufacturers.

The provision of a head and back restraint is the most significant vehicle design change that is necessary. A head and back restraint prevents the head and neck from extending rearwards when the occupant has moved back into their seated position following a collision. A head and back restraint is the only vehicle based means of ensuring that children in wheelchairs are provided with a level of protection from this type of loading that is comparable to that for children in child restraints (or vehicle seats).

### *8.4.2 Annual production estimates*

Le Claire *et al.* (2003) estimated that 10,000 vehicles are registered annually, of which 2,000 were believed to be wheelchair accessible. These figures were based on M2 vehicles with no more than 16 passenger seats.

### *8.4.3 Cost estimates*

The estimated cost incurred to install a head and back restraint in an M2 vehicle is £ 500 per vehicle, based on the cost proposed by Le Claire *et al.* (2003) for an M1 vehicle. To install these features in 2,000 vehicles would cost £ 1,000,000.

## 8.5 M3 vehicles (buses and coaches)

### *8.5.1 Vehicle design changes*

Vehicles intended to carry standing passengers (i.e. urban buses) are not required to be fitted with seat belts and provide only limited protection in the event of a collision. Research carried out in this project (see Section 7) showed that the measures in place to prevent wheelchair movement into the gangway could be improved. However, it was assumed that these improvements could be achieved without significant vehicle costs.

Wheelchair accessible M3 vehicles that do not carry standing passengers are already equipped with a means of transporting children who remain seated in their wheelchairs. Existing technical requirements for the strength of the anchorages in these vehicles and for the provision of space around the wheelchair are unlikely to require significant reappraisal for the carriage of children.

The provision of a head and back restraint is the most significant vehicle design change that is necessary. A head and back restraint prevents the head and neck from extending rearwards when the occupant has moved back into their seated position following a collision. A head and back restraint is the only vehicle based means of ensuring that children in wheelchairs are provided with a level of protection from this type of loading that is comparable to that for children in child restraints (or vehicle seats).

### *8.5.2 Annual production estimates*

Le Claire *et al.* (2003) estimated that there are 100 coaches replaced each year with new wheelchair accessible versions. Since then, the number of buses and coaches produced each year has remained fairly constant (SMMT, 2007). However, it is recognised that the proportion of wheelchair accessible coaches may have increased, due to the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended).

### *8.5.3 Cost estimates*

The estimated cost incurred to install a head and back restraint in an M3 vehicle is £ 500 per vehicle, based on the cost proposed by Le Claire *et al.* (2003) for an M1 vehicle. To install these features in 100 vehicles would cost £ 50,000.

## 8.6 Wheelchairs

### *8.6.1 Wheelchair design changes and indicative cost estimates*

Vehicle design changes will not address all of the issues identified in the project. Changes in wheelchair design and performance (in a collision) are also needed to provide children in wheelchairs with a level of protection that is comparable to that for children in child restraints or vehicle seats. The key wheelchair design and stiffness issues could be addressed by the adoption of technical requirements that are based on the deceleration pulse in UNECE Regulation 44, a performance criterion for abdomen loading, performance criteria for dummy loads and a rear facing front impact test.  These areas are discussed in this section.

It is TRL's experience that the amount of research and development that is invested differs greatly from organisation to organisation.  This experience has been gained through working with the child restraint industry over several years.  TRL expects that similar differences exist in the wheelchair industry and it would be necessary, therefore, to conduct an extensive and wide ranging consultation to ensure that any figures were representative.  This was beyond the scope of this cost analysis and hence the costs presented here are estimates based on TRL's experience in other industries.  These estimates are for indicative purposes only.

*Requirements based on UNECE Regulation 44 deceleration pulse*

The test pulse used in UNECE Regulation 44 could be adopted for use in wheelchair testing with some effort to define the test conditions.  Once some draft text explaining the test conditions had been written in preparation for inclusion in the wheelchair testing standard, it would only remain to have the text approved.  This is likely to take some effort in terms of preparing sufficient documents which contain justification for the change and canvassing groups who may vote on such an amendment. The cost of this effort may be in the region of £ 10,000.

Once the testing requirements have been changed, then the wheelchair manufacturers will need to react to the change and develop more robust wheelchair designs.  There are about 35 manufacturers of wheelchairs which currently sell products in the UK.  Some of these products may meet the new requirements with little or no investment, while others may need significant redesign.  Depending on the extent of the modifications required, each manufacturer would be expected to invest around £ 50,000 to develop more robust wheelchair designs.  This investment would need to cover engineering evaluation, perhaps physical testing and analysis of design efficacy, through a number of potential design iterations.  Multiplication of the cost per manufacturer by the number of manufacturers results in a value of £ 1,750,000 for research and development undertaken by wheelchair manufacturers.

Manufacturing costs would be expected to consist of changes in tooling and the manufacturing process as well as additional material costs. Tooling changes would depend greatly on the extent to which existing wheelchairs need to be modified, but could be in the region of £ 10,000 to £ 200,000 per manufacturer. Material costs could be in the region between £ 5 and £ 20 per wheelchair. Therefore, the total manufacturing costs could be between £ 850,000 and £ 5,500,000.

The total cost to society to adopt technical requirements that are based on the deceleration pulse in UNECE Regulation 44 could range from £ 2,610,100 to £ 7,250,000.

*Performance criterion for abdomen loading*

One of the most direct means of driving improvements in occupant protection for children in wheelchairs would be to set an abdominal loading criterion for use in the front impact dynamic test evaluations of the wheelchairs. This is not a trivial matter, as currently the child dummies available for use in such testing do not have robust instrumentation with which to measure dynamic abdominal penetration or loading. Therefore, some consideration of the potential options for such a criterion would be necessary. It would be expected that a targeted investigation would be needed to decide on the best option for a criterion and to set a limit. This investigation could cost in the region of £ 150,000. Of course, the cost associated with such an investigation would depend on the extent to which the criterion is related to the risk of injury to children in wheelchairs. Most simply, and with minimal cost, this could involve some pragmatic setting of a limit for the criterion.

Once the criterion is set, effort would be required to have this approved for use in test procedures. This could cost in the region of £ 50,000. Wheelchair manufacturers would then need to evaluate their products against the criterion and develop design solutions to limit abdominal loading. The project demonstrated relatively straightforward ways in which wheelchairs could be designed to improve the path of the seat belt. Similar solutions could be implemented at low cost, although it is recognised that some investment would be needed. If each manufacturer invested £ 10,000 to improve this aspect of their range, the total cost to the industry could be around £ 350,000.

The total cost to society to adopt a performance criterion for abdomen loading could range from £ 400,000 to £ 550,000.

*Performance criterion for dummy loads*

It is expected that some benefits in the occupant restraint afforded to children in wheelchairs could be provided with the introduction of conventional dummy based acceleration criteria. The limits for these criteria should be easier to set as limits have already been proposed for the evaluation of other child restraint systems.  This assumes that the criteria could be adopted without large revisions; an assumption which has yet to be confirmed.  However, if this was the case, the costs would be expected to be significantly lower than those associated with the development of an appropriate abdominal loading criterion.  It should be noted, though, that the benefits with respect to the reduction of abdominal injuries would also be smaller as the criteria would not be targeted at that body region.

Some work would be required to have the dummy based performance limits approved for use in test procedures.  This could cost in the region of £ 50,000. Wheelchair manufacturers would then need to evaluate their products against the criteria and perhaps improve their designs.  Some of these products may meet the new requirements with little or no investment, while others may need significant redesign.  Depending on the extent of the modifications required, each manufacturer would be expected to invest around £ 50,000 to meet the new dummy performance limits.  This investment would need to cover engineering evaluation, perhaps physical testing and analysis of design efficacy, through a number of potential design iterations.  Multiplication of the cost per manufacturer by the number of manufacturers results in a value of £ 1,750,000 for research and development undertaken by wheelchair manufacturers.

Additional manufacturing costs could comprise changes in tooling and the manufacturing process as well as additional material costs.  Tooling changes would depend greatly on the extent to which existing wheelchairs need to be modified, but could be in the region of £ 10,000 to £ 100,000 per manufacturer.  Material costs could be in the region of £ 5 to £ 20 per wheelchair.  Therefore, the total manufacturing costs could be between £ 850,000 and £ 5,500,000.

The total cost to society to adopt performance criteria for dummy loads could range from £ 2,650,000 to £ 7,300,000.

*Rear facing front impact test*

There are several components that will contribute to the societal costs associated with the introduction of a rear facing frontal impact test for wheelchairs. Firstly, the test procedure would need to be developed, which would require a targeted investigation to derive, evaluate and validate appropriate test conditions.  For the second stage, it would be necessary to obtain approval for this new test requirement to be adopted. Some testing of wheelchair products against the new requirements would be necessary along with enforcement of compliance with the requirement if it is mandated in some way. Finally, the reaction of the wheelchair manufacturers to the new requirement would be important, along with their provision of new designs which comply with it.

The investigation to develop the new test procedure may cost society up to £ 150,000. A further £ 50,000 could be necessary to provide sufficient justification and political pressure to have the procedure approved. For new wheelchair products to be tested according to the procedure, perhaps £ 50,000 could be needed to cover the costs of the testing and compliance by each wheelchair manufacturer.

Each wheelchair manufacturer may then incur costs of £ 100,000 to ensure that new designs of wheelchair meet the requirement. This would need to cover engineering evaluation, physical testing and analysis of design efficacy. Multiplication of the cost per manufacturer by the number of manufacturers results in a value of £ 3,500,000.

Manufacturing costs would be expected to consist of changes in tooling and the manufacturing process as well as additional material costs. Tooling changes would depend greatly on the extent to which existing wheelchairs need to be modified, but could be in the region of £ 10,000 to £ 100,000 per manufacturer. Material costs could be in the region of £ 5 to £ 20 per wheelchair. Therefore, the total manufacturing costs could be between £ 850,000 and £ 5,500,000.

The total cost to society to adopt a rear facing front impact test could range from £ 6,300,000 to £ 10,950,000.

## 8.7 Comparison of benefits and costs

Five key changes or measures to improve the level of protection afforded to children in wheelchairs have been discussed in this section. These comprise one vehicle measure (a head and back restraint) and four wheelchair measures (technical requirements based on the deceleration pulse in UNECE Regulation 44, a performance criterion for abdomen loading, performance criteria for dummy loads and a rear facing front impact test). The benefit of each measure in terms of the casualty cost saving was estimated by multiplying the child in wheelchair casualties in Table 27 by an effectiveness value for each measure. The effectiveness values are shown in Table 30. An effectiveness value of 0.2 means that the measure is estimated to be effective for 20 percent of all casualties.

**Table 30 Effectiveness values used in the analysis of benefits**

| Proposed measure | Effectiveness |
|---|---|
| Head and back restraint | 0.2 |
| ECE Regulation 44 deceleration pulse | 0.2 |
| Performance criterion for abdomen loading | 0.2 |
| Performance criteria for dummy loads | 0.1 |
| Rear facing front impact test | 0.05 |

The value of prevention was recalculated using the number of casualties that would be expected if each measure was implemented. It was assumed, for the purpose of this analysis, that the measures are complementary, although it is recognised that some casualties would be mitigated by more than one of the measures. In addition, it was assumed that the measures taken would reduce fatal injuries to serious and serious injuries to slight.

For simplicity, the total value of prevention for each measure was determined across all vehicle categories and injury severities. These figures were compared with the costs associated with the implementation of each measure set out in Sections 8.3 to 8.6. This is shown in Table 31. Further analysis of the benefits and costs is shown in Table 32.

**Table 31 Comparison of benefits and costs**

| Proposed measure | Benefit (£) | Cost (£) | |
|---|---|---|---|
| | | From | To |
| Head and back restraint | 496,946 | 4,050,000 | 4,050,000 |
| UNECE Regulation 44 deceleration pulse | 496,946 | 2,610,000 | 7,250,000 |
| Performance criterion for abdomen loading | 496,946 | 400,000 | 550,000 |
| Performance criteria for dummy loads | 248,473 | 2,650,000 | 7,300,000 |
| Rear facing front impact test | 124,236 | 6,300,000 | 10,950,000 |

**Table 32 Analysis of benefits and costs**

| Proposed measure | Benefit – cost (£) | | Benefit/cost (£) | |
|---|---|---|---|---|
| | Best case | Worst case | Best case | Worst case |
| Head and back restraint | -3,553,054 | -3,553,054 | 0.123 | 0.123 |
| UNECE Regulation 44 deceleration pulse | -2,113,054 | -6,753,054 | 0.190 | 0.069 |
| Performance criterion for abdomen loading | 96,946 | 53,054 | 1.242 | 0.904 |
| Performance criteria for dummy loads | -2,401,527 | -7,051,527 | 0.094 | 0.034 |
| Rear facing front impact test | -6,175,764 | -10,825,764 | 0.020 | 0.011 |

## 8.8 Summary

Very limited information was available from which to gather accurate data for the number of journeys made by children in wheelchairs and for their involvement in vehicle collisions. However, it is likely that a relatively large number of journeys are made without significant incident. In these circumstances, it might appear that there are limited benefits to society from new safety measures. This is because such analyses are based on estimates of the reduction in injuries in terms of their economic cost. In fact, there are other benefits of new safety measures, when considering the protection of children in wheelchairs. For example, providing children in wheelchairs with a level of protection that is comparable to that for children travelling in a vehicle based restraint system would help to meet an important responsibility of society to these children.

The project highlighted that vehicle design changes alone will not address all of the issues identified for children in wheelchairs. Wheelchair design changes, encouraged by changes in the relevant performance requirements, are also necessary. A proportion of these costs would be incurred by the wheelchair manufacturing industry. It is TRL's experience that these costs can vary greatly from organisation to organisation. It would be necessary, therefore, to consult a very wide range of organisations to obtain representative estimates of the costs of new requirements. As such, a wide ranging consultation was beyond the scope of this project. TRL provided indicative costs based on our experience of other industry sectors.

# 9 Discussion

The results for each vehicle category and wheelchair direction were discussed in detail within Sections 3 to 7. This section provides an overview of the findings of the whole study and discusses some limitations of the research.

## 9.1 General observations

The main aim of the project was to examine the safety of children in wheelchairs in M category vehicles. The key question was whether children who remain seated in their wheelchair are afforded a level of protection in a front impact that is comparable to that for children travelling in a vehicle based restraint system. Some 32 sled tests were carried out with various wheelchairs and child dummies. In addition, eight sled tests were carried out with the corresponding dummies seated in child restraints or vehicle seats.

The purpose of a restraint system is threefold. Firstly, it must minimise the risk of ejection from the vehicle. Secondly, it must minimise the risk of body contact with the interior of the vehicle. Thirdly, it must absorb and distribute the impact forces over the strongest parts of the body. The three point seat belt is the main type of restraint system for adults in road vehicles, but the vehicle seat also has an important role.

The vehicle seat provides a stable base of support for the occupant during normal driving and in the event of a collision. It is designed (and tested) to work with the restraint system and can improve the interaction between the occupant and the restraint through anti-submarining features. The vehicle seat also contributes to the management of the occupant's loads during a crash and supports the head and neck during the rebound phase of a front impact (i.e. when the occupant moves back into their seat and their head extends rearwards) or during a rear impact. Children require special attention because their tissues have different biomechanical properties compared with adults. Their needs must be met with an additional child restraint system, although they are permitted to use the vehicle seat and adult seat belt in certain circumstances in some vehicles.

