The safety of wheelchair occupants in road passenger vehicles

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Prepared for Mobility and Inclusion Unit, Department for Transport

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Abstract

The work described in this report has been carried out on behalf of the UK Department for Transport by TRL Limited. The aim of the work was to assess the safety of wheelchair users when being transported on all M category vehicles in comparison with travellers seated in conventional seats (fitted with headrests). In cases where the safety of the wheelchair user was lower than that of other passengers, or considered unacceptable for other reasons, modifications were assessed.

The approach to the work involved a programme of numerical simulation followed by an extensive programme of testing involving 37 individual sled impact tests. In addition, the safety of passengers under normal transit conditions was addressed.

The work found that the heads and necks of wheelchair users were particularly vulnerable but that this could be addressed through the use of a head and back restraint. However, such a restraint should meet the requirements of ECE Regulation 17 for strength and energy absorption and the wheelchair should fit well up against the head and back restraint for maximum benefit.

Further recommendations from the work were that an upper anchorage location for diagonal restraints is preferable to a floor mounted location and that the restraint anchorages should meet more rigorous strength requirements than are required at present. A protected space envelope for forward facing wheelchair passengers is also recommended.

Under normal transit conditions a vertical stanchion is preferable to a horizontal bar in terms of preventing excessive movement of the wheelchair.

Glossary of Terms

EC	European Commission
ECE	Economic Commission for Europe
DfT	Department for Transport
TRL	Transport Research Laboratory
MDA	Medical Devices Agency
PSV	Public Service Vehicle
DDA	Disability Discrimination Act
C&U	Road Vehicles (Construction and Use) Regulations 1986
PSVAR	Public Service Vehicles Accessibility Regulations 2000
ISO	International Standards Organisation
EC WVTA	EC Whole Vehicle Type Approval
DPTAC	Disabled Persons Transport Advisory Committee (– the Government's statutory adviser on the transport needs of disabled people)
COST	Co-operation in the field of Scientific and Technical Research
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
MPV	Multi Purpose vehicle
EuroNCAP	European New Car Assessment Programme
NIC	Neck Injury Criteria
DRTF	TRL's Dynamic Restraint Test Facility
FE	Finite Elements
MADYMO	Proprietary 'Multi-body' Numerical Modelling Code
ATF	Aluminium Track Fittings
RAGB	Road Accidents in Great Britain Report

Executive Summary

Over recent years a number of legislative tools and codes of practice have been put in place to provide wheelchair users with greater access and freedom of use of public transport. Such regulations range from guidelines issued by national Governments, with the UK Government taking a lead role, to full EC directives. While these positive steps have achieved the aim of providing a greater choice and freedom of transport use to wheelchair users, the issue of safety in the event of an accident has not been rigorously assessed in a consistent manner across the various categories of road vehicles available to this group of travellers.

This project, commissioned by the UK Department for Transport, aimed to address the safety of adult wheelchair users in M1, M2 and M3 vehicles, i.e. private vehicles, taxis, minibuses, coaches and urban buses. The objective was to make recommendations for requirements on these categories of vehicles that would provide wheelchair users with at least an equivalent level of protection as a passenger seated in a conventional seat (fitted with a headrest) in the event of an accident. In addition, the security of carriage of a wheelchair user in an urban bus under normal operating conditions was also investigated.

The project tackled these issues firstly through a programme of numerical simulation, validated against a limited number of physical tests, the results of which helped to define a wide ranging testing programme. Initial work reviewing suitable test conditions indicated that the scope of vehicles could be addressed by examining 4 sets of conditions:

- Forward facing wheelchair users in M1 or M2 category vehicles.
- Rearward facing wheelchair users in M1 or M2 category vehicles.
- Forward facing wheelchair users in M3 category vehicles.
- Rearward facing wheelchair users in M3 category vehicles.

The protection provided for passengers was tested using conventional automotive crash test dummies, and the risk of injury assessed using the usual injury criteria derived from the dummy outputs. In each case a conventionally seated passenger configuration was tested to determine a comparable level of protection for the wheelchair seated occupant.

M1 and M2 vehicles were able to be considered together as previous research has shown that the same deceleration pulse is appropriate for the majority of both categories.

The modelling work indicated that the most influential parameters on the safety of wheelchair passengers are the location of the diagonal belt upper anchorage (i.e. upper location or floor level), the presence or otherwise of a head and back restraint and the closeness of fit between the wheelchair and the head and back restraint if fitted.

For forward facing occupants in M1 and M2 category vehicles it was apparent that some injury criteria such as head displacement and lumber spine compression were better for the wheelchair occupant than the conventionally seated occupant, however neck loads in particular were higher. The addition of a head and back restraint was found to improve the situation significantly, although the presence of a gap between the head and back restraint and the wheelchair had a detrimental effect. Any such head and back restraint should be compliant with the strength and energy absorption requirements of ECE Regulation 17. In general, an upper anchorage was preferable to a floor mounted anchorage.

Rear facing wheelchair passengers in M1 and M2 vehicles were found to be greatly more at risk than equivalent vehicle seated passengers, particularly in terms of neck and spine loads, the situation being worse still for both smaller and larger than average persons. Again, the situation was mitigated through use of a head and back restraint compliant with ECE Regulation 17, assuming a minimal gap between the wheelchair and the head and back restraint and a minimum horizontal strength requirement of 100kN.

The situation for forward facing passengers in M3 vehicles was similar to that for M1 and M2 vehicles, and the findings were also similar in that a head and back restraint was of benefit (compliant with ECE Regulation 17) with no gap and an upper belt anchorage.

Rear facing wheelchair passengers in M3 vehicles fitted with a back restraint not intended to provide crash protection, were found to be subject to unacceptably high head accelerations. The use of a head and back restraint compliant with Regulation 17 resolved the issue.

In all cases the anchorage loads were recorded and recommendations made for requirements on the anchorage strength in vehicles of each category. Likewise, occupant space requirements were derived from the dummy excursions for forward facing occupants.

The normal transit tests revealed that a vertical stanchion provides a better restraint on excessive wheelchair movement than does a horizontal bar. However, the tests only used a single type of wheelchair and hence any conclusions should consider the potential interaction of these systems with other wheelchair types.

The findings from this work have been developed into a set of recommendations for each category of vehicle which may form the basis for changes to regulations at the discretion of DfT.

1 Introduction

The work described in this report was carried out by TRL Limited under contract to the Mobility and Inclusion Unit of the DfT. The test work took place over a 12 month period from 2001 to 2002 and examined, using both numerical simulation and physical testing, the requirements that should be made of a vehicle such that wheelchair users might be transported without being placed at an unreasonable risk of injury in the event of an accident. The work was overseen by a Steering Committee that comprised representatives from DfT, TRL, a wheelchair tie-down and occupant restraint manufacturer, PSV operator and the Medical Devices Agency (MDA).

While there are a number of regulations and codes of practice that impinge upon the travelling wheelchair user, a definitive programme of work specifically addressing the situation has not been undertaken previously. This work therefore aims to address this deficiency and provide the necessary background understanding as to the safety of wheelchair users in the event of an impact. In making recommendations on the basis of the work carried out, the existing requirements must be considered and any conclusions made in the context of the current regulatory framework.

1.1 Existing regulatory framework

In recent years, there have been significant advances in the availability of accessible transport. Accessibility regulations drafted under the Disability Discrimination Act (1995) will ultimately ensure that all forms of land-based public transport are accessible to wheelchair users and will require operators to provide for people who cannot transfer from their wheelchair into a vehicle seat.

The Road Traffic Act 1988 and the Public Passenger Vehicles Act 1981 (as amended by the Road Traffic Act 1991) provide the framework for most of the important provisions relating to the use of motor vehicles on roads in the United Kingdom. Section 40A of the 1988 Act states that a person is guilty of an offence if a danger or injury is caused to any person because of, for example, the manner in which passengers are carried or the load is secured in a vehicle. The Road Vehicles (Construction and Use) Regulations 1986 (C&U), as amended, govern the construction, equipment, maintenance and use of road vehicles. In addition, buses and coaches that are public service vehicles must comply with the Public Service Vehicles (Conditions of Fitness, Equipment, Use and Certification) Regulations 1981. Neither of these regulations provides requirements for the carriage of passengers in wheelchairs. However Regulation 100 of C&U requires that all passengers be carried in a manner such that ‘no danger is caused to any person’. This generally refers to latent defects or, for example, unsecured loads. However it could be interpreted that if a wheelchair is not secured and an incident occurs as a result, an offence has been committed.

The Disability Discrimination Act, DDA (1995) aims to tackle discrimination against disabled persons. Part V of the act gives Ministers the powers to establish accessibility regulations that will ensure it is possible for wheelchair users to be carried in safety in land-based public transport whilst remaining in their wheelchair. These powers were first exercised for road vehicles in the form of the Public Service Vehicles Accessibility Regulations 2000 (PSVAR). These require regulated buses and coaches of more than 22 passengers on local or scheduled services to be wheelchair accessible. They list a number of requirements related to the safety of passengers in wheelchairs, including the direction in which they must face in the vehicle, the need for active and passive restraint systems and how these and their anchorages should be tested. The regulations initially apply to new vehicles only, but will apply to all regulated vehicles within 20 years.

Accessibility regulations under PSVAR make requirements of the vehicle only, enabling it to be certified for use. Manufacturers of wheelchairs have been aware of the transport needs of their equipment for some time. This area was recognised in legislation in the form of the Medical Device Regulations (1994), recently updated by the 2002 Regulations. These regulations, in accordance with the Consumer Protection Act (1987), require manufacturers to conduct a full risk analysis process to support the CE marking of their products. As part of this risk assessment, an international standard ISO 7176/19 for the impact testing of wheelchairs is given as supporting evidence of the suitability of a wheelchair to travel in a vehicle. This test is essentially a product test – it tests whether the wheelchair is able to take the loads imposed on it in the event of a road traffic accident - although excursion limits are placed on the dummy. However, it could be argued that, given that instrumented dummies are not used in these tests, it is not known whether the occupant would survive the incident as survivability is a compromise between excursion and accelerations to the body.

A number of wheelchair tie-down and occupant restraint systems are available on the market and these can be tested to International Standard ISO 10542. The test is similar to ISO 7176/19 and uses a ‘surrogate’ wheelchair in each test, defined as a ‘rigid, reusable’ wheelchair that simulates a powered wheelchair for the purposes of testing wheelchair tie-down and occupant restraint systems.

The majority of M1 vehicles (see Section 2.1.2) are subject to EC Whole Vehicle Type Approval (EC WVTA) whereby a vehicle must comply with a number of EC Directives. There are no directives covering provisions for the carriage of a wheelchair in these vehicles. Proposals are also in place to extend EC WVTA to other vehicle types including M2 and M3 vehicles. One of the EC Directives for M2 and M3 vehicles is Directive 2001/85/EC with provisions for the carriage of wheelchairs of which some are based on PSVAR.

Apart from legislation, there is also a long-standing Department for Transport code of practice (VSE 87/1) covering the safety of passengers in wheelchairs on buses. Its application is now limited to buses and coaches not covered by the Public Services Vehicles Accessibility Regulations (2000), ie those vehicles that are public service vehicles and require a certificate of initial fitness but are not used on local or scheduled services (eg touring coaches and community transport). It recommends that every wheelchair should be secured in the vehicle and it sets performance requirements for such equipment.