The main purpose of a wheelchair is to aid the mobility of the user. However, wheelchairs are being used increasingly in vehicles because it is inconvenient or sometimes impossible to transfer easily to a vehicle seat. In these circumstances, a wheelchair takes the place of a vehicle seat, although this function may not have been in mind when the wheelchair was designed.

A wheelchair tie-down and occupant restraint system is used to hold the wheelchair and occupant in place during normal driving and in the event of a collision. A wheelchair user has the right to expect a comparable level of protection from their wheelchair and restraint system as any other passenger seated in the vehicle. This was explored in the project.

## 9.2 Wheelchair restraint system

### *9.2.1 Forward facing wheelchairs*

A production model four point wheelchair tie-down system was used for forward facing wheelchairs in the test programme. The webbing straps were secured to the floor of the impact sled in the same manner as they would be in a typical vehicle. The wheelchair tie-down system kept the wheelchairs in place during the test programme with little or moderate displacement. This was expected since this aspect of the performance of the wheelchair tie-down system is addressed in ISO 10542-1:2001 and ISO 10542-2:2001. The distance between the tracking was 330 mm; the tie-down manufacturer's tested dimension and the distance used by TRL for routine wheelchair testing according to ISO 7176-19:2001. The effect of different tracking widths was not examined, but it would appear that 330 mm was appropriate to maintain the stability of children's wheelchairs during normal driving or a collision.

### *9.2.2 Rear facing wheelchairs*

A two point wheelchair tie-down system was used for the rearward facing wheelchairs in the test programme. The webbing straps were secured to the floor of the impact sled after passing them through a slot in the surrogate bulkhead in a similar manner as they would in a typical vehicle. The bulkhead that separates the driver and passenger compartments is the main restraint for the wheelchair, but wheelchair tie-downs are also necessary to prevent the wheelchair from moving around the passenger compartment in normal driving and during the rebound phase of a collision. When a wheelchair is rear facing, rebound refers to the period where the occupant and their wheelchair move away from the bulkhead. The tie-down system was effective in this respect, but several of the wheelchairs rotated about the axis of the rear wheels because the front wheels were unrestrained and because the back of the wheelchair was not well supported. When this occurred, it usually resulted in a secondary impact between the dummy (through the wheelchair backrest) and the bulkhead surface. In contrast, the dummy 'rode down' the impact against the bulkhead when it was seated on the rear facing tip-up seat. Restraining the front wheels would increase the loads on the wheelchair backrest and increase the time taken to restrain the wheelchair. A head and back restraint that supports the wheelchair and the occupant would be the best solution.

## 9.3 Occupant restraint system

### *9.3.1 Forward facing wheelchairs*

A surrogate three point seat belt was used when the wheelchairs were forward facing in the test programme. This included an inertia reel and an upper anchorage point for the diagonal part of the belt. The relative performance of an upper anchorage point for the diagonal belt compared with a floor mounted anchorage was not examined. In previous research for the DfT, Le Claire *et al.* (2003) found that a floor mounted anchorage resulted in greater head excursion and greater lumbar spine loads in an adult dummy compared with an upper anchorage. It seemed likely that similar findings would be made with child dummies so it was agreed with the DfT to use an upper anchorage point in all tests in this project. This represents the best practice for the restraint of all wheelchair users including children.

The surrogate seat belt kept the dummy within each wheelchair during the test programme and prevented excessive head and body excursion if the wheelchair was robust. This was expected since this aspect of the seat belt's performance was examined before the test programme with a dynamic test according to ISO 10542-1:2001. This demonstrated that the surrogate occupant restraint was similar in this respect to other products on the market that also meet the requirements of the Standard.

In addition to preventing ejection and limiting excursion, the surrogate seat belt ensured a reasonable ride-down of the sled deceleration for the dummy. However, it was also the case that the dummy accelerations and forces varied quite markedly across the different wheelchair types. This highlighted the potential influence of the wheelchair as a vehicle seat on the protection that a child would receive in a crash. The management of the occupant's loads is not currently addressed in ISO 7176-19:2001; hence it was unsurprising that the dummy loads varied in this way.

A seat belt must also distribute the restraint forces over the strongest parts of the body. In view of this, the surrogate seat belt was designed to achieve a good fit for the child dummy irrespective of the type and model of the wheelchair. Nevertheless, in some cases the side of the wheelchair obstructed the ideal path of the lap part of the belt, resulting in greater abdomen loading. Furthermore, the seat belt was likely to load the abdomen when the wheelchair compressed or deformed during the impact. Although the path of the seat belt needed to be improved when the dummy was seated on the vehicle seat, it would seem that a child in a wheelchair would be exposed to a greater risk of abdomen injury than a child in a vehicle seat. A child in a child restraint system receives the best protection because, in the case of harness systems, there is a fifth point or crotch strap to keep the lap straps on the pelvis, or in the case of booster systems, there are guides to ensure the lap belt passes over the top of the thighs.

The side view angle of the lap part of the seat belt fell within the range specified in ISO 10542-1:2001 in every test. The belt angle and location of the anchorages was influenced by the use of tracking behind the wheelchair and by the wheels or tipping levers of the wheelchair. The location of the lap belt anchorages in the vehicle was important, but it was also important for the wheelchair to allow the seat belt to be fitted easily over the top of the occupant's thighs. The wheelchair must also maintain a stable seating position for the occupant throughout a collision to reduce the risk of the pelvis passing under the lap part of the belt. The ideal solution would be for the wheelchair to guide the seat belt and hold it in place during the impact in the same way as a booster seat. A wheelchair integrated restraint harness is another solution, although this would increase the loads on the wheelchair.

### *9.3.2 Rear facing wheelchairs*

The surrogate seat belt was also used when the wheelchairs were rearward facing in the test programme. The anchorage positions on the surrogate bulkhead were similar to those observed in real vehicles. Although some of the issues related to the fit of the seat belt were also relevant to the rear facing situation, the main purpose of the seat belt was to restrain the dummy in rebound when the belt loads were much lower.

## 9.4 Head and back restraint

### *9.4.1 Forward facing wheelchairs*

Vehicle seats are designed to support the head and neck of the occupant. However, very few M1 or M2 vehicles provide a head and back restraint when they transport forward facing wheelchair users. A head and back restraint was not used, therefore, in the test programme. As a result, the head of the dummy was unsupported and extended rearwards during the rebound phase of each impact test. Some wheelchairs included a headrest, but the dummy either rode up over the headrest or pushed it away. A child travelling in this way would be at risk of head contact with the vehicle if there was insufficient space behind the wheelchair. They would also be at risk of neck injury. The neck measurements were generally quite low during rebound; however, the neck was bending below the level of the instrumentation. It was possible, therefore, that the dummy was not well suited to neck injury prediction during extension. Nevertheless, the head and neck kinematics did suggest that a child would be at risk of soft tissue neck injury. A child travelling in a child restraint or a vehicle seat would not be exposed to this risk because their head would be supported during rebound. A head and back restraint would provide a child in a wheelchair with a comparable level of protection during rebound as a child in a child restraint or a vehicle seat. However, a wheelchair integrated solution might be necessary for a child in a wheelchair with supportive seating.

### *9.4.2 Rear facing wheelchairs*

Rearward facing wheelchairs were positioned against a generic vehicle bulkhead during the test programme. The head of the dummy was not supported by the bulkhead and extended rearwards during each test. This usually resulted in significant bending of the neck and sometimes head and other body contact with rigid parts of the bulkhead. The dummy measurements were generally high when either of these events occurred. There was a similar outcome when the dummy was seated on the rear facing vehicle (tip-up) seat. However, the loads were sometimes lower because the dummy ‘rode down’ the impact against the bulkhead surface. A head and back restraint would increase the level of protection afforded to children in wheelchairs and to children in rear facing tip-up seats. The head and back restraint in the vehicle would need to be compatible with children’s wheelchairs to be effective. This would be relatively straightforward for manual and electric wheelchairs; however, buggies and wheelchairs with supportive seating would be difficult to accommodate.

## 9.5 Wheelchair design and stiffness

### *9.5.1 Forward facing wheelchairs*

The wheelchairs used in the test programme deformed to a greater extent than desirable for a vehicle seat during a collision.  When the wheelchairs were forward facing, the deformation usually led to greater dummy accelerations and forces or greater loading to vulnerable body regions such as the abdomen.  The UNECE Regulation 44 test conditions used in the study were slightly more stringent than the ISO Standards.  Furthermore, the ISO Standards do not address occupant loading.  A particular issue was found with the performance of a tested base with a tested seating system from different manufacturers.  Although the mass of the seating system and dummy were within the mass limit for the base when used with its own seat, the device failed during the test.

### *9.5.2 Rear facing wheelchairs*

Most wheelchairs were unable to withstand the forces of the impact when they were used rear facing.  ISO 7176-19:2001 does not include a rear facing front impact test and most manufacturers state that the wheelchair should be used forward facing in a vehicle.  A head and back restraint may improve the structural performance of rear facing wheelchairs, but it may also be necessary to carry out rear facing sled tests.  This would ensure that wheelchairs are tested to reflect the way they will be used in certain vehicles.

## 9.6 Limitations of the project

As a starting point, this project addressed the front impact of vehicles only.  It may be desirable, in the future, to examine the safety of children in wheelchairs in vehicles involved in side or rear impacts.  Similarly, the project addressed the safety of children in wheelchairs when best practice was followed and when the equipment was used correctly.  Misuse was not included, but could be addressed by improving the information provided to parents and transport operators.  Children in wheelchairs are sometimes provided with a range of equipment and accessories that are attached to their wheelchairs to aid their independence.  It might be impossible to remove the equipment for transport if, for instance, it is used for breathing assistance or for communication.  The use of such equipment was outside the scope of the project, but it may be worthwhile to consider its effects in the future.

Finally, it should be noted that child dummies approximate the weight and size of an average child at the age they are intended to represent. Disabled children are not likely to be included in studies of child anthropometry and they could have different biomechanical properties. Child dummies may not, therefore, be representative of the general population of children who use wheelchairs. Nevertheless, child dummies are the best available means of investigating the safety of children in wheelchairs in vehicles. In fact, dummies represent a very small group of children. However, they have contributed to significant improvements in the design and performance of child restraint systems for all children. It follows that while the dummies may not represent all child wheelchair users, their use in dynamic tests could achieve similar improvements in wheelchair safety for all children.

Dummies are designed to respond to load in the same way as a living human under the same conditions. There is very little biomechanical data for children on which to base the requirements for child dummies. Biomechanical response requirements for adult dummies are therefore scaled to give corresponding requirements for children. The techniques used and the assumptions made can influence the dummy requirements. The Hybrid III Series of child dummies was used in the project because it represented the best option in terms of measurement capacity and published injury criteria. The injury criteria were developed for non-disabled children. It is possible that children in wheelchairs may have a lower threshold for injury than other children, although no literature was available about this at the time of writing. If this is the case, measures to reduce the loads experienced by disabled children in a collision could be very important. The Hybrid III dummies were not designed to be used rear facing so caution was used when interpreting the test results. Some injury criteria intended for forward facing dummies were invalid when the dummies were rear facing. However, for the purposes of comparative testing it was possible to deduce that a dummy measurement of reduced amplitude indicated a reduced risk of injury, provided that the measurement corresponded with the type of loading expected in children.

# 10 Conclusions

- There is no specific legislation in place to address the protection of children in wheelchairs in the event of a collision.

- Based on the findings of this research, children in wheelchairs do not receive a level of protection comparable to that for children in child restraints or vehicle seats.

- Changes in legislation are required to address and hence improve the protection afforded to children in wheelchairs.

- The protection of children in wheelchairs is influenced by the vehicle, the restraint system and the wheelchair. All three areas must be addressed for improvements in protection to be made.

- The greatest improvements would be realised if vehicle, restraint system and wheelchair manufacturers worked together.

- There must be sufficient space in the vehicle to reduce the risk of child head contact with the interior.

- A head and back restraint needs to be provided for children, irrespective of the direction they face in the particular vehicle.

- A three point seat belt is essential to restrain children in wheelchairs. The best practice is to anchor the diagonal part of the belt to the vehicle above the shoulder level.

- The seat belt should distribute the restraint forces over the strongest parts of a child’s anatomy. Wheelchairs must not interfere with or obstruct the belt.

- A wheelchair needs to be capable of withstanding the forces in a collision of appropriate severity if it is intended for use in a vehicle.

- The dynamic test conditions in UNECE Regulation 44 are appropriate to examine the performance of safety equipment in M1 and M2 vehicles.

- The dynamic test conditions in the ISO Standards for wheelchair transportation are less stringent than the test conditions in UNECE Regulation 44.

- Wheelchairs must be designed, in combination with occupant restraints, to manage the child's loads during a collision.

# 11 Recommendations

## 11.1 M1 and M2 forward facing

### *11.1.1 Vehicle anchorages*

There are a number of different vehicle anchorage systems in use with wheelchair tie-down and occupant restraints. Rail tracking systems are the most common, but individual anchor points are used in some vehicles. Docking systems are also available, although at the present time these are more likely to be found in private vehicles. Differences between these systems are unlikely to affect the loading to a child in a collision, providing that it is part of a complete system that meets the requirements of ISO 10542-1:2001. Hence rail tracking, individual anchors and docking systems can all be recommended for vehicles that may be used to transport children in wheelchairs.

The location of the anchorages in the vehicle needs careful consideration. The tested lateral dimension between the anchorages is 330 mm for most wheelchair tie-down systems. This distance is recommended for children's wheelchairs, unless the manufacturer states otherwise. The wheelchair should be attached so that the tie-downs achieve an angle of 45˚. The occupant restraint anchorages should be positioned to ensure that the lap part of the seat belt rests across the top of the thighs or very low over the front of the pelvis. The preferred zone of 30˚ to 75˚ to the horizontal is described in the ISO Standards, but TRL recommends that lap belt angles below 45˚ are avoided, where possible. This is important for keeping the belt on the pelvis during a collision.

Le Claire *et al.* (2003) recommended that the strength of vehicle anchorages be assessed in a static strength test and proposed requirements for the test. Work is currently ongoing to finalise these requirements. Children and their wheelchairs generate lower forces at the vehicle anchorages than adults and their wheelchairs. It would, therefore, be possible to develop separate requirements for vehicles that are intended to carry children only. Clearly, there would be a number of issues to consider if separate requirements were developed that were dependent on the weight of the occupant or of their wheelchair. Nevertheless, it might be inappropriate to oblige someone to purchase a vehicle that is stronger and hence more expensive than they require. If the DfT wishes to make such requirements for the transport of children, TRL recommends the following performance limits for the static strength test:

- When the anchorage of a rear wheelchair tie-down is combined with the lower anchorage of an occupant restraint system, the combined anchorage point should be able to sustain a force of 28.50 kN when applied along the longitudinal axis of the vehicle and at an angle of 45° to the floor.

- Each of the front wheelchair tie-down anchorages should be able to sustain a force of 2.65 kN when applied along the longitudinal axis of the vehicle and at an angle of 45° to the floor.

- The upper anchorage should be able to sustain a force of 7.30 kN applied at an angle of 45° along the longitudinal axis of the vehicle and at an angle of 45° to the side wall.

- It is suggested that these forces should be sustained without failure for a minimum time period. A minimum period of 0.2 seconds would seem to be appropriate, based on the duration of typical impact pulses.

#### *11.1.2 Occupant restraint*

It is essential that children in wheelchairs are restrained with a three point seat belt. TRL recommends that the diagonal part of the seat belt is anchored to the vehicle above the shoulder level. The lap part of the seat belt may be attached to the vehicle floor or to the rear wheelchair tie-downs. Systems that attach to the rear wheelchair tie-downs appear to provide the best fit, although it was not part of this research to evaluate specific systems. Any occupant restraint should be installed to achieve the best possible belt path for the wheelchair user.

Wheelchair integrated seat belts or harnesses represent the best solution for children, but increase the loads on the wheelchair. Integrated restraints are recommended when the wheelchair has been designed to accommodate an integrated restraint system.

Finally, it is recommended that the occupant restraint incorporates an inertia reel to manage the belt loads applied to the child. Although seat belts are designed to apply the forces to the strongest parts of the anatomy, the skeletal structures of children remain under development throughout childhood. A static three point seat belt should be avoided because it would apply higher loads to these structures.

### 11.1.3 Head and back restraint

TRL recommends that a head and back restraint is provided for children in wheelchairs. This is necessary to prevent the head and neck from extending rearwards when a child moves back into their seated position following a collision. It is very important to prevent this motion; firstly, to reduce the risk of head and neck injury due to head contact with the vehicle interior behind the wheelchair, and secondly, to reduce the risk of soft tissue neck injury due to overextension of the head and neck. A child's skull is less stiff than an adult's and must be protected from impact with the vehicle interior. In addition, the muscles and ligaments of the neck are not fully developed; hence children are particularly vulnerable to overextension of the head and neck.

A vehicle seat or a child restraint system supports the head and neck of a child, thereby reducing the likelihood of injury. A head and back restraint is therefore the only means of ensuring that children in wheelchairs are provided with a level of protection that is comparable to that for children in child restraints (or vehicle seats) when they move back into their seated position following a collision. A vehicle based head and back restraint may be incompatible with some wheelchair types. In this case, a wheelchair integrated solution is recommended.

A vehicle based head and back restraint would need to meet a series of requirements to cover its dimensions, energy absorption and strength. Le Claire *et al.* (2003) proposed a series of requirements, which seem to be appropriate for both adult and child passengers, although it was not part of this research to evaluate these requirements. A wheelchair integrated head and back restraint should be assessed during the dynamic test of the wheelchair for which it is intended to be used. This is because testing with surrogate devices can lead to unexpected results when products are used together.

### 11.1.4 Occupant space

Children in wheelchairs must be provided with sufficient space to reduce the risk of head contact with the interior. Although energy absorbing materials can be added to the interior of a vehicle, glancing head contact on relatively soft materials can result in brain injury through rotation mechanisms and neck injury through shear forces at the junction of the head and neck.

Le Claire *et al.* (2003) recommended a space for a wheelchair and occupant in an M1 or an M2 vehicle. The requirements should not be relaxed for transporting children because the displacement of a child in a collision could be similar to that of an adult.

#### *11.1.5 Wheelchair design and stiffness*

When a child is travelling in a vehicle, they have a number of key needs that must be met by their seat. Firstly, the seat must provide a stable base of support in normal driving and in the event of a collision. The structural characteristics of the seat are therefore very important. Secondly, the seat must allow the seat belt to follow the correct path around the strongest parts of the child's anatomy, while avoiding the weaker areas. Furthermore, the seat must help to maintain the correct belt geometry throughout a collision by preventing the pelvis from moving downwards and hence under the lap part of the seat belt. Finally, the seat must work with the restraint system to manage the child's deceleration. Wheelchairs do not perform these functions adequately for children, when compared with child restraint systems or even vehicle seats. Wheelchairs must be included, therefore, in any effort to improve the level of protection afforded to children in a collision.

The structural characteristics of children's wheelchairs need to improve to provide a level of protection that is comparable to that for child restraint systems. Manufacturers that design wheelchairs for use in a vehicle must develop products with the necessary performance characteristics. TRL recommends that wheelchairs are assessed to the same level of impact severity as that described in UNECE Regulation 44 for the approval of child restraint systems.

There are several ways that children's wheelchairs could be designed to improve the path of the seat belt and maintain the child's position in a crash. These solutions would be encouraged if there was a performance criterion for abdomen penetration included in the dynamic test for wheelchairs. TRL recommends that a performance criterion for belt penetration of the abdomen be developed for children's wheelchairs and applied with an appropriate limit during a dynamic test.

A child's deceleration is managed by coupling them tightly to the vehicle early in the impact and then controlling their subsequent excursion. There are a number of solutions that could be applied in both the wheelchair and the restraint system to optimise their performance in this respect. Manufacturers that design wheelchairs for use in a vehicle should develop solutions, in collaboration with restraint system manufacturers. Performance limits are applied during the dynamic test for child restraint systems in UNECE Regulation 44. If the DfT wishes to provide comparable provision for children in wheelchairs, TRL recommends that dummy loads are measured during dynamic tests of children's wheelchairs with performance limits applied that are in line with the Regulation for child restraints.

## 11.2 M1 and M2 rear facing

### *11.2.1 Vehicle anchorages*

The present system in most vehicles, whereby the wheelchair is restrained against a bulkhead by means of a two point wheelchair tie-down system, is adequate to restrain children's wheelchairs during the rebound phase of a collision when the wheelchair moves away from the bulkhead. TRL recommends that the anchorages of the two point system are located within the bulkhead to ensure that the wheelchair is positioned as close as possible to the bulkhead surface.

A four point wheelchair tie-down system would offer the added benefit of preventing wheelchair rotation during an impact; however, this could also be achieved (with additional benefits) by a head and back restraint. This will be discussed in Section 11.2.3.

Le Claire *et al.* (2003) recommended that the strength of vehicle anchorages be assessed in a static strength test and proposed requirements for the test. Work is currently ongoing to finalise these requirements. It was not within the scope of this study to examine whether the requirements could be relaxed for vehicles intended to carry only children rear facing.

### *11.2.2 Occupant restraint*

The three point seat belt provided for wheelchair users in current vehicles is adequate to restrain children in wheelchairs, during the later phase of a front impact, when they move away from the bulkhead and their wheelchair seat. It is recommended that the upper anchorage of the diagonal part of the seat belt is adjustable to accommodate the lower shoulder heights of children.

### *11.2.3 Head and back restraint*

TRL recommends that a head and back restraint is provided for rear facing children in wheelchairs. This is the only means of reducing the risk of serious head and neck injury in a front impact. Where a vehicle based head and back restraint is incompatible with the wheelchair, a wheelchair integrated solution should be provided.

A vehicle based head and back restraint must meet a series of requirements to cover its dimensions, energy absorption and strength. Le Claire *et al.* (2003) proposed a series of requirements, which seem to be appropriate for both adult and child passengers, although it was not part of this research to evaluate these requirements. A wheelchair integrated head and back restraint should be assessed during the dynamic test of the wheelchair for which it is intended to be used, to avoid unexpected results when the products are used together.

#### *11.2.4 Occupant space*

Le Claire *et al.* (2003) recommended that the space provided for a wheelchair and occupant is at least 1,300 mm measured in the longitudinal plane of the vehicle and 750 mm in the transverse plane of the vehicle, up to a height of 1,500 mm measured vertically from any part of the floor of the wheelchair space. It was not within the scope of this research to suggest modified requirements for vehicles intended specifically to carry children rear facing.

#### *11.2.5 Wheelchair design and stiffness*

Manufacturers of wheelchairs intended for use in a vehicle usually state in their product literature that the wheelchair should only be used forward facing. Nevertheless, there are vehicles in use that transport wheelchair users facing the rear. There are well known advantages to travelling rear facing; however, there is also a risk that a wheelchair would be unable to withstand the forces in a collision because it had not been designed or tested to be used in that way. Children would be particularly at risk due to their anatomy and level of development.

A head and back restraint within the vehicle may support some wheelchairs and improve their capacity to withstand the collision, but this would need to be established. TRL recommends, therefore, that the performance tests for children’s wheelchairs include a rear facing front impact. This would reflect the way that wheelchair users travel in a significant number of vehicles.

### 11.3 M3 forward facing

#### *11.3.1 Vehicle anchorages*

There are a number of different vehicle anchorage systems in use with wheelchair tie-down and occupant restraints. Rail tracking systems are the most common for webbing based tie-down systems, but individual anchor points are used in some vehicles. Docking systems are also available, although at the present time these are more likely to be found in private vehicles. Differences between these systems are unlikely to affect the loading to a child in a collision, providing that it is part of a complete system that meets the requirements of ISO 10542-1:2001. Hence rail tracking, individual anchors and docking systems can all be recommended for vehicles that may be used to transport children in wheelchairs.

The location of the anchorages in the vehicle needs careful consideration. The tested lateral dimension between the anchorages is 330 mm for most wheelchair tie-down systems. This distance is recommended for children's wheelchairs, unless the manufacturer states otherwise. The wheelchair should be attached so that the tie-downs achieve an angle of 45˚. The occupant restraint anchorages should be positioned to ensure that the lap part of the seat belt rests across the top of the thighs or very low over the front of the pelvis. The preferred zone of 30˚ to 75˚ to the horizontal is described in the ISO Standards, but TRL recommends that the further work is done to specify an appropriate zone for children.

Le Claire *et al.* (2003) recommended that the strength of vehicle anchorages be assessed in a static strength test and proposed requirements for the test. Children and their wheelchairs generate lower forces at the vehicle anchorages than adults and their wheelchairs. Nevertheless, it was not within the scope of this project to investigate whether separate requirements could be developed for M3 vehicles that are intended specifically to carry children.

### *11.3.2 Occupant restraint*

It is essential that children in wheelchairs are restrained with at least a three point seat belt. TRL recommends that the diagonal part of the seat belt is anchored to the vehicle above the shoulder level. The lap part of the seat belt may be attached to the vehicle floor or to the rear wheelchair tie-downs. However, TRL recommends that, where possible, the belt is attached to the rear wheelchair tie-downs. This is likely to provide a better path and angle of the lap belt.

Wheelchair integrated seat belts or harnesses represent the best solution for children, but increase the loads on the wheelchair. Integrated restraints are recommended when the wheelchair has been designed to accommodate an integrated restraint system.

Finally, it is recommended that the occupant restraint incorporates an inertia reel to manage the belt loads applied to the child. Although seat belts are designed to apply the forces to the strongest parts of the anatomy, the skeletal structures of children remain under development throughout childhood. A static three point seat belt should be avoided because it would apply higher loads to these structures.

### *11.3.3 Head and back restraint*

TRL recommends that a head and back restraint is provided for children in wheelchairs. This is the only means of ensuring that children in wheelchairs are provided with a level of protection that is comparable to that for children in child restraints (or vehicle seats) when they move back into their seated position following a collision. A vehicle based head and back restraint may be incompatible with some wheelchair types. In this case, a wheelchair integrated solution is recommended.

A vehicle based head and back restraint would need to meet a series of requirements to cover its dimensions, energy absorption and strength. Le Claire *et al.* (2003) proposed a series of requirements, which seem to be appropriate for both adult and child passengers, although it was not part of this research to evaluate these requirements. A wheelchair integrated head and back restraint should be assessed during a dynamic test with the wheelchair for which it is intended to be used. This is because testing with surrogate devices can lead to unexpected results when products are used together.

### *11.3.4 Occupant space*

Le Claire *et al.* (2003) recommended that the space provided for a wheelchair and occupant is at least 1,300 mm measured in the longitudinal plane of the vehicle and 750 mm in the transverse plane of the vehicle, up to a height of 1,500 mm measured vertically from any part of the floor of the wheelchair space. It was not within the scope of this research to suggest modified requirements for M3 vehicles intended to carry only children forward facing.

## 11.4 M3 rear facing

The following recommendations are made with regard to the non-impact protection of children in wheelchairs in low floor buses:

### *11.4.1 Head- and backrest*

It must be possible to position a child's wheelchair against the backrest. However, the gap between the handles of wheelchairs for younger children is likely to be too small for the handles to pass either side of the backrest and the base of some electric wheelchairs might extend further rearwards than the space below the backrest.

The DfT may wish to consider modifying the dimensions and/or location of the backrest in line with the children's wheelchair dimensions provided by Hitchcock (2008) and reported in Section 6.1. This should be considered alongside similar dimensions for adults' wheelchairs to ensure there are no conflicts between children's needs and adults' needs for support.

### *11.4.2 Restricting wheelchair movement into the gangway*

Regulations permit either a vertical stanchion or a horizontal rail to restrict wheelchair movement into the gangway during normal driving manoeuvres; however, TRL recommends that, where possible, a vertical stanchion is used for children in wheelchairs.

The position of the stanchion is very important. The project examined the effectiveness of the stanchion at three positions: 400 mm, 480 mm and 560 mm rearwards of the front of the wheelchair space. The stanchion was effective only when it was positioned 560 mm from the front of the wheelchair space. However, the wheelchairs were not positioned directly against the backrest due to their handles or due to their batteries.

The DfT may wish to consider modifying the range permitted for the position of the stanchion such that the minimum distance rearwards from the front of the space is increased. However, this could affect access to the wheelchair space for some larger wheelchairs. Hence TRL recommends that further research is carried out to investigate these issues.

The stability of an unrestrained wheelchair supported by a backrest is influenced by the front wheels. The wheelchair is more likely to move into the gangway when the front wheels are able to rotate on their castors. TRL recommends that further work is carried out to establish the feasibility of locking the front wheels of children's wheelchairs.

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# Appendix A. Literature and information review

## A.1 Introduction

A literature review was carried out to establish the relevance of any previous research in this area. The review comprised published research from the UK and abroad and any other information that it was possible to obtain.

TRL recognised that a review of this nature would highlight what was known about the safety of children in wheelchairs from a science and engineering point of view. It would also highlight any gaps in the knowledge that should be addressed in the project. However, TRL was concerned that the review contained the requirements of end users: children, parents and transport operators. To give a feel for these practical issues, the literature review was extended to gather relevant information and experiences from other organisations.

## A.2 Legislation and policy background

### A.2.1 All children

#### *A.2.1.1 Introduction*

Road vehicles are subject to comprehensive regulation. The requirements cover both the construction of the vehicle and the use of the safety systems by the occupants. This section provides an overview of the legislation with respect to children.

The Road Traffic Act 1988 is the relevant legislation in the UK and sets out the requirements in law. For instance, under Section 15 of the Act, it is an offence to drive a vehicle with a child under 14 years of age in a front or rear seat if they are not using the appropriate seat belt or child restraint. Detailed requirements about the type of seat belt or child restraint are given in a series of Regulations. Different provision is made depending on the age and/or height of the child. Also, various exemptions are made by vehicle class and the circumstances in which they operate. The key Regulations are the Motor Vehicles (Wearing of Seat Belts by Children in Front Seats) (Amendment) Regulations 2006 (SI 2006 No. 2213) and the Motor Vehicles (Wearing of Seat Belts) (Amendment) Regulations 2006 (SI 2006 No. 1892). These Regulations implement certain provisions of Directive 2003/20/EC (which amends

Council Directive 91/671/EEC relating to the compulsory use of safety belts in vehicles with a gross weight of less than 3.5 tonnes).

The requirements related to the provision of safety equipment within a vehicle are set out in the Road Vehicles (Construction and Use) Regulations 1986 (SI 1986 No. 1078). In fact, the approval of most vehicles is now based around the European Commission Whole Vehicle Type Approval (ECWVTA) system. The basic concept is that a production sample is tested and if it passes the tests and the production methods pass an inspection, vehicles of the same type are approved for production and sale within Europe. A framework Directive lists a series of separate technical Directives that the vehicle must be approved to. In order to gain ECWVTA, a vehicle has to meet the requirements of each of the relevant individual Directives. The scheme was introduced in the 1970s through Directive 70/156/EEC. A recast new framework Directive 2007/46/EC has now been published and extends the scheme to all vehicle categories and includes provisions for wheelchair accessible vehicles.