In addition, the Disabled Persons Transport Advisory Committee (DPTAC – the Government's statutory adviser on the transport needs of disabled people) produced The Recommended Specification for Buses Used to Operate Local Services in 1988, revised 1995. With the development of low floor vehicles, DPTAC produced a new bus specification in 1997 to complement the existing one, and to cover features required for fully accessible vehicles. It is the view of DPTAC that the PSVAR and the Department for Transport's associated guidance document supercede the above DPTAC specifications. However, the PSVAR does not apply to vehicles with fewer than 23 passengers and therefore in December 2001 DPTAC issued their Accessibility Specification for Small Buses designed to carry 9 to 22 passengers (inclusive).

The 'Department for Transport's Agreed Requirements - guidance notes for Vehicle Examiners' is a development of recommendations by the Vehicle Inspectorate to assist their examiners when considering the requirements appropriate to a particular vehicle. The Agreed Requirements are currently limited to the carriage of unrestrained wheelchairs in vehicles that carry standing passengers and not issued with an Accessibility Certificate under PSVAR. For vehicles without standing passengers and not issued with an Accessibility Certificate, the requirements of VSE 87/1 are applied.

While it is not a regulation, a relevant piece of work was carried out under the 'COST' programme sponsored by the European Commission. The COST programme supports co-ordination of research activities between different organisations, but does not fund the research itself. COST 322 addressed the subject of Low Floor Buses with the key objective of gathering information on current European operational experience in order to draw up guidance on best practice. The report provides guidance for the vehicle, the infrastructure and training, but no recommendations relate specifically to safety in the event of an accident.

ECE Regulation 25 specifies requirements for the strength and energy absorbing qualities of head restraints in vehicles. ECE Regulation 17 contains the same requirements for head restraints but in the context of a document with a wider scope. Hence throughout the report reference will be made to ECE Regulation 17 on the understanding that the two regulations are equivalent in this respect.

1.2 Project aim

The DfT wishes to ensure that an appropriate level of safety is afforded to wheelchair users when travelling on public transport and that their needs are appropriately considered in legislation where necessary. This report summarises the results of a research programme devised to identify their level of safety compared to other passengers seated in the vehicle, and to recommend, where necessary, changes in legislation to improve that safety.

1.3 Scope

The scope of the research project was to compare the level of safety afforded to people seated in their wheelchairs with that afforded to non-disabled people (referred to throughout as ‘vehicle seated occupants’) also sitting in the vehicle. By examining the level of safety intended to be afforded to vehicle seated passengers in the safety and crashworthiness directives and regulations, it is possible to make observations regarding the level of protection afforded to wheelchair users in vehicles. The project covered frontal impacts only to M1, M2 and M3 vehicles.

2 Overview

2.1 Impact protection

2.1.1 Approach

To fulfil the objectives of the project, two distinct but complimentary phases of work were carried out. The first phase, a simulation study, was conducted to identify the main factors that influence the safety of wheelchair users in an accident. This was achieved by performing parameter sweeps of the most influential factors such as the wheelchair type, the occupant size, and the wheelchair restraint type, for each vehicle category considered. In addition, the direction in which occupants face within the vehicles, i.e. rearward or forward facing, was also considered. This study provided the information necessary for determining which dynamic tests to perform during the second phase.

The second phase comprised a series of sled tests to compare the level of protection provided to wheelchair seated occupants in comparison with those occupants in vehicle seats. It is from this research that recommendations for vehicle legislation can be derived.

2.1.2 Vehicles

The project considered the safety of wheelchair occupants when travelling in M category vehicles which are defined according to the European directive 92/53/EEC. 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.

2.1.3 Crash test pulses

For each vehicle class a crash pulse was chosen to characterise the occupant compartment deceleration in the event of a severe accident. This choice was based on the crash pulses used in current legislative test procedures for vehicle seated occupants and involved close consultation with the DfT. The pulses for each vehicle category are as follows:

M1 Vehicles UN/ECE Regulation 44, Figure 1, (as used for testing child restraint systems). This pulse was selected on the basis that the deceleration corridor is derived from full scale M1 vehicle crash tests. This was verified by comparing the chassis deceleration recorded from various MPVs in the EuroNCAP programme, carried out at TRL.

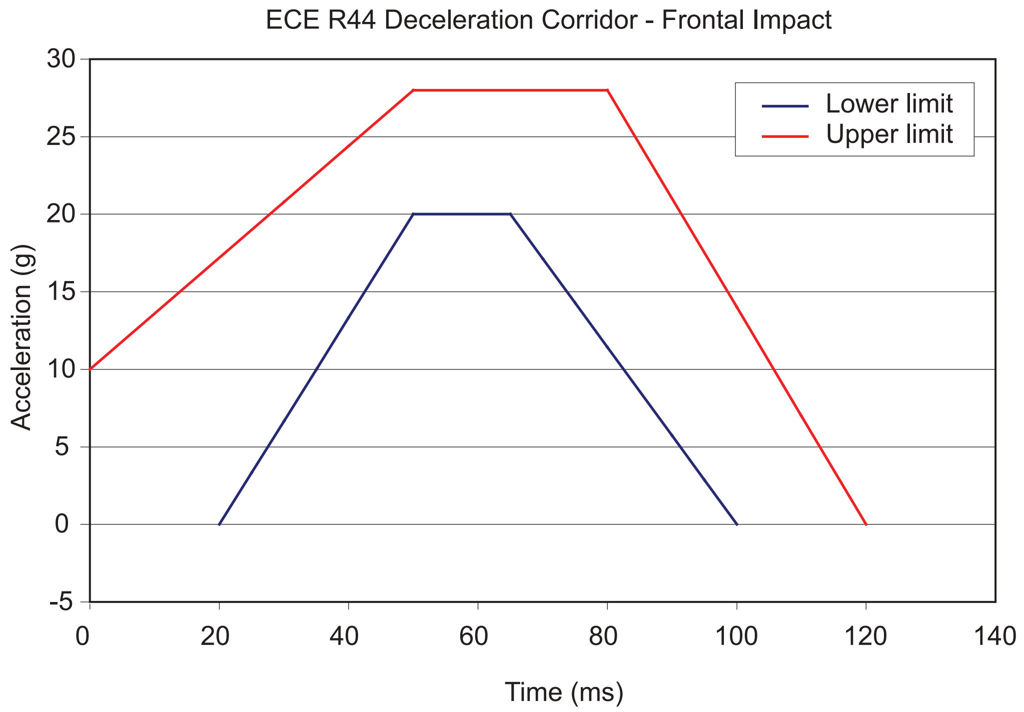

Figure 1 R44 Deceleration corridor

M2 Vehicles UN/ECE R44 as for M1 vehicles.

Based on the results of an accident study, Lawrence (1996) determined that a delta V of 48 km/h addressed 50% of all accidents in which an occupant was fatally or seriously injured. The chassis deceleration during a full-scale monocoque minibus crash test at this velocity, carried out at TRL, was found to be similar to the deceleration corridor in ECE R44. Lawrence therefore recommends that the R44 sled pulse should be used as a basis for sled testing minibus (M2 vehicle) restraint systems. This pulse was taken as representative of all M2 category vehicles.

The test pulse required by ISO 10542 and also PSVAR for M2 vehicles falls within the above corridor in all but one respect: both documents require that 15g is maintained for a minimum of 40ms, which means that an R44 pulse towards the lower bound of the above corridor may not comply with PSVAR.

M3 Vehicles UN/ECE Regulation 80 is used for approval of the seats and their anchorages in large passenger (M3) vehicles. It includes a dynamic test of the seats and Figure 2 shows the deceleration corridor given in the regulation. Being the conventional pulse used for this type of vehicle, it was again applied within this work. It should also be noted that the R80 pulse has been adopted in Directive 96/37 for seat strength.

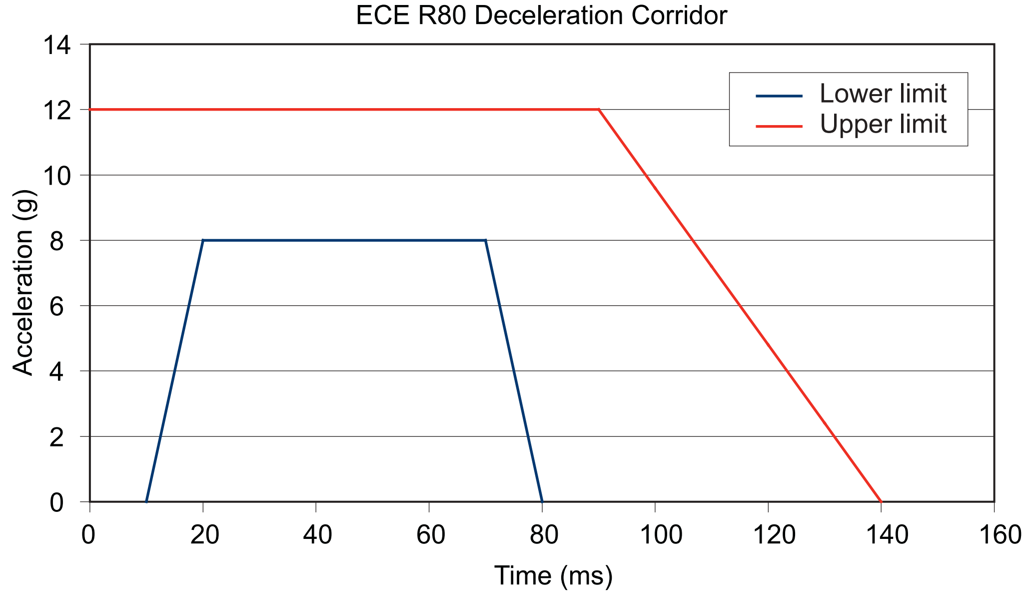

Figure 2 R80 Deceleration corridor

2.1.4 Wheelchair types

Four types of wheelchair design were investigated in the project following advice from the Medical Devices Agency (MDA). The wheelchairs were chosen to reflect the range of masses, stiffnesses and shapes of typical designs. The four wheelchairs selected for testing were:

- A manual wheelchair of relatively low mass (18kg). This was chosen to represent the less stiff and lighter range of wheelchair types.
- An electric wheelchair of mass 57 kg. This was chosen to represent a typical electric wheelchair.
- An electric wheelchair of mass 120 kg. This was chosen to act as a worst case for loading to the anchorages.
- The stiff surrogate wheelchair of mass 85 kg as defined in ISO standard 10542. This wheelchair was chosen because it had a very stiff structure and would provide a worst case in terms of stiffness.

Throughout the remainder of the report these wheelchairs will be referred to as the manual, electric, heavy electric and surrogate wheelchairs, respectively. It was understood that these wheelchairs represented a limited cross section of the available wheelchair designs and that additional design features unaccounted for in these four wheelchairs could affect the results and ultimately the conclusions derived from the investigations. However, it was beyond the scope of the current project to investigate additional wheelchair designs and the proposed selection of chairs was thought to cover the widest range of wheelchair features considered to be of greatest importance in vehicle impacts (i.e. wheelchair mass and stiffness).

The manual wheelchair was a production model, as shown in Figure 3. This is a standard folding wheelchair with a sling canvas seat, weighing 18 kg.

The electric wheelchair was a production model weighing 57 kg as shown in Figure 4. The heavy electric wheelchair was a production model weighing 120 kg, shown in Figure 5. The surrogate wheelchair is described in ISO 10542 part 1 and Appendix D. This wheelchair is regularly used by TRL for dynamic testing of wheelchair restraint systems and is shown in Figure 6.