The technical Directives on vehicle construction cover a range of safety systems including seats, seat belts and their anchorages. The performance of child restraint systems is assessed separately through UNECE Regulation 44.03 or later. Child restraints that meet the requirements of the Regulation are marked with a label (showing ‘E#’ and ‘44.03’ or ‘.03’) and the group number or weight range of the child for which it is designed. These restraints can then be sold anywhere within Europe.

The following sections summarise the requirements for each M category vehicle.

#### *A.2.1.2 M1 vehicles*

The law regarding restraint use by children in M1 vehicles depends on their age and their height. Children up to three must use a correct child restraint system in the front seat. A correct child restraint must be used in the rear also; however, if one is unavailable in a taxi or an emergency vehicle, the child may travel unrestrained.

Children between three and 11 and less than 135 cm must use a correct child restraint in the front seat. They must also use a correct child restraint in the rear seat, provided there is an adult belt; however, there are three exemptions. The first exemption is travelling in a taxi, the second is travelling over a short distance of unexpected necessity and the final exemption is where there are two occupied child restraints in the rear which prevents a third being fitted.  In these circumstances, the adult seat belt must be used.

Children aged 12 and 13 or younger children over 135 cm must use either an appropriate child restraint or else an adult seat belt in the front and the rear.

The vehicle construction requirements for seats, seat belts and their anchorages in M1 vehicles are complex and depend on the age of the vehicle and the seating position.  In general, the majority of M1 vehicles on the road, including taxis, go beyond the minimum legal requirement and are fitted with three point seat belts throughout the vehicle.  The technical Directives include performance requirements which are usually assessed by static pull tests or dynamic tests with crash test dummies.

#### *A.2.1.3 M2 vehicles*

Once again, the law on restraint use depends on the age of the child and their seating position.  For instance, children up to three must use a correct child restraint system in the front seat.  A correct child restraint must be used in the rear also, but only if one is available.

Children between three and 11 and less than 135 cm must use a correct child restraint in the front seat if one is available; if not, an adult seat belt must be used.  The same rule applies in the rear of M2 vehicles, although this applies only if a seat belt is fitted in the vehicle.

Children aged 12 and 13 (and those under 12, but 135 cm or more in height) must use either appropriate child restraints or else an adult seat belt in the front and the rear.  These rules apply to M2 vehicles under 3.5 tonnes.  Vehicles above this weight are effectively grouped with M3 vehicles in the Regulations.

The vehicle construction requirements for seats, seat belts and their anchorages in M2 vehicles are similarly complex and depend on the age of the vehicle and the seating position.  Most M2 vehicles on the road are now fitted with three point seat belts throughout the vehicle.  The technical Directives include performance requirements which are usually assessed by static pull tests.

#### *A.2.1.4 M3 vehicles*

The law on restraint use by children in M3 vehicles depends on the type of vehicle.  Large buses running scheduled local services in built up areas and on which standing is permitted are exempt from the requirements for children to wear seat belts and/or use child restraints.

In other buses and coaches, the requirement to use a child restraint or seat belt in the front seat generally applies; however, there are very few cases where this would apply since relatively few vehicles are fitted with front seats.

There are currently no statutory requirements for children under 14 to wear seat belts or child restraints in the rear seats. European Commission Directive 2003/20/EC requires children aged three years and above to use the seat belts where they are fitted in a bus/coach. However, the UK deferred implementation of the Directive for children under 14 due to the difficulties in identifying who should be responsible for ensuring they are restrained. At the time of writing, the DfT was planning further consultation on how to implement the Directive in a practical way (DfT, 2007).

Inertia reel seat belts or retractable lap belts are required to be fitted in all forward and rearward facing seats in M3 vehicles. Lap belts may only be fitted in forward facing non-exposed seats where an appropriate energy absorbing seat or surface is present in front. The technical Directives include performance requirements which are usually assessed by static pull tests.

### A.2.2 Children in wheelchairs

#### *A.2.2.1 Introduction*

The Disability Discrimination Act 2005 enabled the Government to lift the exemption of certain vehicles from Part 3 of the 1995 Act. This is the part of the Act that deals with access to goods, facilities, services and premises. The Disability Discrimination (Transport Vehicles) Regulations 2005 (SI 2005 No. 3190) were made under this power and came into force from 4$^{th}$ December 2006. With rights of access improving for wheelchair users, this section provides an overview of the safety related legislation with respect to children in wheelchairs.

The legislation on restraint use described in the previous section does not apply to children in wheelchairs. For instance, there are no requirements in UK law for children in wheelchairs to wear a restraint system. However, the general safety requirements in Regulation 100 of the Road Vehicles (Construction and Use) Regulations 1986 (SI 1986 No. 1078) and in Section 40A of the Road Traffic Act 1991 are often mentioned. These require that vehicles are maintained and used in a way that does not pose a danger or nuisance to any person in the vehicle or on the road.

Requirements for the safe transport of children in wheelchairs can also be derived from health and safety legislation. Section 3 of the Health and Safety at Work Act 1974 places a duty on employers (so far as is reasonably practical) not to expose a non-employee to a risk to their health and safety arising from the action of the employer. Section 7 of the Act places a duty on the employees to take reasonable care for the safety of anyone who may be affected by his actions or omissions.

Provisions for a wheelchair space and a restraint system are made within the ECWVTA scheme, which has recently been extended to all M category vehicles by Directive 2007/46/EC, and within Regulations passed under Part 5 of the Disability Discrimination Act 1995. For example, technical requirements for some M category vehicles are covered by the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended).

Wheelchairs are subject to the Consumer Protection Act 1987. This gave Ministers the power to make the Medical Device Regulations 1994 (SI 1994 No 3017; as amended). As part of their CE marking process (which indicates that one or more of the procedures referred to in the Regulations have been followed), manufacturers of wheelchairs are required to consider the risks associated with the usage of their products. For the transportation elements of their risk management, many wheelchair and seating manufacturers carry out dynamic sled tests according to the relevant International Standard, such as ISO 7176-19:2001.

The following sections summarise the particular requirements for each M category vehicle.

#### *A.2.2.2 M1 vehicles*

Part 5 of the Disability Discrimination Act 1995 allows the Government to make accessibility regulations for taxis. The ergonomics of taxi design for people with disabilities has been examined and full scale evaluation trials have been carried out. The research established that the floor height, door height and internal space (floor and head room) of current purpose built or adapted taxis represent significant barriers to accessibility (Richardson and Yelding, 2004). The work to develop proposals for taxis is ongoing, but in the meantime, all licensed taxis in

London have had to be wheelchair accessible from January 2000. Also, outside London, some local authorities will give new licences only to taxis that can carry passengers who remain seated in their wheelchairs.

While this has led to increasing numbers of wheelchair accessible taxis on the road, the type and performance of the equipment within the vehicle was largely unregulated. However, the new framework Directive 2007/46/EC includes provisions for special purpose vehicles within the ECWVTA scheme. This extends to wheelchair accessible vehicles, which are defined as vehicles within the M1 category constructed or converted specifically to accommodate one or more persons seated in their wheelchair. For type approval to be granted, the vehicle manufacturer or converter will have to demonstrate compliance with a series of individual technical Directives. These include Directives on the seats, seat belts and seat belt anchorages. A wheelchair location is considered a seating position in the framework Directive and must be equipped with a wheelchair tie-down and occupant restraint system that meets the requirements of the same technical Directives as any other seating position as well as the requirements of ISO 10542-1:2001. This is also the case for the anchorages of the restraint system.

The proposals for taxis and the Directive 2007/46/EC have gone some way to ensure that accessible M1 vehicles are equipped with the hardware necessary to transport wheelchair seated passengers with a degree of protection. However, no special provisions are made for children; hence the geometry of the restraint may not be suited to their anatomy.

#### *A.2.2.3 M2 vehicles*

Until recently, there were relatively few regulations governing wheelchair use and safety in M2 vehicles, for adults or children. However, the ECWVTA scheme has now been extended to cover M2 vehicles by framework Directive 2007/46/EC. The individual technical Directives cited in the framework Directive include Directive 2001/85/EC. This prescribes technical requirements for a wheelchair space and restraint system in buses and coaches including M2 vehicles. Once again, no special provisions are made for children.

The Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No. 1970; as amended) apply to vehicles that carry more than 22 passengers on local or scheduled services.

#### *A.2.2.4 M3 vehicles*

A public service vehicle carrying more than 22 passengers is likely to fall within the M3 category and is therefore subject to the Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No 1970; as amended). The Regulations include technical requirements for boarding aids, for access from the door to a designated wheelchair space and for the restraint of the wheelchair and user. In urban buses, the wheelchair faces rearwards against a padded backrest and adjacent to a device such as a fixed stanchion to stop the wheelchair swinging into the gangway. In coaches, the wheelchair faces forwards and must be restrained by a tie-down system and the occupant must be provided with a seat belt. Relevant performance tests are included or referenced for the equipment but there are no specific requirements for children.

As mentioned above, the ECWVTA scheme has now been extended to cover M3 vehicles by framework Directive 2007/46/EC. The individual technical Directives cited in the framework Directive include Directive 2001/85/EC. This prescribes technical requirements for a wheelchair space and restraint system in buses and coaches including M3 vehicles. Once again, no special provisions are made for children.

## A.3 Biomechanics of children

### A.3.1 All children

#### *A.3.1.1 Introduction*

The purpose of a restraint system is threefold. Firstly, it must minimise the risk of ejection from the vehicle. Secondly, it must minimise the risk of body contact with the interior of the vehicle. Thirdly, it must absorb and distribute the impact forces over the strongest parts of the body. The three point seat belt is the main type of restraint system in road vehicles. It has been fundamental to the protection of adults since it became compulsory to wear one (in the front seat) in 1983. The Government estimates that seat belts have reduced minor casualties by 1,590,000, serious casualties by 590,000 and deaths by 50,000 (www.thinkseatbelts.com).

It is well known that although seat belts provide a high level of protection for adults, children cannot achieve the correct placement and fit of the belt. Furthermore, in the case of young children, it is necessary to apply the restraint forces over different areas of the body. An appreciation of the anatomy, growth and development of children has been critical to the design of effective child restraint systems. Children require special attention because their tissues have different biomechanical properties compared with adults. Furthermore, their needs from a restraint system change as they grow.

There are three stages of development before adulthood is reached. Infancy is the first stage and refers to the period from birth to 18 months. The second stage is childhood and ranges from 18 months to 12 years and includes toddlers (18 months to four years) and primary school aged children (four to 12 years). The final stage is adolescence and is usually considered to begin around the age of 13 years. Most children are tall enough to use the adult seat belt safely by this stage. The following sections examine the anatomy and physiology of children during infancy and childhood, focusing on the implications for their protection in a collision.

#### *A.3.1.2 Infancy*

The skull of an infant is a series of broadly spaced elastic bones. The spaces between the bones are called fontanels and allow the skull to change size and shape during birth and permit rapid brain growth during infancy. The fontanels are gradually replaced by bone until they become sutures. The largest of the fontanels, along the midline of the skull closes around 18 - 24 months after birth (Tortora and Gabrowski, 1996). The presence of the fontanels and the thickness of the bone mean that an infant's skull is relatively flexible; hence low levels of impact loading can result in significant deformation of the skull and brain. Another important feature of the skull during infancy is its size and weight in relation to the rest of the body. This, combined with developing neck structures, is thought to be involved in some neck injury mechanisms (Fuchs *et al.,* 1989).

The flexibility of the spine is also important. In fact, immature spines are much more flexible than relative size alone would predict (Kumaresan *et al.,* 2000 referenced from Weber, 2000). This is due, in part, to the ligaments, which are flexible to accommodate growth. The key point from the literature is that the spinal column and ligaments of infants are relatively elastic allowing elongation of up to two inches (50.8 mm), whereas the spinal cord ruptures if stretched more than ¼ inch (6.35 mm) (Leventhal, 1960 referenced from Huelke, 1998). For these reasons, it is important that a restraint system for infants prevents motion of their head with respect to their torso.

Adult restraint systems such as three point seat belts apply some of the restraint forces to the chest. This is inappropriate for infants because the skeletal system is still developing from cartilage and therefore maintains a high degree of flexibility. As a result, loading to an infant's chest from a seat belt or harness would lead to deformation of the chest wall onto the thoracic organs. Similarly, seat belts are designed to engage with the pelvis, but an infant's pelvis is relatively small and unstable. It would be unable to withstand the loading from a belt or harness. Furthermore, blunt trauma to the abdomen would be injurious because the muscle wall is undeveloped with little or no skeletal protection. The liver is particularly at risk because it occupies two-fifths of the abdominal cavity in infants and is not protected by the rib cage (Sturtz, 1980; Huelke, 1998).

As a result of these developmental issues, infants must use a rear facing child restraint system. These devices distribute the impact forces over the strongest and widest area possible: the infant's back. They have proven very effective in protecting young children in vehicle collisions although their performance is sometimes reduced by misuse.

#### *A.3.1.3 Childhood*

The fontanels have closed by the time childhood is reached; however, the thickness and composition of a child's skull is different from an adult's. The process of forming bone (called ossification) is not completed until the age of six or seven years and throughout childhood the stiffness of the skull is less than that of an adult (Sturz, 1980). It is important, therefore, that a child restraint system limits forward, vertical and rearward head excursion.

During childhood, the muscles and ligaments in the spinal column strengthen, the bones reach a mature shape and size and areas of cartilage are replaced by normal bone (Yoganandan *et al.,* 1999). Most researchers agree, therefore, that if necessary, children may face forwards in a car from the age of one year (Bull and Sheese, 2000). Nevertheless, parents are encouraged to keep children rear facing for as long as possible. In the UK, the advice is that a child can travel forward facing only if they have exceeded the maximum weight for their seat (typically 13 kg) or their head is higher than the top of their seat, or their seated height is too tall for the harness (www.thinkroadsafety.gov.uk).

The chest increases in width and depth during childhood and a process of elongation occurs. This raises the child's seated height and affects the fit of the restraint system. Child restraints include some means of adjusting the shoulder straps or belt to accommodate these changes. The rib cage grows downwards during childhood to provide some protection to the liver, spleen and kidneys (Huelke, 1998). Normal calcified bone replaces the cartilage in the ribs and hence their strength increases, although they remain somewhat flexible. Similarly, the pelvis grows larger and offers greater protection to some abdominal organs such as the bladder. However, the key development in the pelvis, the formation of the superior anterior iliac spines, is not complete until at least ten years of age. With a small, underdeveloped pelvis, there is a risk that the lap part of the seat belt can slip off during a crash and penetrate the abdomen.

Although a number of developmental changes have taken place by childhood, the protection of the head remains the priority. It is critical, therefore, that contact with the interior of the vehicle is prevented. The risk of neck injury due to inertial loading from the head is reduced in childhood because the muscles and ligaments are stronger. As a result, children are able to travel forward facing with relatively low risk of serious neck injury if head contact is prevented. Nevertheless, the way the child is secured in the child restraint is important for the protection of the chest and abdomen. In early childhood (until approximately four years), the ribs and pelvis are relatively small and somewhat flexible so a child restraint with an integral harness is used to reduce the risk of restraint induced injury. The harness must include a fifth point or crotch strap to keep the lap straps on the pelvis and prevent submarining. In later childhood (from approximately four years), when a child has outgrown the harness or exceeded the weight limit for their seat, a booster seat is used. This lifts the child's seating position to produce a more favourable interaction with the adult belt geometry. Booster seats include two sets of guides. The lower guides ensure the lap part of the seat belt passes over the top of the thighs. These guides also keep the lower part of the diagonal belt adjacent to the pelvis. The upper guide ensures that the upper part of the diagonal belt lies flat on the centre of the shoulder and therefore crosses the centre of the chest. A booster seat is necessary throughout childhood because the pelvis has not developed fully and the child's seated height is likely to be too low for an adult seat belt.