Figure 3 Manual wheelchair

Figure 4 Electric wheelchair

Figure 5 Heavy electric wheelchair

Figure 6 Surrogate wheelchair

2.1.5 Anthropometric dummy selection

From the Hybrid III family of dummies, the 5th percentile female, the 50th percentile male and the 95th percentile male were selected. These dummies were used to represent the wheelchair occupant for both the modelling and testing work. The reason for this choice was that the Hybrid III family of dummies, and mainly the 50th percentile male, are used for most frontal impact legislative crash testing and hence can be regarded as the current world standard for this type of testing.

It was originally proposed that the BIORID dummy would be used to assess occupant safety in all rear facing impacts as it is more biofidelic than the Hybrid III dummy, having both a flexible spine and a biofidelic flexible neck. However, the BIORID dummy has been specifically designed and tested for impact speeds lower than 25 km/h, whereas the R44 and R80 pulses chosen for the investigations represent impact speeds of 50 km/h and 30 km/h, respectively. Consequently, there were concerns that the BIORID dummy could be damaged if used in these tests and that there would also be difficulties with the interpretation of test results given that the dummy has not been validated at these high impact speeds.

A suggested compromise was to use a Hybrid III dummy with a T-RID neck. However, as with the BIORID dummy, this dummy configuration was designed and validated at medium to low impact speeds. Discussions with the neck developers at TNO established that although the T-RID neck is more biofidelic than the Hybrid III dummy neck at low to medium severity impacts, it would be expected that the response of a restrained T-RID neck will match that of the Hybrid III neck at high impacts. Unrestrained, it is thought that the response of the Hybrid III neck would be more biofidelic than the T-RID neck. As a result of these discussions it was decided that, although not ideal, the complete Hybrid III dummy would be used for the rear facing impact investigations for both the modelling and the testing phases of the project. However, it must be remembered that the HYBRIDIII dummy was developed for forward facing frontal impacts and as such its biofidelity for rear impacts cannot be taken for granted. Hence, any injury criteria values measured for rear impact should be treated with caution as they may not be representative of real injuries.

The tests were carried out using Hybrid III 5th, 50th and 95th percentile dummies. The dummies were fitted with triaxial accelerometers in the head, chest and pelvis and fore/aft accelerometers on the upper and lower neck. The dummies also contained upper neck load cells and a chest potentiometer, and the 50th percentile was fitted with a lumbar spine load cell. In tests where the dummy was restrained by an occupant restraint the belt loads were also recorded. The masses of the dummies are given in Table 1.

Table 1 Hybrid III dummy masses

Dummy	*Mass (kg)*
5th	50
50th	75
95th	100

2.1.6 Injury criteria

A number of injury criteria with associated performance limit values were used to assess the likelihood of the occurrence of injury. These values were used to interpret the results obtained from both the modelling and testing studies. Where available, the criteria and performance limit values for the 50th percentile male were taken from current legislation such as the Directive on frontal impact, 96/79/EC. In order to offer equivalent levels of protection in accidents for wheelchair seated occupants compared with vehicle seated occupants, future vehicle safety legislation will need to specify performance limits that take into consideration the potential loadings on the vehicle from wheelchairs and their restraint systems. Additional criteria, especially for the 5th and 95th percentile dummies, were obtained from the literature. A summary of the injury criteria and associated performance limit values is given in Appendix 1.

The Neck Injury Criteria (NIC) was considered for assessing the potential for whiplash injuries in the neck under rear impact. However, because of the high severity of the impacts used in this project, it was found that NIC would not be suitable as it is generally only applicable for low to medium severity rear impacts. In addition, no current legislation uses the Neck Injury Criterion. In the absence of injury criteria for high speed rear impacts and because this was a comparative study, the injury criteria for the Hybrid III under frontal impact were used.

2.1.7 Impact test equipment

The Dynamic Restraint Test Facility (DRTF), at TRL, was used for the test programme. The DRTF comprises a rail mounted sled which is accelerated by elastic cords and decelerated by polyurethane deceleration tubes and olives. Dummy signal data was recorded by a Kayser-Threde data acquisition system. The data were analysed to ISO 6487 (2000).

Kinematic motion of both dummy and sled set up throughout the event were recorded using high speed video equipment (1000 fps) and two high speed cine cameras (400 fps). One camera showed the lateral view of the dummy at the point of impact and during its subsequent motion. The additional camera, where possible, showed the longitudinal view.

2.1.8 Simulation

All of the computer models used for the project were developed and run under MADYMO version 5.4.1. MADYMO is a proprietary software package which analyses the dynamic response of moving systems through the idealisation of the structure into rigid and flexible bodies connected by joints. Surfaces can be attached to these bodies which can then be used to show how the bodies interact with each other. MADYMO also has the capacity to utilise Finite Elements (FE), whereby the structure is divided into many shapes that are subject to certain conditions or limitations in order to represent the surface structure of an object more accurately. The programme uses the equations of motion to calculate the dynamic interaction and the forces involved. MADYMO is recognised internationally as ‘state of the art’ and is widely used in the automotive industry for the simulation of occupant kinematics.

For all the models, contact stiffnesses were defined between:

- The wheelchair and the ground.
- The dummy and the wheelchair.
- Wherever contact occurred between:
  - the vehicle interior and the dummy;
  - the vehicle interior and the wheelchair.

Where experimental data was lacking, the contact stiffnesses were either estimated or derived from other MADYMO models.

2.2 Non impact protection

2.2.1 Background

TRL has previously conducted a field study of longitudinal and lateral accelerations on buses. Accelerations were measured on a range of vehicles over routes known to be particularly difficult to negotiate. Lateral accelerations over 0.2g were recorded on all the journeys in the study and in 18% of cases, accelerations over 0.35g were measured. In a few instances the acceleration exceeded 0.4g.

In general, the larger buses sustained fewer lateral accelerations over 0.35g, and low floor buses were marginally better than conventional buses.

2.2.2 Approach

A study was undertaken as part of this project to determine the extent of wheelchair movement on board a large bus (M3) under normal driving conditions, i.e. non-impact conditions.

2.2.3 Vehicle

An 11.5 m long Optare Excel, which is compliant with the Public Service Vehicles Accessibility Regulations 2000, was used for these tests. The regulations allow the wheelchair user to travel unrestrained in a rear facing position against a head and back restraint.

2.2.4 Driving conditions

The vehicle was driven in a semicircle with a radius of 20 metres, at a velocity of 38 – 40 kilometres per hour.

2.2.5 Wheelchair types

The wheelchair used for these experiments was the PSVAR reference chair.

3 M1 and M2 forward facing

3.1 Simulation study

Twenty-eight analyses of the numerical model were carried out as described in Appendix 2. Various combinations of wheelchair, dummy size and restraint system were examined along with an investigation into the influence of the deceleration level within the ECE R44 corridor.

The results suggested that a floor anchored occupant restraint might be less favourable, compared with an upper anchorage location. This was based on both the dummy kinematics and the predicted occupant loading during the impact. When using the floor mounted restraint, the upper body rotated forwards about the waist, resulting in a high head excursion and in some cases head contact with the legs. In general, the dummy forces and accelerations were higher also, and there were more instances where the injury limits were exceeded.

There was not a significant difference in the dummy load levels between different wheelchairs. The method of wheelchair restraint was also found to have little effect, although greater wheelchair excursion was predicted when clamps were used.

The simulations predicted that dummy excursion and loading were linked to occupant size. In general, analyses with the Hybrid III 95th percentile predicted the highest values of these parameters, but the injury limits for this dummy were also greater and so the higher readings did not necessarily indicate greater injury risk.

Finally, equivalent models were subjected to two different deceleration pulses, both within the ECE R44 corridor. The results indicated that although the R44 corridor allows for acceleration variations of up to 8g, differences of only 5g in the peak deceleration level could noticeably affect the predicted dummy loads. This finding should be borne in mind when interpreting the predictions.

3.2 Scope of testing

To further investigate forward facing occupants in M1 and M2 category vehicles a series of dynamic tests were carried out. The findings from the simulation work were considered when planning the test programme.

The primary objective for the test series was to assess whether the wheelchair seated occupant was provided with an equivalent level of safety as the vehicle seated occupant, through the use of instrumented dummies to compare the loading on the occupant.

In addition to this, the effect of diagonal belt anchor location was examined. The simulation work suggested that use of a floor anchored occupant restraint could have a negative effect on occupant protection when compared with an upper anchorage location. It was therefore necessary to revisit this issue in the test series.

The effects of a head and back restraint were also investigated to determine whether this could improve the protection for the occupant with respect to neck extension and movement in rebound.

The occupant space required within the vehicle was also assessed along with the loads that the vehicle anchorages would be required to withstand, in order to set requirements for vehicles.

3.3 Test design

In order to investigate M1 and M2 vehicle requirements eight sled tests with various set ups were carried out.

3.3.1 Occupant loading

Six of the eight tests investigated occupant loading. A vehicle seated baseline test was completed for comparative purposes using a Hybrid III 50^{th} percentile dummy in a commercially available seat that incorporated a three-point occupant restraint and head restraint integrated into the seat. This is shown in Figure 7. Figure 8 shows a typical set up for the wheelchair seated occupant.

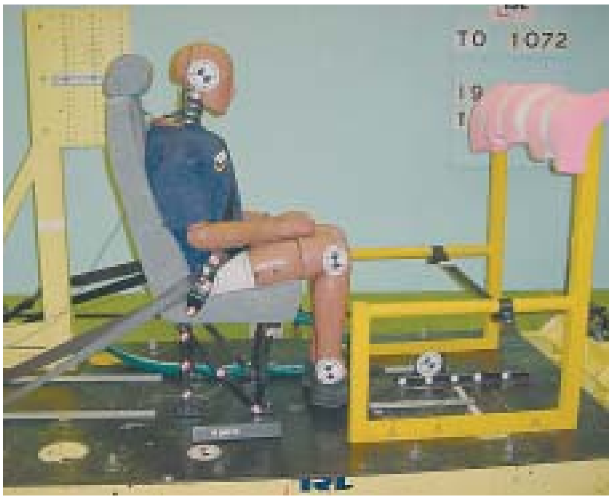

Figure 7 M1 and M2 forward facing – vehicle seated

Figure 8 M1 and M2 forward facing – wheelchair seated

3.3.2 Vehicle loading

Two tests investigated the loadings to the vehicle anchorage systems. Two different occupant restraint anchorage locations were used, one floor and one upper, and the wheelchair was restrained with a four point tie-down. In order to create the worse case situation for the vehicle anchorages the heavy electric wheelchair was used with the 95^{th} percentile dummy. These set ups are shown in Figure 9 and Figure 10.

Figure 9 Set up with upper anchorage location for diagonal occupant restraint

Figure 10 Set up with floor anchorage location for diagonal occupant restraint

3.3.3 Sled configuration

The vehicle environment for a minibus and taxi was represented on the sled. A production model minibus seat was used for the vehicle seated occupant test which incorporated an integrated 3-point restraint system.

The wheelchairs were restrained by a four point webbing tie-down secured to the floor by purpose designed Aluminium Track Fittings (ATF). The dummy was restrained independently by a lap and diagonal inertia restraint in all tests. Two types of wheelchair occupant restraint were investigated to compare the effects of different shoulder belt anchor locations. These were anchored to either an upper location or the floor.

The test set up for measurement of the restraint anchorage loading required additional instrumentation adjacent to all anchor locations in order to record the forces generated during the impact. Markers were positioned to enable measurement of the restraint angles at peak loading.

All wheelchair tie-down and occupant restraints were installed according to the manufacturer’s instructions and the ISO standards.

Table 2 details the various test configurations used for the forward facing M1 and M2 vehicle research.