### A.3.2 Children in wheelchairs

#### *A.3.2.1 Introduction*

A child that uses a wheelchair is subject to the same fundamental changes in their physical development as any other child. Furthermore, their basic needs from a restraint system are likely to be similar. There may, however, be additional issues to consider. For instance, it would be useful to understand how children in wheelchairs compare with the average population of children in terms of their anthropometry. This information would help to inform discussions about the use of child dummies to represent child wheelchair users. It would also be useful to understand whether children in wheelchairs have any additional needs and how these might be accommodated. This section provides an overview of the literature that was found to be relevant to these issues.

#### *A.3.2.2 Anthropometry*

The Office of Population Census and Surveys (OPCS) completed four large national surveys of disability between 1985 and 1988. The Department of Health and Social Security (DHSS) requested the surveys to provide up to date information about the number, characteristics and circumstances of disabled adults and children in the UK for the purposes of planning benefits and services. Although a great deal of information was compiled following the surveys, it did not include any information about the fundamental anthropometry of children in wheelchairs. In fact, there is a lack of accurate data available to establish the total number of disabled children in Britain, the nature of their disabilities and the range of needs arising from their disabilities (Research in Practice, 2005; Hutchison and Gordon, 2004).

One study examined the height, weight and prevalence of feeding problems among disabled children. This concluded that feeding problems contribute to short stature and low weight in severely disabled children (Thommessen *et al.,* 1991). Similar research has looked at the risk of undernutrition and the pattern of growth for children with cerebral palsy (Hung *et al.,* 2003; Krick *et al.,* 1996). However, it was not possible to find clear, detailed information in the literature about the characteristics of children in wheelchairs. There are a wide variety of medical conditions that can lead to temporary or permanent wheelchair use by children. It seems likely that the anthropometry of children in wheelchairs will be different depending on their condition. TRL was able to examine some anonymous height and weight data provided by a UK charity. The sample was too small for scientific analysis and was biased by the children’s medical conditions. Nevertheless, it suggested that children in wheelchairs tend to be smaller for a given age than the average population, which child dummies represent.

#### *A.3.2.3 Additional needs*

Many children in wheelchairs use supportive seating systems for postural management. Generally, this seating is intended to prevent problems that can result from uneven weight bearing or from the inability to move out of poor positions (Disabled Living Foundation, 2003). A number of different approaches are taken by manufacturers of these systems. Some systems try to achieve a symmetrical and balanced sitting posture with a neutral alignment of the spine (Active Design, 2003). They aim to prevent unwanted movement, while allowing movement within safe boundaries. They also provide a stable base of support to allow head and arm movement without loss of balance.

Often a positioning belt or harness is incorporated into the seat; however, these are rarely crash tested. As a result, the child needs to wear an additional restraint during transport. This can lead to children travelling with several straps across their chest, possibly affecting the fit of the main crash tested restraint. In addition, the structure of the seating system with its pads and inserts may also interfere with the seat belt. These could be important issues given the capacity of the torso to bear loads during childhood.

## A.4 Current practices

### A.4.1 Introduction

Governments and researchers can benefit from an understanding of the real world issues and the concerns of all interested parties. Thornthwaite and Pettitt (1993) examined current school transport practice in the UK and USA, but more up to date information is required. The information in this section was compiled following discussions with mobility centres, transport operators, local authorities, charities and following observations of wheelchair transportation at a special school. It was not intended to be a scientific study, but instead provides a useful insight into the current situation in M category vehicles.

### A.4.2 M1 vehicles

Wheelchair accessible M1 vehicles are very convenient for parents of children in wheelchairs and offer something approaching the freedom to travel that many people enjoy. However, these vehicles are expensive to buy or to lease, although grants are sometimes available. As a result, many parents maintain a conventional vehicle and transfer their child to a child restraint, or to a vehicle seat, before a journey. A child is likely to receive better protection in the event of a collision from travelling in this way and there are special needs child restraint systems available. Nevertheless, many parents arrive at mobility centres with back problems through lifting their child into their vehicle. It is a particularly difficult movement, which involves twisting and stooping with a child in their arms who is unable to assist or who may spasm. This process can continue into adolescence, depending on the ability or health of the parent. It would appear from discussions with mobility centre staff that parents would appreciate more advice about transporting children with special needs, including when a child should travel in their wheelchair.

Taxis are sometimes used by parents of children in wheelchairs, but there can be a wide variation in the quality of the vehicle, the awareness of the driver of safety issues and also in their helpfulness. Manufacturers of taxis include training on the use of wheelchair tie-down and occupant restraints as part of the vehicle hand-over process; however, there is a large second-hand market and it is possible, therefore, that some drivers are not receiving this training.

### A.4.3 M2 vehicles

M2 vehicles are used widely for community transport and for taking children to school. In fact, a child may start to travel in their wheelchair for the first time when they reach school age. This is because it is not always practical to transfer every child in a wheelchair to a vehicle seat. Although different policies are in place, some operators prefer not to transfer children due to manual handling issues or due to parents' sensitivities. However, it should be noted that the Manual Handling Operations Regulations 1992 (SI 1992 No. 2793) do not prevent transport operators from lifting children into a vehicle seat. Instead, they place a requirement on the employer to assess the situation, reduce the risk of injury and provide information to employees.

Community transport differs from public transport in that the operators know who will be using their service on each trip. Special provisions can therefore be made to meet each individual's needs. This usually means that there is a risk management process for each child, with some transport operators adopting a passport system to compile all the necessary information. This would typically include details of the equipment needed to restrain the child and their wheelchair. Diligent transport operators are putting these systems in place to ensure that children in wheelchairs are accommodated in vehicles with the correct equipment for their wheelchairs. However, a child on a school or community bus would not usually be subject to an individual risk assessment or required to have a 'passport'. Effective standardisation should remove the necessity for such tailored solutions because all wheelchair tie-down and occupant restraint systems would be compatible with all wheelchairs.

There are several wheelchair tie-down and occupant restraint systems on the market; however, wheelchair manufacturers tend to recommend only one or two systems for use with their wheelchairs. It is important, therefore, for transport operators to be able to identify the make and model of the wheelchair in order to use the correct equipment. This can prove difficult if the wheelchair instructions are lost or if the labelling on the wheelchair has worn away.

Ideally, every wheelchair that is intended for use on a vehicle would be fitted with clearly marked attachment points for a wheelchair tie-down and occupant restraint system. Stickers on the wheelchair frame are currently used on some wheelchairs, but these can be difficult to find and can be positioned inconsistently. Instead, a system of colour coding could be used to assist transport operators in finding the correct attachment point. In addition, the attachment points could be designed in such a way to be compatible with any wheelchair tie-down and occupant restraint system, irrespective of the manufacturer. This would lead to a universal system whereby any combination of wheelchair and wheelchair tie-down and occupant restraint system could be used. This is addressed to some extent by ISO 7176-19:2001; however, it would appear that the Standard is not always implemented fully.

Community transport operators face a number of additional challenges. For example, the children may have behavioural issues and not want to be restrained. In addition, the drivers and their escorts need to monitor all the children in the vehicle, which may include ambulant children, while the wheelchair users are being restrained. It is important, therefore, that the wheelchair tie-down and occupant restraints are easy to use and can be fitted quickly. It seems likely that any efforts to bring transport operators, wheelchair manufacturers and restraint system manufacturers together would be beneficial.

TRL's observations suggest that there could, once again, be a wide variation in the standard of vehicles and restraint systems in use. Furthermore, few vehicles appear to be fitted with an upper anchorage point for the diagonal part of the seat belt. Anecdotally, vehicles have been reported as old and frequently unreliable with restraint equipment, in some cases, that is in a poor state of repair. Concerns have also been expressed about the level of staff training and frequent staff changes. However, it is often the case that good practice is unreported;

hence it is inappropriate to draw firm conclusions from these observations.  A survey of vehicles, equipment and training would be a useful way of establishing the current situation.

### A.4.4 M3 vehicles

The Public Service Vehicles Accessibility Regulations 2000 (SI 2000 No.1970; as amended) have led to increasing numbers of buses that provide access for wheelchair users and a designated wheelchair space. Nevertheless, the following comment was made by a parent in a report by the Audit Commission (2003):

*I know they do have those low floor buses but round here it's touch and go whether you get one, or if there is one then there's already a buggy on there. The Saturday before, we didn't get home until eight o'clock in the evening because I waited two hours for a bus.*

It seems likely that the situation will have improved since the time of the Audit Commission report; however, parents may still find these services difficult to use.  Many buses in urban areas are busy at peak times and hence the gangway and wheelchair space might be occupied by other passengers.  While signs in buses make it clear that the space is for wheelchair users, it is not clear to what extent this would be enforced by drivers or adhered to by other passengers.  In addition, parents of children in wheelchairs can have a number of items to carry such as specialist foods or changing pads and may have other children accompanying them.  Clearly, an accessible bus service will not meet everyone's needs, but there are limits to what is practicable and it would appear that the latest vehicles offer a good service within these limits.

## A.5 Performance of children's wheelchairs and restraint systems

### A.5.1 Accident studies

It is important to monitor the performance of vehicle safety equipment in real accidents.  For a given type of accident or scenario, vehicle safety researchers would typically seek to discover which areas of the body are being injured and what the contributing factors are.  This information helps policy makers to identify priorities for regulation.

It is well known that, traditionally, there has been very little information available on the performance of wheelchairs and their restraint systems in real accidents.  One of the challenges is that the accident databases used for such research are not detailed enough to identify passengers seated in a wheelchair. One such database is STATS19, a national road accident database named after the code number of the collection form. Road accidents in the UK that involve personal injury are recorded using the STATS19 collection system if they are reported to the police within 30 days. The form comprises a brief record of the accident location, the vehicles involved and the casualties, but it does not provide any detail such as the use of a restraint system. Nevertheless, STATS19 is a useful way of identifying accidents involving particular vehicles or occupant groups. More detailed reports of each accident may then be obtained from other sources. This approach was taken by TRL in a previous project for the DfT (PPAD 9/72/106). The findings were reported by Webster (2006). STATS19 was used to identify single-vehicle accidents involving a bus, a coach or a minibus, where pedestrians were not involved. Each accident and casualty was investigated further to obtain information about the activity of the passengers and use of a wheelchair or other mobility aid. This information was obtained from the relevant police force or local authority. Single-vehicle accidents were selected by Webster (2006) because this met the needs of the project (PPAD 9/72/106). However, most collisions involve another vehicle or vehicles. Single-vehicle collisions are much less common. As a result, there were no collisions in the accident data presented by Webster (2006). Instead, the accidents occurred during boarding and alighting, braking or normal manoeuvring. Several of these cases involved injury to wheelchair users while their vehicle was in motion, but restraint systems were not used or they were used incorrectly. For example, a 12 year old child was injured because their wheelchair restraint ‘gave way’ when the vehicle braked. The child received a number of fractures, although it was known that he had a brittle bone condition.

Other studies investigating injuries to wheelchair users make similar observations. For example, Richardson (1991) examined accident data from the National Electronic Injury Surveillance System (NEISS) in the USA. Based on the sample, Richardson (1991) estimated that there were around 2,200 injuries nationwide among wheelchair users in motor vehicles from 1986 to 1990. However, most of the injuries were attributed to improper restraint during sudden braking or sharp turns. Children were not identified in the study. Shaw (2000) made a similar analysis of the NEISS database for 1988 to 1996 and estimated that there were around 1,320 injuries nationwide. Once again, injuries were attributed to abrupt vehicle manoeuvres. Frost and Bertocci (2006) carried out a retrospective study of wheelchair related incident reports from a metropolitan area in the USA between 2002 and 2005. The study focused on large, public transport buses and found that the majority of incidents (73.2 percent) occurred when the bus was stationary. Of the incidents that occurred when the bus was in motion, most occurred in normal driving (72.7 percent) while the remainder occurred in emergency manoeuvres. There were no incidents involving a bus crash and there was no reference to children.

Although these studies did not identify any vehicle collisions, they highlight the need for appropriate restraint for passengers seated in wheelchairs. It is of some concern that despite the availability of such equipment, wheelchair users were injured in normal driving or emergency manoeuvres. These studies provide no information about the performance of appropriate equipment when it is used correctly in a collision. In fact, only one study was found that included detailed case reports featuring wheelchair seated occupants and these were adults. Schneider *et al.* (2003) described two real world accident cases; in one case, a 28 year old passenger in the rear of a minivan was injured during a moderate 20 mph collision. His electric wheelchair was restrained well by a four point tie-down system that was compliant with SAE J2249:1996. However, he was not wearing a seat belt and was injured after the postural belt he was wearing failed. In the other case, a passenger in a manual wheelchair was ejected from the vehicle during a roll-over. The driver of the vehicle had reported that the wheelchair user was restrained with a four point wheelchair tie-down and a three point seat belt that were both compliant with SAE J2249:1996. Following an investigation, Schneider *et al.* (2003) concluded that the seat belt buckle released after contacting the wheel rim during the impact. The occupant was thrown through a side window fracturing their legs on contact with the ground outside the vehicle while the wheelchair remained in place.

In an effort to obtain more information, the Cooperative Crash Injury Study (CCIS) database was examined by TRL. The CCIS is a collaborative project to investigate and document accidents in the UK. The project is managed by TRL on behalf of the DfT and a number of vehicle manufacturers that also support the study. Investigation teams monitor the details of all injury accidents that are reported within their limited geographical areas. From these accidents, cases are selected for possible inclusion in the study based on a number of strict criteria. There were 13,835 occupants in the database at the time of the investigation; however, only one child was found with special needs and she was not a wheelchair user. A search of the internet found an accident involving a minibus carrying children to a special needs school in Ireland. Two children were killed; however, reports of the accident did not state whether any children were wheelchair users (BBC News, 1998).

### A.5.2 Laboratory tests and simulations

The safety of passengers who remain seated in a wheelchair has interested governments and researchers since the late 1970s. However, in the absence of detailed accident information, researchers have been limited to the use of laboratory sled testing and computer simulation to draw conclusions about the safety of wheelchair occupants. Studies from this period highlighted three broad, but now well-established principles:

- The wheelchair must be restrained and there must also be a means of protecting the occupant (Rider *et al.,* 1976).

- Wheelchairs are not just mobility aids; they must be capable of withstanding the forces in a crash (Kallieris *et al.,* 1981).

- Wheelchair users should not travel facing sideways in a vehicle (Schneider and Melvin, 1978).

Most physical testing and computer simulations carried out to date have used 50$^{th}$ percentile male dummies. There is much less research focusing on children in wheelchairs. Nevertheless, several early studies examined the crashworthiness of wheelchairs and restraint systems for disabled children (Schneider *et al.,* 1979; Khadilkar and Will, 1980; Seeger and Caudrey, 1983; Benson and Schneider, 1984). However, examining these studies in depth reveals that children's wheelchairs have changed considerably since that time.