3.4 Findings

3.4.1 Relative safety of current situation (Tests 1, 2 and 3)

In order to compare the safety of the wheelchair seated occupants with the safety of the vehicle seated occupants the occupant loadings have been expressed as a percentage of the injury threshold values. Where there are no injury criteria limits the vehicle seated results have been used as a base line (i.e. 100%), these results are shown in Table 3.

Table 2 Test matrix – M1 and M2 forward facing

Test	*Dummy seating position*	*Wheelchair tie-down*	*Dummy*	*Occupant restraint diagonal belt anchorage location*	*Head / back restraint*
1	Minibus seat	N/A	Hybrid III 50th	Integral 3 point	N/A
2	Manual wheelchair	4 point webbing	Hybrid III 50th	Floor	No
3	Manual wheelchair	4 point webbing	Hybrid III 50th	Upper	No
4*	Manual wheelchair	4 point webbing	Hybrid III 50th	Upper	Yes
5	Manual wheelchair	4 point webbing	Hybrid III 50th	Upper	Yes
6	Manual wheelchair	4 point webbing	Hybrid III 50th	Upper	With gap
7	Heavy electric wheelchair	4 point webbing	Hybrid III 95th	Upper	No
8	Heavy electric wheelchair	4 point webbing	Hybrid III 95th	Floor	No

* *On test 4 the wheelchair collapsed, requiring a repeat test (test 5). Test 5 used a different head and back restraint however.*

The various parameters measured such as loads on the dummy, accelerations and excursions, would not be expected to be completely independent. For instance, if an occupant, whether seated in a wheelchair or not, is more securely restrained, then the accelerations seen by that occupant would be closer in magnitude to the high accelerations of the sled (or vehicle) than those of a more loosely restrained occupant who would experience lower accelerations due to the greater flexibility of the restraint. Higher accelerations imply higher forces to generate those accelerations, although lower excursions would also result. Hence the performance of a restraint system implies balance between accelerations and loads (which can be harmful) against extent of excursion (which can also be harmful). A decrease in one of these will usually imply an increase in the other.

Table 3 Injury criteria comparison

	50%ile	*Vehicle seated*	*Wheelchair seated/ tie downs + upper anchorage*	*Wheelchair seated/ tie downs + floor anchorage*
Head acceleration	80g	67%	78%	62%
Head displacement	650mm	103%	70%	94%
Lumbar spine compression	Vehicle seated baseline	100%	35%	60%
Neck flexion moment	190Nm	40%	56%	52%
Neck extension moment	57Nm	42%	44%	64%
Chest	60g	64%	70%	56%
Diagonal belt	7kN	96%	132%	103%
Lap belt loading	Vehicle seated baseline	100%	89%	66%

In general for this series of tests, the wheelchair occupant was found to be at a higher level of risk than a vehicle seated occupant, but not in all areas. The head acceleration, neck moment and chest loading measurements were all higher for the wheelchair occupant, but the head displacement, lumbar load and lap belt loading were all lower. These results would be expected in any system which results in lower excursions at the cost of higher belt loads and greater occupant accelerations as described above.

When comparing the wheelchair seated condition with the vehicle seated condition, the occupant with the diagonal part of the occupant restraint anchored at the upper location underwent greater head accelerations than the vehicle seated occupant, however the head accelerations were all below the injury criteria limits. The head displacement of the vehicle seated occupant exceeded the threshold by 3% whereas the wheelchair seated occupants were within the limits. It was also noted that the head displacement of the occupant with the diagonal belt anchored at the upper location, was much lower than both the vehicle seated occupant and the wheelchair seated occupant with the diagonal belt anchored to the floor.

The injury criteria limits for chest acceleration were not exceeded by any occupants, however the wheelchair seated occupant with the diagonal belt anchored at the upper location received greater chest accelerations than the vehicle seated occupant. This would be expected as the vehicle seated occupant exceeded the head displacement limit and the wheelchair seated occupant was restrained more securely in this case with lower head displacements. The greater security of restraint was due to the conventional seat's upper anchorage being fixed to the seat itself. This allowed the seat to deflect and allow greater flexibility in the restraint system. The occupant restraint, however, is attached to the floor via a guide at the upper location which is a more secure system. Occupant protection is a compromise between the displacement of the body parts (where contact can be made with the vehicle interior) and accelerations caused by restraining the body. This effect is also seen in the loading of the diagonal belt where the wheelchair seated occupants exceeded the injury criteria limit but also had reduced head displacements.

The vehicle seated and wheelchair seated occupants were all within the injury criteria for neck extension, however the injury risk for wheelchair seated occupants was greater than for the vehicle seated occupants.

3.4.2 Effect of restraint geometry (Tests 2 and 3)

When the diagonal section of the occupant restraint was anchored directly to the floor, the dummy was subjected to a downward force that resulted in high loads on the wheelchair, reducing its structural performance. When the test was conducted with the diagonal belt passing through an upper anchorage location this downward force was minimal and the wheelchair did not deform to the same extent.

The upper anchorage location provided better restraint for the torso of the dummy, reducing the head excursion compared with the floor anchored system, where the upper body rotated about the waist. However, because occupant protection is a compromise between displacement and loadings, the head acceleration, chest acceleration and diagonal belt loadings were all greater in the case of the upper anchorage although only the loading to the diagonal belt exceeded the criteria threshold. This outcome indicates that an occupant restraint that is anchored to the upper location is more likely to provide a balanced level of protection between loadings and excursion. It should be considered, however, that in general excursion will be of less concern for a wheelchair seated occupant than a conventionally seated occupant as vehicle interior structure is not usually placed within the excursion zone.

The other important observation that arose when comparing these two occupant restraint systems related to the loadings on the neck and spine. The floor anchored diagonal restraint system generated greater compressive loads on the lumbar spine, and created greater flexion and extension on the neck. A compressive load of 1.58 kN was recorded in the lumbar spine during the floor mounted test and the corresponding figure for the upper anchorage test was 0.92 kN. However, as no injury criteria exist for the Hybrid III lumbar spine, it is not possible to determine whether this would lead to lumbar spine compression fractures.

The results from this comparison show that an occupant restrained with an upper anchorage mounted diagonal belt is better controlled in terms of injury prevention, than an occupant in a restraint system where the diagonal shoulder strap is anchored to the floor.

3.4.3 Effect of occupant size

This was not examined for M1 and M2 forward facing.

3.4.4 Effect of wheelchair stiffness

This was not examined for M1 and M2 forward facing.

3.4.5 Effect of a head and back restraint (Tests 3, 5 and 6)

It was proposed that the addition of a head and back restraint may be able to increase the level of protection provided to the wheelchair seated passenger to a comparable level with the vehicle seated passenger, in terms of neck injury. This was investigated by the addition of a head and back restraint to the test configuration that had been tested to the requirements of Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles.

As part of the preparation for this investigation a database of photographs of wheelchairs was analysed to derive the range of dimensions of their rear profiles. The information was used to determine the average gap that would be created between a wheelchair and a head and back restraint if the head and back restraint was designed so that its profile was in a single plane from head down to seat level.

Two tests were carried out, one with a wheelchair seated occupant against a head and back restraint where there was no gap between the two and one test with a wheelchair seated occupant against a head and back restraint where a gap of 222mm had been created (this figure was based on the mean seat-back to battery edge distance for an electric wheelchair). Figure 11 shows a dynamic still from the test without a head and back restraint and dynamic stills from tests with a head and back restraint are shown in Figure 12 and Figure 13.

Figure 11 (no head and back restraint) demonstrates how the occupant rises up out of the wheelchair and the neck over extends under these conditions. When a head and back restraint is put in place as demonstrated by Figure 12 the occupant does not rise up out of the seat as much and the neck extension is controlled. In contrast to this, when there is a gap between the wheelchair and the head and back restraint the occupant’s head rotates before making contact with the restraint resulting in a loaded neck extension. This situation also results in very high head accelerations for the occupant.

As a result of these tests, it is apparent that the addition of a head and back restraint will improve the safety for a forward facing wheelchair occupant, and will provide a level of protection closer to that of a vehicle seated occupant than if a head and back restraint were not present.

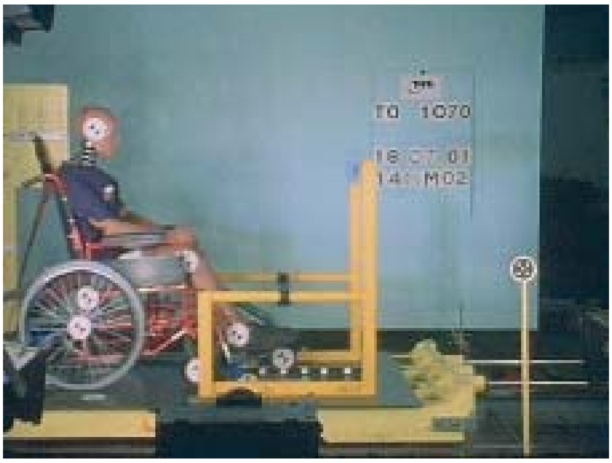

Figure 11a Set up with no head and back restraint

Figure 11b Wheelchair occupant with no head and back restraint

Figure 12a Set up with a head and back restraint

Figure 12b Wheelchair occupant with a head and back restraint

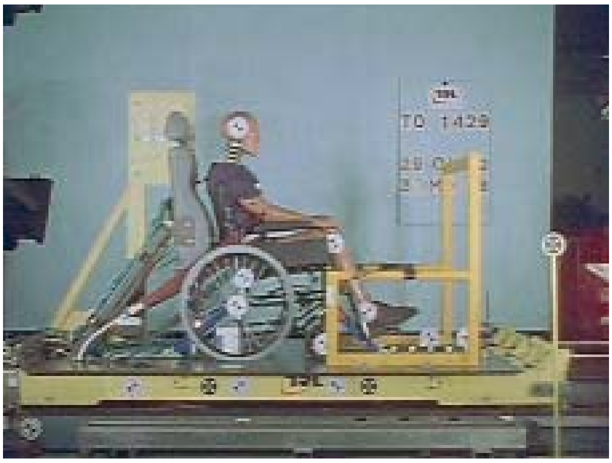

Figure 13a Set up with a gap between head and back restraint and occupant

Figure 13b Wheelchair occupant with a gap between head and back restraint and occupant

However, even without a head and back restraint all injury criteria are below the conventional threshold values, although it should be considered that wheelchair users may have a lower tolerance to injury than indicated by the conventional threshold values.

It is necessary to ensure that there is no gap between the wheelchair and the head and back restraint to gain maximum benefit. The same conclusion would apply to a vehicle seated occupant and their head restraint.

3.4.6 Head and back restraint strength

This was not examined for M1 and M2 forward facing.

3.4.7 Anchorage loading (Tests 7 and 8)

Two tests as described in Section 3.3.2 investigated the loading on the vehicle anchorages.

All the forces measured in these tests were resolved to 45 degrees to provide a consistent basis for recommendations on the necessary anchorage strength in vehicles. Table 4 shows the resolved forces.

Table 4 M1 and M2 forward facing – restraint anchorage loads

	Load (kN)
Wheelchair tiedown – front	4
Wheelchair tiedown – rear	31
Dummy restraint – lower – buckle side	31
Dummy restraint – lower – shoulder belt side	25
Dummy restraint – upper anchorage	8

3.4.8 Occupant space requirements (Tests 2 and 3)

Occupant injuries can be reduced if sufficient space is provided within the vehicle to prevent occupant contact with the interior. Figure 14 shows the minimum space required for forward facing wheelchair seated passengers in M1 and M2 vehicles.