More recently, Colvin *et al.* (1999) investigated some products intended to improve the protection afforded to children. These included a support strap to improve the connection between a wheelchair and a seating system, a wheelchair integrated lap belt, a wheelchair integrated upper torso restraint and a prototype garment to provide support and comfort to wheelchair users. Unfortunately, no test results were presented and the conclusions of the study were limited.

In another study, Ha *et al.* (2004a) developed and validated a six year old wheelchair seated occupant model in MADYMO for use in their research studies. The model comprised a Hybrid III six year old dummy seated in a common manual wheelchair from the USA. It was subsequently used to investigate the forces acting on a wheelchair during a 20 g/48 kph front impact (Ha *et al.,* 2004b). Forces were extracted from the model at several locations. A parameter sweep was then carried out to examine the effect of a number of wheelchair set up adjustments on these forces. The authors anticipated that the study would provide wheelchair and seating manufacturers with an insight into the magnitude of the forces that would act on their products in a front impact (of the same severity). It was probably outside the scope of the paper presented by Ha *et al.* (2004b); however, it would have been useful to include the effect of the various wheelchair adjustments on the dummy excursions and loads in the model.

Three sled tests were carried out to validate the MADYMO model. These were reported initially by Ha *et al.* (2004a), but in more detail by Ha and Bertocci. (2007). In the later study, the dummy accelerations and forces were compared with performance limits in FMVSS 213 and FMVSS 208. The chest acceleration was within the limit in FMVSS 213; however, the results exceeded the $N_{ij}$ limit in FMVSS 208 and were approaching the chest compression limit. The authors concluded that children who remain seated in their wheelchair may be at risk of injury, especially to the neck and chest, but they also noted that concerns had been raised elsewhere about the biofidelity of the dummy neck. Baseline tests with a child in a vehicle seat or child restraint were not carried out in the study, but other authors have noted high $N_{ij}$ values when the Hybrid III child dummy was seated in a child restraint (Sherwood *et al.,* 2003). This injury criterion was developed for adults, but has been scaled for use with children (Eppinger *et al.,* 2000; Mertz *et al.,* 2003). Although it is often used in research studies in the USA, it has not been validated for children and should therefore be used with caution.

The use of wheelchair integrated restraint systems has interested researchers for several years (Van Roosmalen and Bertocci, 2000; Van Roosmalen *et al.*, 2001). Much of this interest has focused on adult dummies in computer models of the surrogate wheelchair. However, Manary *et al.* (2006) performed sled tests to examine the feasibility of integrating a five point harness into a common manual wheelchair. The Hybrid III three year old dummy was used in the study. The backrest of the manual wheelchair failed in the first test. This was attributed to the additional loading from the dummy during the impact. The wheelchair was strengthened and performed well during the second test. It must be noted that both wheelchairs were described as ‘previously used’ although no details were provided. A baseline test with a three point seat belt instead of the harness was not carried out, but the authors reported that the harness had the potential to improve occupant protection for small children who remain in their wheelchair. The ANSI/RESNA WC/19:2001 Standard was the main focus for the analysis but some dummy loads were also included. These fell below the performance limit in FMVSS 213.

The studies described so far have focused on forward facing wheelchairs in front impact tests. Manary *et al.* (2007) carried out a series of rear impact tests with a range of wheelchairs. A Hybrid III 50$^{th}$ percentile male dummy was used, except in one test, where a Hybrid III fifth percentile female dummy was used. The test conditions (25 kph/14 g) were intended to represent a moderate severity rear impact for a forward facing passenger in a minivan. The wheelchair backrest failed in most of the tests, resulting in the dummy coming to rest on the floor of the sled. It was also noted that the front wheelchair tie-down attachment points failed in a third of the tests, which contributed to the violent kinematics of the dummy. The study highlights that rear impact has not been addressed in any way by wheelchair manufacturers.

Fuhrman *et al.* (2007) carried out rear impact tests with a Hybrid III six year old dummy seated in a manual wheelchair. The test conditions were similar to those used by Manary *et al.* (2007). Tests were carried out with and without a headrest attached to the wheelchair. In this study, the wheelchair withstood the loading from the dummy during the impact. The headrest was designed for posture only, but appeared to support the head and neck in these rear impact tests.

## A.6 Discussion

Legislation for the protection of occupants in road vehicles can be divided into three groups. Firstly, there are technical requirements for the type and specifications of the restraint system in the vehicle. Secondly, there are technical requirements for the performance of the restraint system, which are assessed by static pull tests or dynamic impact tests with dummies. Within this group, children are addressed specifically by UNECE Regulation 44. Finally, there are requirements to use a restraint system when travelling in a vehicle. Once again, there are specific requirements for children.

For wheelchair users, there is an extra dimension, which is access to the vehicle or to the service provided by the vehicle. This has improved considerably with the introduction of the Disability Discrimination Act 1995 and the associated Regulations. For children in wheelchairs, the legislation currently in place (or coming into force) covers the type and specification of the restraint system in the vehicle. However, the technical requirements for the performance of the restraint system (including the wheelchair) do not address the protection of children directly in the way that UNECE Regulation 44 does. In addition, there is no legislation governing the use of a restraint system by wheelchair users including children. It could be argued, therefore, that children in wheelchairs do not receive comparable safeguards in legislation as other children.

There is a significant amount of research in child biomechanics that can be drawn on by designers of child restraint systems. This has led to a number of different solutions that are tailored to the stage in the child's growth and development. Decades of research carried out to monitor the performance of child restraints in real accidents has shown that children can withstand the forces in a collision when they are restrained appropriately according to their level of development. Although there was little or no information on the biomechanical characteristics of children that use wheelchairs, the same principles for restraint design should apply.

There is a wide range of equipment on the market to restrain children and their wheelchairs in vehicles. Manufacturers of this equipment include instructions about the use of their products in vehicles, but this can vary in detail and quality. Parents and carers of children in wheelchairs would probably appreciate, therefore, any advice on the most appropriate way to restrain their children and when it is safe for them to travel while seated in their wheelchair.

There are reasonably mature Standards in place that govern both the design and performance of wheelchairs and wheelchair tie-down and occupant restraints. Nevertheless, there can be compatibility issues among devices intended for use on a vehicle. It would appear, therefore, that these Standards are not being implemented fully. In addition, more information is needed on the way the Standards are driving the development of equipment and whether this equipment meets the needs of children, parents and transport operators.

There is almost no information available about the performance of wheelchairs and their restraint systems in real accidents. It is possible that very few accidents have occurred involving a vehicle that is carrying children in wheelchairs. However, it would be highly beneficial to develop some means of identifying such cases. For example, STATS19 could be used to identify accidents involving a child passenger in a minibus, bus or coach. Reports of each accident could then be obtained from the police, or from other sources, and the involvement of any wheelchair seated children could be determined. Another approach would be to set up a monitoring system to identify any accidents that occur in the future. This could take the form of a questionnaire study similar to that carried out by TRL (for the DfT) to obtain information about the performance of child restraint systems in accidents (Visvikis and Le Claire, *Child occupant protection – accident analyses*, 2003; unpublished Project Report PR SE/760/03).

There have been relatively few laboratory studies of the safety of children in wheelchairs in vehicles. The studies carried out to date have, in most cases, focused on manual wheelchairs with the Hybrid III six year old dummy to represent a child. Further research is needed to examine the level of protection afforded to children in a broader range of wheelchairs. This research should consider the use of dummies to represent both the smallest and the largest children that use each wheelchair.

### A.7 Conclusions

- There is no all-encompassing legislation in place to address the protection of children in wheelchairs in vehicles.

- Transfer to a rear facing child restraint system is the best solution for infants.

- Transfer to a forward facing child restraint is the best solution for young children.

- In later childhood, children need to travel in their wheelchair.

- More information is needed on the number and characteristics of children in wheelchairs.

- A significant number of children travel in wheelchairs without incident.

- The performance of children's wheelchairs in real accidents needs to be understood.

- The ability of children's wheelchairs to limit biomechanical loading needs to be understood.

### A.8 Recommendations

- The test programme should examine the safety of children from three years until 1.35 metres or 12 years of age.

- Supportive seating is important for postural management and should be considered in the test programme.

- All vehicle categories need to be considered in the development of the test programme.

- Road traffic legislation should include disabled children.

- Children's wheelchairs designed for use in a vehicle should be treated as child restraint systems and similar limits should be applied to their use and performance.

- Clear guidance should be given to parents and transport operators on the way children must travel at each stage of their development.

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# Appendix B. Field study of vehicle and wheelchair interaction

## B.1 Introduction

Laboratory studies of wheelchair seated occupant protection are carried out with a simple representation of the vehicle interior. This is usually limited to the floor and to the anchorage points of the restraint system. This approach removes any effects that the design of a specific vehicle might have on the test results. However, it can result in a test set up that is somewhat detached from the situation in real vehicles.

The field study was devised to improve our understanding of the way that children and their wheelchairs interact with real vehicles and restraint systems. The aim of the study was to identify potential problems in the orientation of the wheelchair, the location of the vehicle structures and the geometry of the (wheelchair and occupant) restraint system. A range of representative wheelchairs and vehicles were used in the study. In each vehicle, child dummies were seated in the wheelchairs and restrained using whatever means were provided in the vehicle. It was recognised that this sometimes differed from the wheelchair manufacturer's instructions for transport.

A number of different M category vehicles were examined in the field study. These were grouped as follows:

- M1 and M2 vehicles with forward facing wheelchair passengers. These included both converted small multi-purpose vehicles and minibuses.
- M1 and M2 vehicles with rear facing wheelchair passengers. In fact, no M2 vehicles were found in which a wheelchair user regularly travels rear facing. The vehicles examined were all M1 vehicles that were purpose built or specially adapted to function as a taxi.
- M3 vehicles with forward facing wheelchair passengers. These were coaches.
- M3 vehicles with rear facing passengers. These were buses used on scheduled urban services.

For each group, a number of different vehicles were examined to ensure that the findings were not influenced by a particular example.

Four wheelchairs were used during the field study. The wheelchairs were selected to represent the many different devices that children use. The four wheelchairs were:

- A folding manual wheelchair with a sling canvas seat.
- A rigid manual wheelchair for active users.
- An electric wheelchair with a reclining or tilting function.
- A buggy style wheelchair with a seat comprising a postural positioning system.

All four wheelchairs were production models loaned to TRL by the manufacturers. The manual wheelchair, electric wheelchair and buggy were suitable for use in a vehicle as stated in the product literature. The active user wheelchair was not suitable for use in a vehicle; however, this type of wheelchair is popular with some children and may be used in transport despite the manufacturer's instructions. The wheelchairs are shown in Figure B1.

Basic manual wheelchair

Active wheelchair

 

Electric wheelchair — Buggy style wheelchair

**Figure B1** Wheelchairs used in the field study

It was understood that these wheelchairs represented a limited cross section of the devices available for children. However, for the purposes of the field study, they included a number of key features shared by the many different designs that are found. It was concluded, therefore, that the selection of wheelchairs covered the widest range of features considered to be important for the investigation of wheelchair interaction with vehicles.

The following sections present the findings of the field study for each of the four groups described above.

## B.2 M1 and M2 forward facing

The field study included several M1 and M2 vehicles in which a passenger in a wheelchair travels forward facing. Some examples are shown in Figure B2 and Figure B3. Figure B2 shows the multi-purpose vehicles used in the study. These were small vehicles defined as M1 according to the system of classification in the European Commission Directive 2007/46/EC (Annex 2). The vehicle on the left of Figure B2 featured a permanent space for a wheelchair seated passenger and is an example of the type of vehicle that a parent might purchase or lease for their private use. It included a four point wheelchair restraint and a three point seat belt. The seat belt was similar in design to a traditional automotive belt and included an upper anchorage for the diagonal part of the belt.

The image on the right of Figure B2 shows the other multi-purpose vehicle used in the study. This vehicle was accessible to wheelchair users only when the rear seats were folded away and is an example of the type of vehicle that is sometimes used for private hire. It included an aftermarket wheelchair tie-down and occupant restraint system (i.e. supplied separately to the original vehicle) that would be fitted by the driver. There was no upper anchorage point for the diagonal part of the seat belt.

Figure B3 shows examples of the minibuses used in the field study. These were defined as M2 according to the system of classification in the European Commission Directive 2007/46/EC (Annex 2). All of the minibuses included a flexible interior layout and were examples of the type of vehicles that are sometimes used for school or community transport. A space was reserved for wheelchair users towards the rear of the vehicles to allow ingress and egress via a lift. Aftermarket wheelchair tie-down and occupant restraint systems were included, to be fitted by the driver or the escort. None of the minibuses were fitted with an upper anchorage point for the diagonal part of the seat belt and it would appear that such anchorages are rarely found.

M1 vehicle with permanent wheelchair space

M1 vehicle with flexible wheelchair space

**Figure B2** Passenger compartment in some M1 vehicles

M2 vehicle with flexible wheelchair space

M2 vehicle with flexible wheelchair space

**Figure B3** Passenger compartment in some M2 vehicles

The multi-purpose vehicle with a permanent wheelchair space was fitted with lap belt anchorages that were relatively wide, to allow access to the space from the rear and to accommodate a range of wheelchairs and occupants. This is illustrated in Figure B4. The image on the left shows the rear view when the electric wheelchair was positioned in the wheelchair space. The image on the right shows the front view and the path of the belt around the dummy. The position of the lap part of the seat belt with respect to the dummy's pelvis was reasonable with this arrangement (if not ideal). However, the contact area between the belt and the pelvis was reduced as a result of the location of the anchorages in the vehicle on either side of the wheelchair. Clearly, it would be very difficult to locate these anchorages in the optimum position for every wheelchair user that might travel in the vehicle.

**Figure B4** Lap belt anchorage location in an M1 vehicle with a permanent wheelchair space and the effect on belt path

In M1 and M2 vehicles with a flexible wheelchair space, the anchorages for the lap part of the seat belt and consequently the seat belt buckle were attached to the floor tracking behind the wheelchair. As a result, it was sometimes the case that a gap was created where the diagonal part of the seat belt would ideally meet with the lap part of the belt. The diagonal part of the belt passed high across the ribs of the dummy before joining the lap belt at the buckle behind. This is highlighted in the image on the left of Figure B5. The image on the right of Figure B5 shows how parts of the wheelchair sometimes obstructed the ideal path of the seat belt. In this instance, the buggy style wheelchair, with its support pads, illustrates this issue. It also shows how the positioning harness can obstruct the belt.

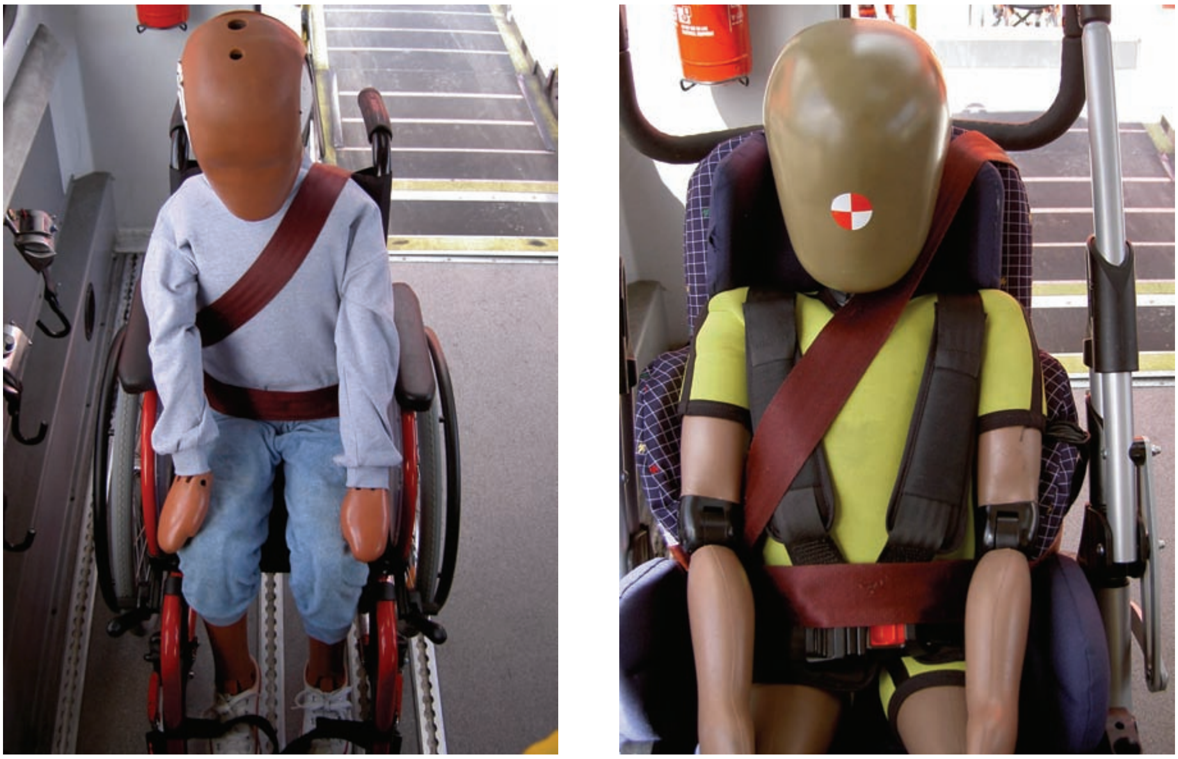

**Figure B5** Seat belt geometry in a typical M2 vehicle with a flexible wheelchair space

None of the M1 and M2 vehicles examined in the field study provided a head and back restraint for the wheelchair user. Furthermore, in the smaller vehicles, the rear of the dummy's head was in close proximity to the vehicle structure or boarding aid. This is illustrated in the image on the left of Figure B6. The amount of space in front of the wheelchair was also important, but varied significantly between vehicles. In one of the smallest vehicles, the space was limited and the legs of the dummy were adjacent to rigid parts of a folded seat. This is illustrated in the image on the right of Figure B6. It is possible that the head of a child in a similar position may also have been able to contact these parts in a collision.

**Figure B6** Wheelchair space in two typical M1 vehicles

### B.3 M1 and M2 rear facing

Three vehicles were examined in which a passenger in a wheelchair travels rear facing. These were all M1 category vehicles and were either purpose built or specially adapted to function as a taxi. No M2 vehicles were found in which a wheelchair user regularly travels rear facing. Figure B7 shows the passenger compartment in a typical vehicle. The image on the left shows the bulkhead that separates the driver and passenger compartments and the image on the right shows the forward facing vehicle seats at the rear of the passenger compartment.


**Figure B7** Passenger compartment in a typical purpose built or adapted taxi

Figure B7 highlights the key features of purpose built or adapted taxis that are relevant to the carriage of children in wheelchairs. Firstly, there is the bulkhead that separates the two compartments and is used to support the back of a wheelchair. In all three vehicles, the surface of the bulkhead was uneven with a range of materials used for the various fittings. In addition, there were several interior projections within the passenger compartment. A two point wheelchair tie-down was incorporated into the bulkhead to hold the wheelchair in position during normal driving and in the event of a collision. The vehicle shown in Figure B7 also included the option of fitting two further attachments to the front of the wheelchair. All vehicles provided a three point seat belt for the wheelchair user, which included an upper anchorage on the B pillar.

The tie-down system in purpose built or adapted taxis usually attaches to the rear of the wheelchair. However, one of the vehicles examined in the field study included a new system that attaches to the front of the wheelchair. This is shown in Figure B8. Although it was not part of the field study to evaluate this system, it seemed likely that it would not be as effective as a traditional system that attaches to the rear of the wheelchair.

**Figure B8** Wheelchair tie-down system in one purpose built taxi

None of the purpose built or adapted taxis examined during the field study provided a head and back restraint for rear facing passengers. Figure B9 shows some examples of the surfaces and structures in the vehicles that were adjacent to the heads of the dummies when they were seated in wheelchairs. The distance between the head and these surfaces varied significantly depending on the wheelchair type and particular vehicle. In one vehicle, an 80 mm thick foam head support was attached to the clear centre division, but it was unlikely to afford any protection in a collision. In the event of a collision, a child's head would strike one of these surfaces, which could result in serious head and neck injuries. It also seems likely that the neck would bend significantly, possibly leading to extension injury to the cervical spine.

**Figure B9** Proximity of head to vehicle structures in purpose built or adapted taxis

Contact between the rear of the wheelchair backrest and the bulkhead was prevented by either the push handles or the rear wheels of the wheelchairs. The size of the gap between the backrest and the bulkhead depended on the vehicle and the type of wheelchair. An example is shown in Figure B10 with the electric wheelchair.  It seems likely that the wheelchair backrest would fail in these circumstances because it would not be supported by the vehicle.  Alternatively, the wheelchair would rotate about the rear wheels.  In either event, the child could contact the bulkhead with considerable force, which would potentially result in multiple injuries.

**Figure B10** Example of the gap between the bulkhead and the backrest that can result in purpose built or adapted taxis

When a wheelchair user is travelling rear facing, the main function of the seat belt is to minimise contact with any vehicle structures and to help to distribute the forces across the stronger parts of their body.  In a front impact, the belt may help to reduce the amount that the occupant would ride up the wheelchair backrest and would minimise excursion towards the rear of the vehicle as they came back into their wheelchair.  All of the purpose built or adapted taxis in the field study provided a three point seat belt.  The anchorages of the lap part of the belt were located at the bottom of the bulkhead and were relatively wide, probably to accommodate larger wheelchairs.  The anchorage of the diagonal part of the seat belt was located on the B pillar above the shoulder level.

The field study revealed that the path of the seat belt in a purpose built or an adapted taxi can be influenced by the wheelchair.  Figure B11 shows a six year old dummy seated in a manual wheelchair.  The image on the left shows the lap part of the seat belt positioned over the top of the armrests.  The image on the right shows the lap part of the belt threaded through a small gap in the armrests and side guards.  Clearly, the geometry of the lap part of the seat belt is much better in the image on the right of the figure.  However, this set up was difficult to achieve and involved a lot of contact with the dummy around the hips.  This would be time consuming for the taxi driver and a child and their parent are unlikely to welcome such contact when the driver fits the restraint. The diagonal part of the seat belt is also better in the image on the right, but the ideal route cannot be achieved because the upper anchorage cannot be adjusted.  It must be pointed out, once again, that manufacturers of wheelchairs intended for use on a vehicle usually state that the wheelchairs should be used only forward facing.  There is, therefore, a discrepancy between the recommended use outlined by wheelchair manufacturers and the situation in some vehicles.

**Figure B11** Seat belt geometry with a manual wheelchair in an adapted taxi

Although the effects of poor seat belt geometry may be less important for rear facing children compared with forward facing children, it might lead to greater vertical excursion and less favourable belt paths.  A child would therefore be at risk of head and neck injury due to head contact and a greater risk of soft tissue injuries from the seat belt.

## B.4  M3 forward facing

Two M3 vehicles were included in which a passenger in a wheelchair would travel forward facing.  These were coaches.  Although they were not certified as compliant with the Public Service Vehicles Accessibility

Regulations 2000 (SI 2000 No.1970; as amended), they included a wheelchair space that was consistent with the requirements of the Regulations.  Figure B12 shows the wheelchair space in one of the vehicles.  Aftermarket wheelchair tie-down and occupant restraint systems were included in the vehicle, to be fitted by the driver.  There was no upper anchorage point for the diagonal part of the seat belt, hence it would need to be positioned over the shoulder and anchored to the floor of the vehicle.  The benefit of an upper anchorage point compared with a diagonal belt attached directly to the floor was established for adults by Le Claire *et al.* (2003).

**Figure B12** Wheelchair space in the coach

The wheelchair space and the arrangement of the wheelchair tie-down and occupant restraint system in the coaches was very similar to that observed in minibuses.  As a result, the main findings of the study were also very similar.  For instance, the anchorages of the lap part of the belt and consequently the seat belt buckle were attached to floor tracking behind the wheelchair.  This meant that, once again, the diagonal part of the seat belt passed high around the ribs before joining the lap belt at the buckles.  This is illustrated with the manual wheelchair in Figure B13. While this was an important observation about the fit of the seat belt for children, it was also recognised that this was influenced by the design of the seat belt.  Another seat belt design, such as one that attached directly to the wheelchair, or to the wheelchair tie-down, would have led to a different fit.

**Figure B13** Seat belt geometry with a manual wheelchair in a coach

Figure B13 also highlights that the coaches did not provide a head and back restraint for the wheelchair.  Although there is no requirement to fit a head and back restraint, some coaches on some scheduled interurban services are equipped with them.  The vehicles examined in the field study therefore represent the worst case.  In a collision, a child's neck would extend rearwards following the main impact phase when they move back into their wheelchair seat.  This would increase the risk of head contact behind the seating position and could lead to soft tissue neck injuries.

## B.5  M3 rear facing

The field study included two vehicles in which a passenger in a wheelchair travels rear facing.  Both vehicles were typical examples of the low floor buses that are used on scheduled services in urban areas.  A dedicated wheelchair space was provided in each bus and they both included a padded backrest to support the wheelchair.  One bus was equipped with a vertical stanchion to keep the wheelchair within the space during normal driving manoeuvres.  The other bus was equipped with a retractable horizontal rail in place of the vertical stanchion.

The wheelchair space in each bus is shown in Figure B14.  The images in the top row of the figure show the bus that was fitted with a vertical stanchion.  The images in the bottom row show the bus that was fitted with a retractable rail.

Bus fitted with a cranked vertical stanchion

Bus fitted with a retractable rail

**Figure B14** Wheelchair space in low floor buses

The study highlighted some potential issues of compatibility between children's wheelchairs and the padded backrest in low floor buses. This is illustrated in Figure B15. The image on the left of the figure shows that the backrest was wider than the distance between the handles on the manual wheelchair used in the study. This meant that the handles were unable to pass either side of the backrest. Instead, they rested against the padded surface, resulting in a gap between the backrest and the dummy. The head of a child travelling in this way would extend rearwards in the event of a heavy braking or a collision. This motion might result in a soft tissue neck injury.

The image on the right of the figure shows that the base of the electric wheelchair pressed against the mounting structure below the padded surface of the backrest. Once again, this introduced a gap between the backrest and the dummy, and hence a child travelling in this way might be at risk of soft tissue neck injury in the event of heavy braking or a collision.

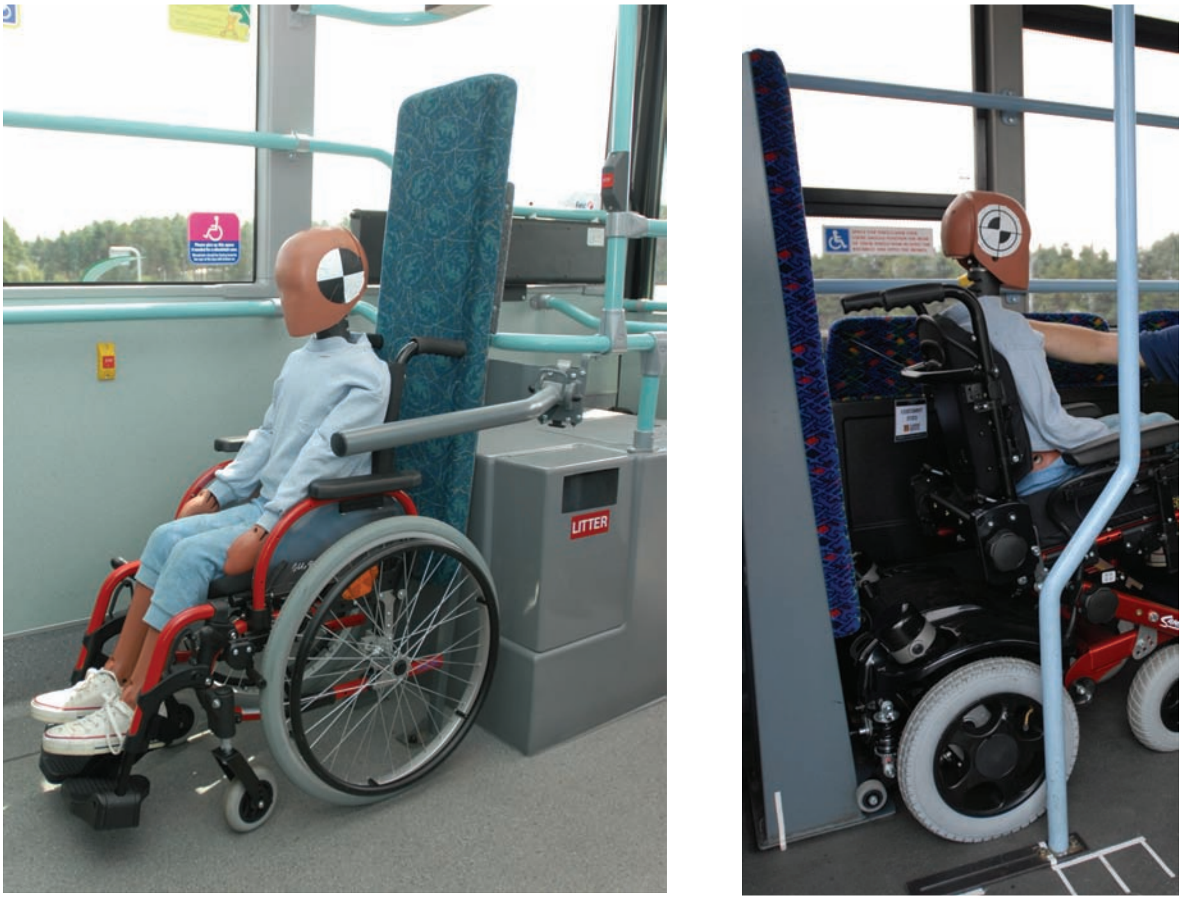


**Figure B15** Wheelchair and backrest interaction in low floor buses

## B.6 Conclusions

- The path of the lap part of the seat belt around the dummy was influenced by the location of the belt anchorages in the vehicle.

- The contact area between the dummy pelvis and the belt was reduced when the lap belt anchorages were positioned on either side of the wheelchair, compared with anchorages behind the wheelchair.

- The diagonal part of the seat belt passed high across the ribs of the dummy when the lap belt anchorages were positioned behind the wheelchair.

- The path of the seat belt was influenced by its design and arrangement. In the case of aftermarket occupant restraints, it was recognised that there were a number of different designs that were available that would result in different belt paths.

- The path of the seat belt was influenced by the design of the wheelchairs. In certain circumstances, the wheelchairs obstructed the ideal path of the belt.

- Some of the vehicle types did not include an upper anchorage for the diagonal part of the seat belt. It would appear that few of these vehicles currently include such an anchorage.

- Some of the vehicle types did not include a head and back restraint for the wheelchair user. It would appear that few of these vehicles currently include a head and back restraint.

## B.7 Recommendations

- Manufacturers of wheelchairs, vehicles and restraint systems should be encouraged to work together to improve the path of the seat belt for children who travel while seated in their wheelchair.