The space was derived from dummy head, knee and ankle excursion recorded during tests two and three, i.e. a test with an upper anchorage for the shoulder belt *and* a test with a floor mounted anchorage, (see Table 2). It therefore assumes a 50th percentile occupant travelling in a manual wheelchair restrained by a four point tie-down, with no head and back restraint.

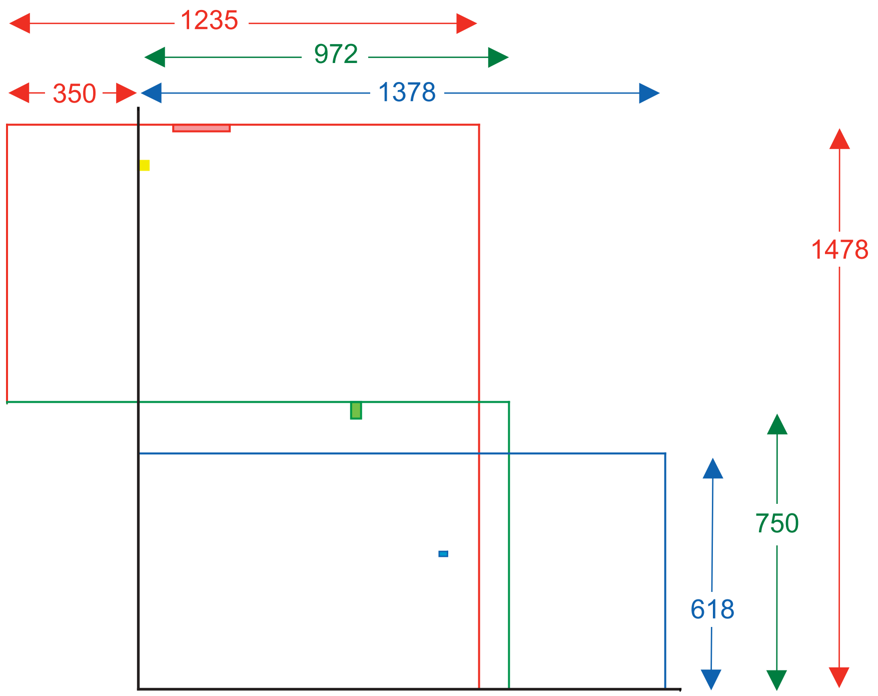

Figure 14 M1 and M2 forward facing – occupant space

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, whilst horizontal measurements were related to the upper anchorage position, which in itself was in fixed relation to the occupant but not necessarily the wheelchair. In the figure, the black vertical line indicates the plane of the upper anchorage position and the black horizontal line indicates the plane of the floor.

3.5 Conclusions

The principal findings for forward facing in M1 and M2 vehicles are provided in the following summary. A formal set of recommendations are given in Section 11.

Restraint geometry:

- If a head and back restraint is used then where possible an upper anchorage diagonal occupant restraint should be installed in preference to a floor mounted diagonal occupant restraint. However, if a head and back restraint is not used then use of a floor mounted diagonal belt anchorage should not be precluded.

Head and back restraint:

- Use of a head and back restraint is recommended as it provides a level of protection closer to that of an occupant seated in a vehicle seat with a head restraint, but it is not absolutely necessary to prevent injury. However, the project did not examine any increased susceptibility of wheelchair users to injury, and hence it is a matter of risk assessment, taking into account the cost of fitting such devices, as to whether a head and back restraint should be fitted for forward facing wheelchair users.

  The occupant should be positioned so that their torso is against the head and back restraint. The head and back restraint should be tested to the requirements of Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles.

- Wheelchair and vehicle manufacturers should be aware of the detrimental effect of a gap between the wheelchair and head and back restraint, and should work with all involved to minimise this gap. This requires an understanding of the issues, and effective communication between the wheelchair tie-down and occupant restraint manufacturer and the vehicle manufacturer.

Vehicle anchorages:

- When a wheelchair has a four point tie-down system each of the front anchorages should be able to withstand a loading of 5kN in a rearward and upward direction at an angle of 45 degrees to the horizontal. Each of the rear anchorages should be able to withstand a load of 30kN applied in a forward and upward direction at an angle of 45 degrees to the horizontal.

- The anchorages of an occupant restraint system should be able to withstand 10kN at the upper anchorage applied forward and downward at a 45 degree angle to the horizontal and 30kN at each of the floor anchorages applied in a forward and upward direction at an angle of 45 degrees to the horizontal.

Occupant space:

- Based on an enclosing area summarising the measurements given in Figure 14, any wheelchair space should comply with the following requirements.

A wheelchair space shall not be less than:

- 1300mm measured in the longitudinal plane of the vehicle up to a height of 1500mm;

- 1750mm measured in the longitudinal plane of the vehicle up to a height of 750mm (for prevention of contact between the lower extremities and the vehicle interior).

4 M1 and M2 rear facing

4.1 Simulation study

Twelve analyses of the numerical model were carried out for this condition as described in detail in Appendix 2. The model included a representation of a typical vehicle environment around the wheelchair based on a purpose built taxi. The wheelchair was positioned rear facing against the bulkhead separating the driver and passenger compartments.

Manual, electric and surrogate wheelchair models were compared as part of the study and additional analyses were carried out with a head and back restraint to determine whether this would reduce occupant loading.

The results suggested that a head and back restraint would be needed if the injury criteria limits were not to be exceeded as there was excessive rearwards head movement and over extension of the neck predicted by most of the analyses. The recommendations for the testing programme were to compare the protection afforded to the wheelchair occupant with and without a head and back restraint, with consideration being given to the energy absorption characteristics of the head and back restraint.

4.2 Scope

To further investigate rear facing occupants in M1 and M2 vehicles a series of dynamic tests were carried out. The findings from the simulation work were considered when planning the test programme.

The primary objective in the test series was to assess whether the wheelchair seated occupant was provided with the same level of safety as the vehicle seated occupant, through the use of instrumented dummies to compare the occupant loading.

In addition, the effects of occupant size and wheelchair stiffness were investigated. The use of a head and back restraint was also examined, to see whether its use could improve the protection provided for the occupant with respect to neck extension and movement.

Finally, a test was carried out to determine the dynamic strength requirements for a head and back restraint for rear facing wheelchair users in M1 and M2 vehicles.

4.3 Test configuration

In order to investigate rear facing M1 and M2 vehicle requirements, ten sled tests with various configurations were carried out (see test matrix, Table 5).

Table 5 Test matrix – M1 and M2 rear facing

Test	*Dummy seating position*	*Wheelchair restraint*	*Dummy*	*Occupant restraint diagonal belt anchorage location*	*Head / back restraint*
1	Vehicle seat	N/A	Hybrid III 50^{th}	Upper	N/A
2	Manual wheelchair	2 point webbing	Hybrid III 50^{th}	Upper	No
3	Surrogate wheelchair	2 point webbing	Hybrid III 50^{th}	Upper	No
4	Surrogate wheelchair	2 point webbing	Hybrid III 5^{th}	Upper	No
5[1]	Manual wheelchair	2 point webbing	Hybrid III 50^{th}	Upper	Yes
6[1]	Surrogate wheelchair	2 point webbing	Hybrid III 50^{th}	Upper	Yes
7	Electric wheelchair	2 point webbing	Hybrid III 95^{th}	Upper	No
8[2]	Manual wheelchair	2 point webbing	Hybrid III 50^{th}	Upper	Yes
9[2]	Manual wheelchair	2 point webbing	Hybrid III 50^{th}	Upper	With gap
10	Heavy electric wheelchair	2 point webbing	Hybrid II 50^{th}	Upper	Yes

[1] *These were initial tests using a bodyshell and a head and back restraint subsequently shown to be too stiff.*

[2] *These later tests used no bodyshell but the head and back restraint conformed to M1 strength and energy absorption requirements.*

4.3.1 Occupant loading

Tests 1 – 9 concerned rear facing occupant loading. A vehicle seated baseline test was carried out for comparative purposes using a Hybrid III 50^{th} percentile dummy in a fold down seat and restrained with a three point belt. This is shown in Figure 15. Figure 16 shows a typical set up for the wheelchair seated occupant.

Figure 15 M1 and M2 rear facing – vehicle seated

Figure 16 M1 and M2 rear facing – wheelchair seated

4.3.2 Vehicle loading

Test 10 examined the loading on a head and back restraint in order to define strength requirements for rear facing head and back restraints in M1 and M2 vehicles. A 50th percentile Hybrid II dummy was seated in a heavy electric wheelchair. The wheelchair was positioned rear facing against three force measuring plates that corresponded to the dummy head, torso and base of the wheelchair. The set up for the test is shown in Figure 17.

Figure 17 M1 and M2 rear facing – head and back restraint load

4.3.3 Sled configuration

For the vehicle and wheelchair seated comparisons, the investigations into occupant size and wheelchair stiffness and the initial work on head and back restraint, a taxi bodyshell was mounted on the sled. For the remaining tests, the wheelchair and restraint system only were mounted on the sled.

The wheelchairs were restrained by a 2 point webbing tie-down system. This consisted of a Y-shaped heavy duty webbing strap that attached to the rear of the wheelchair by means of two large hooks. The dummy was restrained independently with a three point lap and diagonal inertia restraint.

4.4 Findings

4.4.1 Relative safety of current situation (Tests 1, 2 and 3)

In order to compare the safety of wheelchair seated occupants with the safety of vehicle seated occupants the occupant loadings have been expressed as a percentage of the injury threshold values. Where there are no injury criteria limits the vehicle seated results have been used as a base line (i.e. 100%), these results are shown in Table 6.

Table 6 Injury criteria comparison

	50%ile injury limit	*Vehicle Seated*	*Manual Wheelchair*	*Surrogate Wheelchair*
Head acceleration	80g	97%	121%	146%
Neck tension	Vehicle seated baseline	100%	199%	179%
Lumbar spine compression	Vehicle seated baseline	100%	141%	207%
Chest acceleration	60g	55%	66%	48%

In general, the wheelchair seated occupant was at greater risk of injury than the vehicle seated occupant. All injury criteria showed an increased level of risk up to double that of an occupant seated in a baseline vehicle seat fitted with a head restraint.

The results in the table indicate that the dummy head accelerations were greater for the wheelchair seated occupants and exceeded the injury criteria limits by 21% for the manual wheelchair and 46% for the surrogate. The corresponding vehicle seated result was just within the injury limit. The greater head acceleration for the surrogate wheelchair occupant was a result of head contact with the roof.

The level of tensile loading in the neck was significantly greater for the wheelchair seated occupants. However, the dummy kinematics indicate that neck injury is a concern for all rear facing occupants. When seated in the vehicle fold down seat without a head restraint, the dummy's head shattered the glass partition that separated the driver and passenger compartments, resulting in extension of the neck.

The injury criterion for chest acceleration was not exceeded. However the manual wheelchair seated occupant received greater chest accelerations than the vehicle seated occupant. This was due to the dummy loading the bulkhead after the stitching in the canvas seat back of the manual wheelchair partially failed.

The level of lumbar spine compression was greatest for the wheelchair seated occupants. However no injury criteria exist for the Hybrid III lumbar spine, so it is not possible to determine whether this would lead to lumbar spine injury.

The comparison of rear facing vehicle and wheelchair seated occupants indicates that head acceleration and neck loading are the primary areas of concern for the wheelchair seated occupants.

4.4.2 Effect of restraint geometry

This was not examined for M1 and M2 rear facing.

4.4.3 Effect of occupant size (Tests 3, 4 and 7)

Table 7 shows the important results from the tests examining the effect of occupant size. This was investigated using the 5th percentile small female dummy seated in the surrogate wheelchair. The loadings have been expressed as a percentage of the injury criteria.