- The test programme should examine three main areas of concern for forward facing wheelchairs: the geometry of the restraint system, the protection of the child's head behind the wheelchair and the amount of clear space around the child.

- The test programme should examine three main areas of concern for rear facing wheelchairs: the protection that a child's head and neck would receive in a collision, the protection that a child's torso would receive during a secondary collision with the bulkhead and the geometry of the restraint system.

## B.8 References

**Le Claire M, Visvikis C, Oakley C, Savill T, Edwards M and Cakebread R (2003).** *The safety of wheelchair occupants in road passenger vehicles.* Wokingham: TRL.

# Appendix C. Injury criteria and associated performance limits

## C.1 Hybrid III three year old dummy

| **Injury assessment criteria** | **Value** | **Source** |
|---|---|---|
| 15-ms HIC | 570 | Eppinger *et al.*, 2000 |
| | 568 | Mertz *et al.*, 2003 |
| 36-ms HIC | 1,000 | FMVSS 213 |
| | 1,000 | Kleinberger *et al.*, 1998 |
| Head acceleration – peak (g) | 175 | Mertz *et al.*, 2003 |
| Head acceleration – 3 ms (g) | | No limit found |
| Neck flexion moment (Nm) | 42 | Mertz *et al.*, 2003 |
| Neck extension moment (Nm) | 21 | Mertz *et al.*, 2003 |
| Neck axial tension (N) | 1,430 | Eppinger *et al.*, 2000 |
| | 1,430 | Mertz *et al.*, 2003 |
| Neck axial compression (N) | 1,380 | Eppinger *et al.*, 2000 |
| | 1,380 | Mertz *et al.*, 2003 |
| Neck fore/aft shear (N) | 1,070 | Mertz *et al.*, 2003 |
| Chest compression (mm) | 34 | Eppinger *et al.*, 2000 |
| | 28 | Mertz *et al.*, 2003 |
| Chest compression rate (m/s) | 8.5 | Mertz *et al.*, 2003 |
| Chest acceleration – 3 ms (g) | 55 | Eppinger *et al.*, 2000 |

## C.2 Hybrid III six year old dummy

| Injury assessment criteria | Value | Source |
|---|---|---|
| 15-ms HIC | 700 | Eppinger *et al.*, 2000 |
| | 723 | Mertz *et al.*, 2003 |
| 36-ms HIC | 1,000 | FMVSS 213 |
| | 1,000 | Kleinberger *et al.*, 1998 |
| Head acceleration – peak (g) | 189 | Mertz *et al.*, 2003 |
| Head acceleration – 3 ms (g) | | No limit found |
| Neck flexion moment (Nm) | 60 | Mertz *et al.*, 2003 |
| Neck extension moment (Nm) | 30 | Mertz *et al.*, 2003 |
| Neck axial tension (N) | 1,890 | Eppinger *et al.*, 2000 |
| | 1,890 | Mertz *et al.*, 2003 |
| Neck axial compression (N) | 1,820 | Eppinger *et al.*, 2000 |
| | 1,820 | Mertz *et al.*, 2003 |
| Neck fore/aft shear (N) | 1,410 | Mertz *et al.*, 2003 |
| Chest compression (mm) | 40 | Eppinger *et al.*, 2000 |
| | 31 | Mertz *et al.*, 2003 |
| Chest compression rate (m/s) | | No limit found |
| Chest acceleration – 3 ms (g) | 60 | Eppinger *et al.*, 2000 |

## C.3 Hybrid III ten year old dummy

| Injury assessment criteria | Value | Source |
|---|---|---|
| 15-ms HIC | 741 | Mertz *et al.*, 2003 |
| 36-ms HIC | 1,000 | NHTSA, 2005 |
| Head acceleration – peak (g) | 190 | Mertz *et al.*, 2003 |
| Head acceleration – 3 ms (g) | | No limit found |
| Neck flexion moment (Nm) | 78 | Mertz *et al.*, 2003 |
| Neck extension moment (Nm) | 40 | Mertz *et al.*, 2003 |
| Neck axial tension (N) | 2,290 | Mertz *et al.*, 2003 |
| Neck axial compression (N) | 2,200 | Mertz *et al.*, 2003 |
| Neck fore/aft shear (N) | 1,710 | Mertz *et al.*, 2003 |
| Chest compression (mm) | 44 | NHTSA, 2005 |
| | 36 | Mertz *et al.*, 2003 |
| Chest compression rate (m/s) | 8.4 | Mertz *et al.*, 2003 |
| Chest acceleration – 3 ms (g) | 60 | NHTSA, 2005 |

## C.4 References

**Eppinger R, Sun E, Kuppa S and Saul R (2000).** *Supplement: development of improved injury criteria for the assessment of advanced automotive restraint systems II.* Washington DC: National Highway Traffic Safety Administration, US Department of Transportation.

**Kleinberger M, Sun E, Eppinger R, Kuppa S and Saul R (1998).** *Development of improved injury criteria for the assessment of advanced automotive restraint systems.* Washington DC: National Highway Traffic Safety Administration, US Department of Transportation.

**Mertz H J, Irwin A L and Prasad P (2003).** *Biomechanical and scaling bases for frontal and side impact injury assessment reference values.* Proceedings of the 47th Stapp Car Crash Conference. Warrendale, PA: Society of Automotive Engineers, pp. 155-188.

**NHTSA (2005).** *Federal motor vehicle safety standards: child restraint systems. Notice of proposed rulemaking.* Docket No. NHTSA-2005-21245. Washington DC: National Highway Traffic Safety Administration, US Department of Transportation.

# Appendix D. Test results

The following pages summarise the key test results for each of the two impact conditions examined in the test programme. Each test is defined further in the relevant section of the main body of the report.

## D.1 M1 and M2 forward facing test results

| Wheelchair | Backrest angle | Dummy | Head res. 3 ms | Upper neck shear force | | Upper neck axial force | | Upper neck moment | | Chest | | Lumbar spine comp. | Pelvis res. 3 ms | Diag. belt force |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Fore | Aft | Tens. | Comp. | Flex. | Ext. | Res. 3 ms | Comp. | | | |
| | | | g | kN | kN | kN | kN | Nm | Nm | g | mm | kN | g | kN |
| M1 vehicle seat and child restraint | | 3 year old | 62 | 0.03 | 0.93 | 1.20 | 0.07 | 8 | 21 | 48 | 34 | 0.27 | 50 | No record |
| M2 vehicle seat and child restraint | | | 71 | 0.09 | 1.21 | 1.62 | 0.36 | 25 | 25 | 56 | 32 | 0.59 | 60 | No record |
| M2 vehicle seat | | | 84 | * | 0.80 | 2.20 | * | 19 | 31 | 48 | 27 | 0.46 | 57 | 2.74 |
| Buggy – supportive | Reclined | | 113 | 0.04 | 2.33 | 4.22 | 0.06 | 26 | 33 | 53 | 35 | 0.16 | 54 | 2.14 |
| Manual – basic | Upright | | 59 | 0.07 | 1.29 | 2.17 | 0.03 | 12 | 21 | 43 | 26 | 0.37 | 53 | 1.20 |
| | Upright (M1) | | 68 | 0.07 | 1.64 | 2.40 | 0.05 | 19 | 31 | 54 | 31 | 0.84 | 45 | 2.10 |
| Supportive seating unit | Upright | | 48 | 0.02 | 0.77 | 1.28 | 0.02 | 7 | 20 | 42 | 39 | 0.49 | 41 | 1.42 |
| | Tilted | | 73 | 0.10 | 1.32 | 2.31 | 0.03 | 17 | 22 | 41 | 27 | 0.07 | 52 | 2.74 |
| | Tilted (guide) | | 70 | 0.07 | 1.32 | 2.13 | 0.07 | 30 | 20 | 42 | 22 | 0.24 | 41 | 1.78 |
| | Tilted (5 pt) | | 72 | 0.09 | 0.36 | 1.34 | 0.26 | 16 | 10 | 30 | 8 | 1.37 | 41 | N/A |
| M2 vehicle seat | | 6 year old | 93 | 0.05 | 0.82 | 3.04 | 0.42 | 20 | 54 | 54 | 39 | 0.12 | 64 | 5.24 |
| Buggy – basic | Reclined | | 83 | 0.02 | 0.83 | 2.57 | 0.04 | 9 | 27 | 43 | 17 | 0.07 | 47 | 4.60 |
| Buggy – supportive | Upright | | 87 | 0.66 | 0.90 | 4.80 | 0.02 | 37 | 40 | 56 | 36 | 0.67 | 59 | 5.54 |
| Electric | Upright | | 79 | 0.13 | 0.80 | 2.57 | 0.08 | 22 | 30 | 76 | 29 | 3.35 | 87 | 4.18 |
| Manual – basic | Reclined | | 103 | 0.11 | 1.03 | 4.40 | 0.03 | 19 | 42 | 47 | 36 | 0.07 | 42 | 4.65 |
| | Reclined | | 73 | 0.07 | 0.68 | 3.31 | 0.09 | 17 | 26 | 39 | 23 | 1.16 | 40 | 3.63 |

*The neck load cell developed a fault during this test; however, the fault occurred after the main loading phase.

## D.1 M1 and M2 forward facing test results (continued)

| Wheelchair | Backrest angle | Dummy | Head res. 3 ms | Upper neck shear force | | Upper neck axial force | | Upper neck moment | | Chest | | Lumbar spine comp. | Pelvis res. 3 ms | Diag. belt force |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Fore | Aft | Tens. | Comp. | Flex. | Ext. | Res. 3 ms | Comp. | | | |
| | | | g | kN | kN | kN | kN | Nm | Nm | g | mm | kN | g | kN |
| M2 vehicle seat | | 10 year old | 88 | 0.16 | 1.19 | 4.32 | 0.89 | 36 | 58 | 50 | 28 | 1.07 | 48 | 4.71 |
| Buggy – basic | Upright | | 64 | 0.11 | 0.99 | 2.85 | 0.26 | 29 | 33 | 45 | 20 | 0.72 | 46 | 3.82 |
| Electric | Upright | | 84 | 0.14 | 1.63 | 4.23 | 0.12 | 14 | 45 | 44 | 27 | 0.89 | 35 | 2.73 |
| Manual – active | Upright | | 84 | 0.32 | 1.19 | 3.63 | 0.40 | 37 | 52 | 41 | 34 | 0.50 | 40 | 2.14 |
| Manual – basic | Upright | | 75 | 0.14 | 1.11 | 3.47 | 0.03 | 43 | 54 | 45 | 23 | 0.28 | 42 | 2.66 |
| Supportive seating unit | Upright | | 59 | 0.09 | 1.24 | 2.76 | 0.06 | 5 | 37 | 47 | 37 | 0.45 | 35 | 3.11 |
| | Upright (5pt) | | 33 | 0.04 | 0.51 | 1.09 | 0.06 | 10 | 26 | 28 | 17 | 1.14 | 39 | N/A |
| | Tilted | | 93 | 0.01 | 1.54 | 4.90 | 0.07 | 32 | 55 | 47 | 28 | 0.03 | 48 | 3.98 |

## D.2 M1 and M2 rear facing test results

| Wheelchair | Backrest angle | Dummy | Head | | Upper neck shear force | | Upper neck axial force | | Upper neck moment | | Chest | Lumbar spine comp. | Pelvis res. 3 ms |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Res. 3 ms | $HIC_{36}$ | Fore | Aft | Tens. | Comp. | Flex. | Ext. | Res. 3 ms | | |
| | | | g | | kN | kN | kN | kN | Nm | Nm | g | kN | g |
| Vehicle seat | N/A | 3 year old | 102 | 717 | 0.32 | 0.15 | 0.58 | 0.42 | 23 | 3 | 50 | 0.31 | 65 |
| Manual – basic | Upright | | 124 | 3982 | 0.63 | 0.34 | 2.54 | 0.53 | 28 | 20 | 51 | 0.48 | 55 |
| Supportive seating unit | Upright | | 141 | 2239 | 1.20 | 0.31 | 2.20 | 1.07 | 77 | 12 | 148 | 1.09 | 113 |
| | Tilted | | 77 | 585 | 0.12 | 0.98 | 0.56 | 0.19 | 14 | 46 | 87 | 0.67 | 117 |
| Vehicle seat | N/A | 6 year old | 124 | 1152 | 1.77 | 0.13 | 1.99 | 1.44 | 70 | 10 | 59 | 0.30 | 44 |
| Buggy – supportive | Upright | | 99 | 657 | 0.70 | 0.65 | 3.80 | 1.10 | 109 | 42 | 69 | 0.62 | 72 |
| | Reclined | | 123 | 949 | 0.28 | 0.18 | 1.37 | 0.40 | 33 | 10 | 70 | 1.08 | 88 |
| Electric | Upright | | 55 | 350 | 0.50 | 1.06 | 1.71 | 0.40 | 36 | 88 | 46 | 0.75 | 42 |
| Vehicle seat | N/A | 10 year old | 127 | 922 | 1.19 | 0.32 | 3.22 | 1.29 | 140 | 29 | 52 | 3.02 | 77 |
| Buggy – basic | Upright | | 114 | 1482 | 1.02 | 1.25 | 7.82 | 0.88 | 88 | 76 | 74 | 2.88 | 67 |
| | Reclined | | 105 | 825 | 0.93 | 0.70 | 1.83 | 0.60 | 92 | 64 | 70 | 3.15 | 200 |
| Electric | Upright | | 83 | 399 | 0.35 | 0.18 | 0.93 | 0.55 | 28 | 34 | 53 | 3.20 | 49 |
| Manual – active | Upright | | 134 | 973 | 0.97 | 1.50 | 2.50 | 0.70 | 99 | 86 | 77 | 1.78 | 64 |
| Manual – basic | Upright | | 120 | 1161 | 0.94 | 1.44 | 2.10 | 1.10 | 88 | 100 | 68 | 5.57 | 54 |
| Supportive seating unit | Upright | | 69 | 467 | 0.81 | 0.34 | 2.28 | 0.70 | 64 | 35 | 57 | 1.31 | 40 |
| | Tilted | | 63 | 265 | 0.17 | 0.34 | 1.93 | 0.51 | 27 | 12 | 74 | 5.24 | 100 |

# The safety of child wheelchair occupants in road passenger vehicles

This TRL Report presents the findings of a study carried out by TRL for the UK Department for Transport (DfT). The aim of the study was to examine the safety of children in wheelchairs in road passenger vehicles. The key question was whether children who remain seated in their wheelchairs are afforded a level of protection that is comparable to that for children travelling in a vehicle based restraint system.

The study comprised a number of elements leading to a dynamic sled test programme with instrumented child dummies. The research found that children in wheelchairs do not receive a level of protection that is comparable to that for children in child restraints or vehicle seats. Changes in legislation are therefore required to address and hence improve their protection. There are three key influences: the vehicle, the restraint system and the wheelchair. All three areas must be addressed for improvements in protection to be made, and for the greatest improvements, vehicle, restraint system and wheelchair manufacturers must work together.

**Related publications**

| | |
|---|---|
| **TRL559** | Review of the road safety of disabled children and adults. K Williams, T Savill and A Wheeler. 2002 |
| **PPR076** | Development of measures for improving child protection in minibuses, buses and coaches. G J L Lawrence and W M S Donaldson. 2006 |
| **CT22.4** | Transport for the elderly and disabled update (2004-2007) |
| **CT111.2** | Taxi and paratransit update (2001-2005) |
| **TRF8** | The safety of wheelchair occupants in road passenger vehicles. M Le Claire, C Visvikis, C Oakley, T Savill and M Edwards. 2003 |

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