Table 7 Occupant size comparison

	Target limit		*Results*	
	5th %	*50th %*	*5th %*	*50th %*
Head acceleration	[80g]	80g	167%	146%
HIC	1113	1000	165%	105%
Chest acceleration	73g	60g	123%	48%

Very high accelerations were recorded from the 5th percentile dummy. The resultant head acceleration and HIC exceeded the injury criteria limits for this dummy by 67% and 65% respectively. The corresponding figures for the 50th percentile dummy in the same wheelchair were 46% and 5%.

There were also greater chest accelerations with the 5th percentile dummy. The chest resultant acceleration exceeded the injury criteria limit by 23% in the 5th percentile dummy but in the equivalent test with the 50th percentile dummy the chest acceleration was within the limit for that dummy.

For both occupants, the wheelchair rotated during the test and the occupant ‘rode up’ the seat back until the head contacted the roof. This was particularly damaging for the 5th percentile occupant because the neck had fully extended when head contact occurred resulting in a loaded neck extension as the torso continued to rise.

An additional test was carried out with the 95th percentile, large male dummy seated in an electric wheelchair. As a different wheelchair was used in this test, it cannot be used for direct comparison with the tests with 5th and 50th percentile dummies. However it can be used to give an indication of the outcome for an occupant of this size seated in a taxi.

High accelerations were recorded in this test, most noticeably in the chest. The high chest accelerations were probably due to loading from a horizontal bar in the seatback structure of the electric wheelchair. The chest resultant acceleration exceeded the limit for this dummy by 182%. The resultant head acceleration exceeded the injury criteria limit by 44%.

Due to the size of the dummy there was not as much room in the taxi for the neck to extend. Consequently, the head made contact with the rigid section at the top of the bulkhead. At the same time the torso was stretched around the bulkhead causing the front of the lumbar spine to fail in tension. When compared with a human, the Hybrid III lumbar spine is relatively stiff to provide the required posture in a vehicle seat.

4.4.4 Effect of wheelchair stiffness (Test 2 and 3)

Table 8 shows the important results from the tests examining the effect of wheelchair stiffness. The table compares the manual and surrogate wheelchair results. The occupant loadings have been expressed as a percentage of the injury threshold values. Where there are no injury criteria limits the surrogate wheelchair results have been expressed as a percentage of the manual wheelchair results.

Table 8 Wheelchair stiffness comparison

	50th % injury limit	*Manual wheelchair*	*Surrogate wheelchair*
Head acceleration	80g	121%	146%
Neck tension			10% < manual wheelchair
Chest acceleration	60g	65%	48%
Lumbar compression			47% > manual wheelchair

The choice of wheelchair had a marked effect on the kinematics of the wheelchair and occupant and consequently on the recorded injury criteria.

The surrogate wheelchair rotated about the rear wheel axis and this rotation, combined with the stiff seat structure, enabled the dummy to ‘ride up’ until head contact occurred with the roof. This explains the higher levels of head acceleration recorded for this test. Greater lumbar spine compression was also recorded.

The manual wheelchair rotated to a lesser extent, but the stitching in the soft seat back failed, and as a result the dummy did not ride up and there was no head contact with the vehicle. However, significant neck extension occurred when the dummy head passed through the glass partition separating the driver and passenger compartments.

The results have shown that a stiff wheelchair structure and in particular a stiff seat back can act as a ‘launch pad’ for the occupant, leading to head contact with the vehicle interior.

4.4.5 Effect of a head and back restraint (Test 5, 6, 8 and 9)

Two initial tests using the taxi bodyshell demonstrated that a head and back restraint could offer improvements in occupant protection with respect to neck loading and kinematics. However the head and back restraint did not have sufficient energy absorbing characteristics and as a result the occupant head acceleration increased.

It was proposed that a head and back restraint may have the potential to offer improved protection to the wheelchair seated passenger relative to the vehicle seated passenger, in terms of both neck injury and head acceleration. This was investigated using a head and back restraint that had been tested to the requirements of Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles. It should be noted that the vehicle seated passenger was not adequately protected as the occupants head shattered the glass partition resulting in over extension of the neck. Hence this situation should be addressed in itself, and the protection for a wheelchair seated occupant should, in this case, exceed that of the vehicle seated occupant.

As part of the preparation for this investigation a database of photographs of wheelchairs was analysed to determine the measurements of their rear profiles. The information was used to determine the average gap that would be created between a wheelchair and a head and back restraint if the head and back restraint was designed such that its profile was in a single plane from head down to seat level. The gap dimension used in the tests was 222 mm.

Two further tests were carried out, one with a wheelchair seated occupant against an M1approved head and back restraint where there was no gap between the two and one test with a wheelchair seated occupant against a head and back restraint where a gap had been created. Figure 18 shows a dynamic still from the bodyshell test without a head and back restraint in which the bulkheads glass has been shattered and the occupant’s neck is in extension. Figure 19 and Figure 20 show the effect of a gap between the occupant and the head and back restraint.

Figure 18a Set up with no head and back restraint

Figure 18b Wheelchair occupant with no head and back restraint

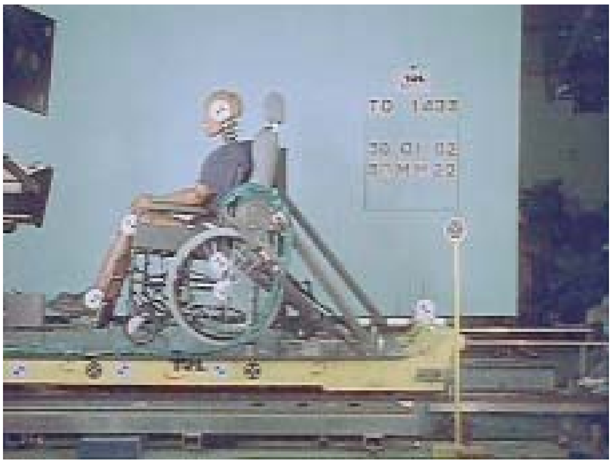

Figure 19a Set up with a head and back restraint

Figure 19b Wheelchair occupant with a head and back restraint

Figure 20a Set up with a gap between head and back restraint and occupant

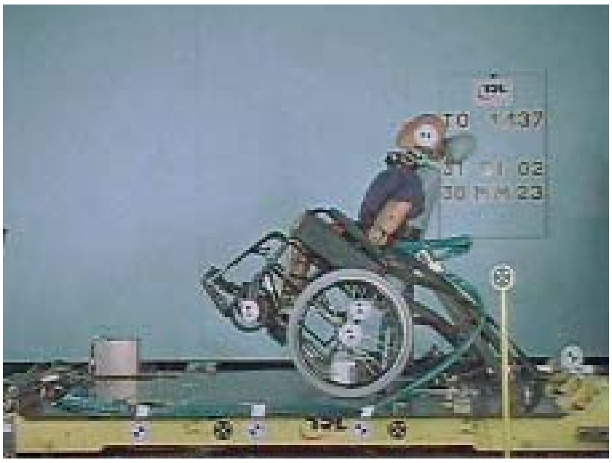

Figure 20b Wheelchair occupant with a gap between head and back restraint and occupant

Figure 18, in which the wheelchair occupant does not have a head and back restraint shows how the neck over extends. When a head and back restraint is put in place the neck extension is controlled. In contrast to this, when a gap is present between the wheelchair and the head and back restraint, the occupant's head rotates before making contact with the head and back restraint resulting in a loaded neck extension, as shown in Figure 20. This situation also results in very high head accelerations for the occupant.

Based on the results of these tests, the addition of a head and back restraint appears to improve the safety for a rear facing occupant but it is necessary to ensure that there is no gap between the wheelchair and the head and back restraint for maximum benefit.

4.4.6 Head and back restraint strength (Test 10)

The sled test described in Section 4.3.2 was carried out to define dynamic strength requirements for a rear facing wheelchair head and back restraint in M1 and M2 vehicles.

The overall force with inertia compensation was calculated for each load plate and this was used to determine the total load acting on the three plates at any one time. The results are shown in Table 9.

Table 9 Head and back restraint loads

Force plate	*Peak force (kN)*
Top	7
Middle	42
Bottom	53
Maximum load	91

The results of this test show that a rear facing wheelchair head and back restraint in an M1 or M2 vehicle must have sufficient strength to withstand loads up to 91kN.

4.4.7 Anchorage loading

This was not examined for M1 and M2 rear facing.

4.4.8 Occupant space requirements

This was not examined for M1 and M2 rear facing.

4.5 Conclusions

The principal findings for rear facing in M1 and M2 vehicles are provided in the following summary. A formal set of recommendations are given in Section 11.

Head and back restraint:

- A head and back restraint tested to the requirements of Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles is required for rear facing occupants, in a single plane from head down to seat level in order to prevent relative displacement between the head and torso. The head and back restraint should meet the requirements for energy absorption and strength in ECE Regulation 17.
- It is important that there is no gap between the wheelchair and head and the head and back restraint.
- The head and back restraint needs to withstand a horizontal loading of 100kN.

5 M3 forward facing

5.1 Simulation work

Ten model analyses of the numerical model were completed and are described in detail in Appendix 2. Various combinations of wheelchair, dummy and restraints were investigated.

The simulation work suggested that there would be a low likelihood of serious injury in this type of impact as the dummy loads were well below the injury thresholds in most cases. The wheelchair tie-down system had little effect on dummy loading when the diagonal part of the belt was mounted in the upper location. The effect of using floor mounted occupant restraints was not investigated in the simulation work.

5.2 Scope

To further investigate forward facing occupants in M3 category vehicles a series of dynamic tests were carried out. The findings from the simulation work were considered when planning the test programme.

The primary objective for forward facing occupants in M3 category vehicles was to assess whether the wheelchair seated occupant was provided with an equivalent level of safety as the vehicle seated occupant, through the use of instrumented dummies to compare the occupant loading.

In the dynamic testing, along with a comparison of the safety of vehicle and wheelchair seated passengers the different combinations of wheelchair restraint and occupant restraint geometry were investigated. This was examined to determine whether there was a negative effect on the protection to the occupant. Wheelchair stiffness and occupant size were also investigated.

The effect of a head and back restraint was then investigated to determine whether this could improve the protection provided for the occupant with respect to neck extension and movement in rebound.

In order to set requirements for vehicles, the occupant space required within the vehicle was examined along with the loads that the vehicle anchorages would have to withstand.

5.3 Test configuration

In order to investigate M3 vehicle requirements, thirteen sled tests were carried out with various configurations (see test matrix, Table 10).

5.3.1 Occupant loading

Tests 1 - 11 concerned occupant loading in M3 vehicles. A vehicle seated baseline test was completed for comparative purposes using a Hybrid III 50^{th} percentile dummy in a commercially available coach seat that included an integrated three-point occupant restraint and a head restraint. This is shown in Figure 21. A series of wheelchair seated tests then followed to investigate the issues outlined in the scope. Figure 22 shows a typical set up for the wheelchair seated occupant.

Table 10 Test matrix – M3 forward facing

Test	*Dummy seating position*	*Wheelchair restraint*	*Dummy*	*Occupant restraint diagonal belt anchorage location*	*Head / back restraint*
1	Coach seat	N/A	Hybrid III 50^{th}	Integral 3 point	No
2	Surrogate wheelchair	4 point webbing	Hybrid III 50^{th}	Floor	No
3	Surrogate wheelchair	4 point webbing	Hybrid III 50^{th}	Upper	No
4	Manual wheelchair	4 point webbing	Hybrid III 50^{th}	Upper	No
5	Manual wheelchair	4 point webbing	Hybrid III 50^{th}	Floor	No
6	Manual wheelchair	Clamps	Hybrid III 50^{th}	Upper	No
7	Manual wheelchair	Clamps	Hybrid III 50^{th}	Floor	No
8	Surrogate wheelchair	4 point webbing	Hybrid III 95^{th}	Upper	No
9	Surrogate wheelchair	4 point webbing	Hybrid III 5^{th}	Upper	No
10	Manual wheelchair	4 point webbing	Hybrid III 50^{th}	Upper	Yes
11	Manual wheelchair	4 point webbing	Hybrid III 50^{th}	Floor	Yes with gap
12	Heavy electric wheelchair	4 point webbing	Hybrid III 95^{th}	Upper	No
13	Heavy electric wheelchair	4 point webbing	Hybrid III 95^{th}	Floor	No

Figure 21 M3 forward facing - vehicle seated

Figure 22 M3 forward facing wheelchair seated

5.3.2 Vehicle loading

Tests 12 and 13 investigated the loading on the vehicle anchorages. Two different occupant diagonal belt systems were used, one with a floor mounted diagonal anchorage and one with an upper mounted diagonal anchorage. The wheelchair was restrained with a four-point webbing tie down system. These set ups are shown in Figure 23 and Figure 24. The Hybrid III 95th percentile dummy was seated in a heavy electric wheelchair as this represented the likely worst case for the restraint anchorage loads.

Figure 23 Set up with an upper location for the diagonal belt anchorage

Figure 24 Set up with a floor location for the diagonal belt anchorage

5.3.3 Sled configuration

The vehicle environment for a coach was set up on the sled. A production model coach seat was used for the vehicle seated occupant test. The seat had an integrated 3-point restraint system.

The wheelchairs were restrained by either a four point webbing tie-down system or two clamps to determine whether the wheelchair restraint had an effect on the occupant loading. Both systems were secured to the floor by purpose designed Aluminium Track Fittings (ATF). The dummy was restrained independently by a lap and diagonal inertia restraint in all tests. Two types of wheelchair occupant restraint were investigated to compare the effects of different shoulder belt anchor locations. These were anchored to either the upper location or the floor.

The test set up for measurement of the restraint anchorage loads required additional instrumentation adjacent to all anchorage points to record the loads generated during the impact. Markers were placed to enable measurement of the restraint angles at peak loading.

All wheelchair and occupant restraints were installed according to the manufacturer's instructions and the ISO standards.

5.4 Findings

5.4.1 Relative safety of current situation (Tests 1, 4, 5, 6, 7)

Table 11 compares the vehicle seated baseline test with selected wheelchair results. The table shows that a wheelchair seated passenger in an M3 vehicle can be provided with an equivalent level of safety. In some cases the dummy loads for the vehicle seated test exceeded those for wheelchair seated tests, however the recorded injury limits were not exceeded in any tests, irrespective of restraint type.

5.4.2 Effect of restraint geometry (Tests 4, 5, 6 and 7)

Table 11 shows that the combination of clamps with a floor mounted occupant restraint is the least favourable combination of those tested. The

Table 11 Injury criteria comparison

		Results				
	50^{th} % injury limit	*Vehicle seated*	*Manual wheelchair tiedowns + upper anchorage location*	*Manual wheelchair clamps + upper anchorage location*	*Manual wheelchair tiedowns + floor*	*Manual wheelchair clamps + floor*
Head acceleration	80g	40%	30%	28%	34%	77%
Chest acceleration	60g	20%	20%	19%	17%	18%
Diagonal belt	[7kN]	60%	74%	80%	68%	59%
Lumbar compression	Vehicle baseline	100%	57%	57%	88%	64%

torso of the dummy ‘jack-knifed’ during this test resulting in dummy head contact with the knees causing much higher head accelerations.

The upper anchorage occupant restraints provided better restraint of the torso but the diagonal belt load was higher compared with the floor mounted restraints as would be expected.

5.4.3 Effect of occupant size (Tests 3, 8, 9)

Table 12 shows the important results from the tests examining the effect of occupant size. The loadings have been expressed as a percentage of the injury threshold limits. Where there are no injury criteria limits the vehicle seated results have been used as a base line (i.e. 100%). The results show that different sized occupants have a comparable level of safety in M3 vehicles.

Table 12 Occupant size comparison

	Target limit			*Results*		
	5^{th} %	*50^{th} %*	*95^{th} %*	*5^{th} %*	*50^{th} %*	*95^{th} %*
Head acceleration	[80g]	80g	[80g]	39%	30%	35%
Head displacement	[650mm]	[650mm]	[650mm]	43%	46%	49%
Chest acceleration	73g	60g	54g	35%	20%	53%
Diagonal belt	[7kN]	[7kN]	[7kN]	58%	63%	76%

In general, the dummy accelerations were greater for the 5^{th} and 95^{th} percentile dummies in comparison with the 50^{th}, probably because restraint systems are optimised and tested using a 50^{th} percentile dummy. The head displacement and belt loads were greatest for the 95^{th} percentile and least for the 5^{th} percentile.

5.4.4 Effect of wheelchair stiffness (Tests 11 and 12)

Table 13 shows the important results from the tests examining the effect of wheelchair stiffness. The loadings have been expressed as a percentage of the injury threshold values. Where there are no injury criteria limits the vehicle seated results have been used as a base line (i.e. 100%). The table compares the manual and surrogate wheelchair results for both occupant restraint types. The wheelchairs were restrained by a 4 webbing strap tie-down system.

The results show that wheelchair stiffness influenced the level of compression of the lumbar spine. This was due to the manual wheelchair deforming during the impact and absorbing some of the energy, however the stiffer surrogate wheelchair did not deform resulting in greater loads on the dummy.

Table 13 Wheelchair stiffness comparison

	50th % limit injury	Floor anchorage		Upper anchorage	
		Manual	*Surrogate*	*Manual*	*Surrogate*
Head acceleration	80g	34%	42%	29%	30%
Chest acceleration	60g	17%	24%	20%	20%
Diagonal belt	[7kN]	68%	74%	74%	63%
Lumbar compression	Vehicle seated	88%	136%	57%	105%

5.4.5 Head and back restraint (Tests 10 and 11)

It was proposed that the addition of a head and back restraint may have the potential to increase the level of protection provided to the wheelchair seated passenger in comparison to that offered to the vehicle seated passenger in terms of neck injury. This was investigated by adding to the test set-up a head and back restraint tested to Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles.

As part of the preparation for this investigation a database of photographs of wheelchairs was analysed to determine the measurements of their rear profiles. The information was used to determine the average gap that would be created between a wheelchair and a head and back restraint if the head and back restraint was designed such that its profile was in a single plane from head to seat level.

Two tests were carried out, one with a wheelchair seated occupant against a head and back restraint where there was no gap between the two and one test with a wheelchair seated occupant against a head and back restraint where a gap had been created. Figure 25 shows a dynamic still from the test without a head and back restraint, and dynamic stills from the tests with the head and back restraint fitted are shown in Figure 26 and Figure 27.

Figure 25**,** in which the wheelchair occupant does not have a head and back restraint, shows how the occupant rises up out of the wheelchair and the neck over extends. When a head and back restraint is put in place as demonstrated by Figure 26, the occupant does not rise up out of the seat so much and the neck extension is controlled. Although a loaded neck extension did not occur in these tests, unlike the situation for M1 and M2 vehicles (Section 4.4.5), there was no evidence that it could not occur. For this reason it is recommended that a gap should not be permitted between the wheelchair and the head and back restraint in the same manner as for M1 and M2 vehicles.

As a result of these tests, it is apparent that the addition of a head and back restraint will improve the safety for a forward facing wheelchair occupant, and will provide a level of protection closer to that of an occupant seated in a vehicle seat with a head restraint than if a head and back restraint were not present. However, even without a head and back

Figure 25a Set up with no head and back restraint

Figure 25b Wheelchair occupant with no head and back restraint

Figure 26a Set up with a head and back restraint

Figure 26b Wheelchair occupant with a head and back restraint

Figure 27a Set up with a gap between head and back restraint and occupant

Figure 27b Wheelchair occupant with a gap between head and back restraint and occupant

restraint all injury criteria are below the conventional threshold values, although it should be considered that wheelchair users may have a lower tolerance to injury than indicated by the conventional threshold values.

It is necessary to ensure that there is no gap between the wheelchair and the head and back restraint to gain maximum benefit. The same conclusion would apply to a vehicle seated occupant and their head restraint.

5.4.6 Head and back restraint strength

This was not examined for M3 forward facing.

5.4.7 Anchorage loadings (Tests 12 and 13)

Two tests as detailed in 5.3.2 investigated the loading on the vehicle anchorages.

All the forces measured in these tests were resolved to 45 degrees to provide consistent recommendations for the necessary anchorage strengths in vehicles. Table 14 shows the resolved forces.

Table 14 M3 forward facing – restraint anchorage loads

	Load (kN)
Wheelchair tiedown - front	5
Wheelchair tiedown - rear	20
Dummy restraint - lower - buckle side	19
Dummy restraint - lower - shoulder belt side	16
Dummy restraint – upper anchorage	5

5.4.8 Occupant space requirements (Tests 2 - 7)

Occupant injuries can be reduced if sufficient space is provided within the vehicle to prevent occupant contact with the vehicle interior.

Figure 28 shows the minimum space required for the head, knee and ankle of a 50th percentile occupant travelling in a manual wheelchair restrained by either four point webbing straps or clamps, and representing both floor and upper anchorage mounted shoulder belts. 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. The black vertical line indicates the plane of the upper anchorage position and the black horizontal line indicates the plane of the ground.

The minimum vehicle space requirement will be the perimeter of the combined shape of these areas.

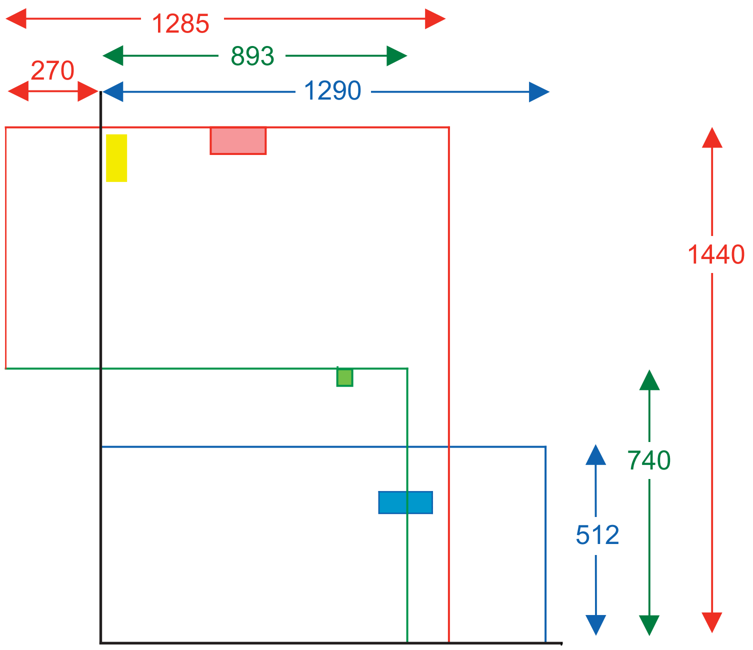

Figure 28 M3 forward facing – occupant space

5.5 Conclusions

The principal findings for forward facing in M3 vehicles are provided in the following summary. A formal set of recommendations are given in Section 11.

Restraint geometry:

- Where possible an occupant restraint with an upper anchorage location should be installed in preference to a floor anchorage, especially if the wheelchair is restrained using clamps.

Head and back restraint:

- Use of a head and back restraint is recommended as it provides a level of protection closer to that of an occupant seated in a vehicle seat with a head restraint, but it is not absolutely necessary to prevent injury. However, the project did not examine any increased susceptibility of wheelchair users to injury, and hence it is a matter of risk assessment, taking into account the cost of fitting such devices, as to whether a head and back restraint should be fitted for forward facing wheelchair users.
- The occupant should be positioned so that their torso is against the head and back restraint. The head and back restraint should meet the M1 requirements for energy absorption and strength in Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles.

Vehicle anchorages:

- When a wheelchair has a four point tie down system each of the front anchorages should be able to withstand a loading of 5kN in a rearward and upward direction at an angle of 45 degrees to the horizontal. Each of the rear anchorages should be able to withstand a load of 20kN applied in a forward and upward direction at an angle of 45 degrees to the horizontal.

- The anchorages of an occupant restraint system should be able to withstand 5kN at the upper anchorage applied forward and downward at a 45 degree angle to the horizontal and 20kN at each of the floor anchorages applied in a forward and upward direction at an angle of 45 degrees to the horizontal.

Occupant space:

- Based on an enclosing area summarising the measurements given in Figure 28, any wheelchair space should comply with the following requirements:

A wheelchair space shall not be less than:

- 1300mm measured in the longitudinal plane of the vehicle up to a height of 1500mm;

- 1600mm measured in the longitudinal plane of the vehicle up to a height of 750mm (if contact between the lower extremities and the vehicle interior is to be avoided).

6 M3 rear facing

6.1 Simulation study

Six analyses of the numerical model were carried out and these are described in detail in Appendix 2.

The simulation work suggested that the occupant could experience high levels of neck bending and chest acceleration if seated in the surrogate wheelchair. The reason for this observation was that the stiff wheelchair structure keeps the dummy back away from the back restraint, hence allowing more relative rearward motion between the head and shoulders.

6.2 Scope

To further investigate rear facing occupants in M3 category vehicles a series of dynamic tests were carried out. The findings from the simulation work were considered when planning the test programme.

The primary objective for rear facing occupants in M3 vehicles was to assess whether the wheelchair seated occupant was provided with the same level of protection as the vehicle seated occupant, through the use of instrumented dummies to compare the loading to the occupant.

6.3 Test configuration

In order to investigate M3 vehicle requirements six sled tests were carried out with various configurations as shown in the test matrix, Table 15.

6.3.1 Occupant loading

Occupant loading was investigated in tests 1 – 5. A vehicle seated baseline test was completed for comparative purposes using an unrestrained Hybrid III 50th percentile dummy in a commercially available rear facing fold down seat as shown in Figure 29. Figure 30 shows a typical set up for the wheelchair seated occupant in which the wheelchair and dummy are both unrestrained.

6.3.2 Vehicle loading

Test 6 examined the loading on a head and back restraint in order to define strength requirements for rear facing head and back restraints in M3 category vehicles. A 50th percentile Hybrid II dummy was seated in a heavy electric wheelchair and the wheelchair was positioned rear facing against three force measuring plates that corresponded to the dummy head, torso and base of the wheelchair. The set up is shown in Figure 31.

6.3.3 Sled configuration

Various M3 vehicle environments were created on the sled. For the vehicle

Table 15 Test matrix – M3 rear facing

Test	*Dummy seating position*	*Wheelchair restraint*	*Dummy*	*Occupant restraint diagonal belt anchorage location*	*Head / back restraint*
1	Fold down seat	N/A	Hybrid III 50th	None	Yes
2	Surrogate wheelchair	None	Hybrid III 50th	None	Yes
3	Manual wheelchair	None	Hybrid III 50th	None	Yes
4	Manual wheelchair	2 point webbing	Hybrid III 50th	Upper	Yes
5	Manual wheelchair	2 point webbing	Hybrid III 50th	Upper	Yes with gap
6	Heavy electric wheelchair	2 point webbing	Hybrid III 50th	Upper	Yes

Figure 29 M3 rear facing – vehicle seated

Figure 30 M3 rear facing – wheelchair seated

and wheelchair seated comparisons, and the investigations into wheelchair stiffness the wheelchair space seen in current low floor urban buses was recreated on the impact sled, according to the Public Service Vehicle Accessibility Regulations 2000 (PSVAR). In some buses it is possible for the wheelchair wheels to interact with the bus structure, however in these tests all wheelchair contact was with the back restraint only.

Figure 31 M3 rear facing – head and back restraint load

In the remaining tests, the wheelchair and head and back restraint system only were mounted on the sled, i.e. in these cases there was no representation of the wheelchair space as defined in PSVAR 2000.

6.4 Findings

6.4.1 Relative safety of current situation (Tests 1 - 3)

For this series of 3 tests, the wheelchair and occupant were unrestrained. In order to compare the safety of wheelchair seated occupants with that of vehicle seated occupants, the important results have been expressed as a percentage of the injury threshold limits and shown in Table 16.

Table 16 Injury criteria comparison

	50th % injury limit	*Results*		
		Vehicle seated	*Manual*	*Surrogate*
Head acceleration	80g	69%	100%	115%
HIC	1000	22%	46%	56%
Neck tension	Vehicle seated	100%	87%	115%
Chest acceleration	60	13%	13%	17%

In general, the occupant forces and accelerations were low, suggesting that the current practice of allowing wheelchair users to travel unrestrained when rear facing against a head and back restraint is acceptable. However the table shows that the occupant head acceleration was greater when the occupant was wheelchair seated. In the surrogate wheelchair test the injury criteria limit was exceeded by 15 percent.

The main concern that arises from the current situation when comparing vehicle and wheelchair seated occupants is therefore injuries to wheelchair seated occupants caused by head contact with the head and back restraint.

6.4.2 Effect of occupant size

This was not examined for M3 rear facing.

6.4.3 Effect of wheelchair stiffness (Tests 2 and 3)

The influence of wheelchair stiffness can be investigated by comparing the manual and surrogate wheelchair results shown in Table 16 (the wheelchair and occupant were both unrestrained in both cases).

The stiff wheelchair structure kept the dummy away from the head and back restraint as predicted by the simulation study. This allowed greater rearward motion of the dummy, which contributed to the increased head and neck loads seen with this wheelchair.

6.4.4 Head and back restraint (Tests 4 and 5)

It was proposed that further tests with a head and back restraint approved to Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles may be able to reduce the occupant head acceleration. This would then offer the wheelchair seated passenger an equivalent level of protection to that of an occupant seated in a vehicle seat with a head restraint.

As part of the preparation for this investigation a database of photographs of wheelchairs was analysed to determine the measurements of their rear profiles. The information was used to determine the average gap that would be created between a wheelchair and a head and back restraint if the head and back restraint was designed so that its profile was in a single plane from head to seat level.

Two tests were carried out, one with a wheelchair seated occupant against a head and back restraint where there was no gap between the two and one test with a wheelchair seated occupant against a head and back restraint where there was a gap created. In both cases the wheelchair was restrained with a 2-point webbing system and the occupant was restrained with a 3 point restraint, the diagonal being attached at the upper anchorage location.

The results of these tests were compared with results for the original head and back restraint (in which the wheelchair and occupant were unrestrained) and are shown in Table 17. The occupant loadings are expressed as a percentage of the injury criteria limit.

When the occupant was seated against a head and back restraint that met M1 requirements for energy absorption the head acceleration and HIC were reduced to levels comparable with the vehicle seated passenger.

The injury criteria limits for the chest were not exceeded, however the addition of the M1 tested head and back restraint increased chest

Table 17 Head and back restraint comparison

	50th % injury limit	Results: Original head and back restraint	Results: M1 head and back restraint	Results: M1 head and back restraint with gap
Head acceleration	80g	100%	54%	73%
HIC	1000	46%	21%	44%
Chest acceleration	60g	13%	41%	70%

accelerations. This was due to the presence of additional bracing behind the head and back restraint which was necessary to ensure that it could be tested repeatedly, but which had a detrimental effect on the occupant chest acceleration. Recorded neck extension moments were relatively low in magnitude, however dynamic analysis indicated that bending did occur but at a location low down the neck, away from the load cell location at the head/neck interface. These data could therefore not be quantified, but the indications were that neck extension was not anticipated to cause problems.

Dynamic stills from these tests are shown in Figure 32 and Figure 33.

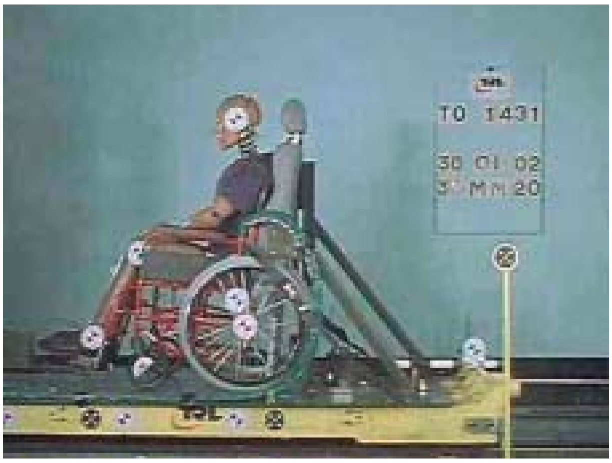

Figure 32a Set up with a head and back restraint

Figure 32b Wheelchair occupant with a head and back restraint

When a head and back restraint is put in place with no gap as demonstrated by Figure 32 the neck extension is controlled. In contrast to this, when there is a gap between the wheelchair and the head and back restraint the occupant's head rotates before making contact with the restraint resulting in a loaded neck extension. This situation also results in higher head accelerations for the occupant.

Figure 33a Set up with a gap between head and back restraint and occupant

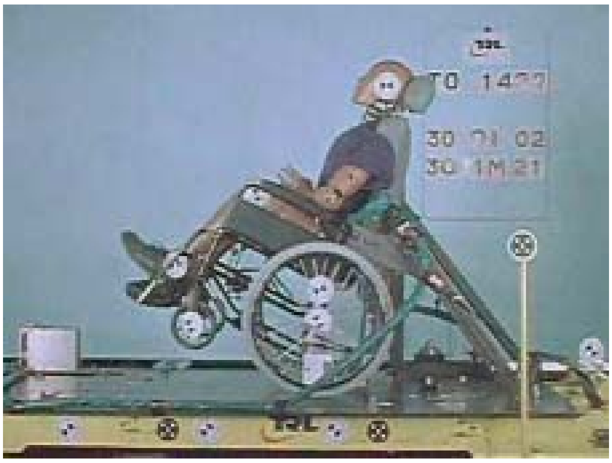

Figure 33b Wheelchair occupant with a gap between head and back restraint and occupant

The results have demonstrated that a rear facing head and back restraint in an M3 vehicle should have the energy absorption characteristics of an M1 seat. Furthermore, the manner in which the head and back restraint is mounted can adversely affect occupant protection and stiff bracing structures should be avoided.

The results have also shown that it is necessary to ensure that, where possible, there is no gap between the wheelchair and the head and back restraint.

6.4.5 Strength of head and back restraint (Test 6)

The sled test detailed in 6.3.2 was carried out to define dynamic strength requirements for a rear facing wheelchair head and back restraint in M3 vehicles. The wheelchair in this case was restrained with a 2 point webbing system and the occupant with a 3 point restraint mounted at the upper location.

The overall force with inertia compensation was calculated for each load plate. This was used to determine the total load acting on the three plates at any one time. The results are shown in Table 18.

Table 18 Head and back restraint loads

Force plate	*Peak force (kN)*
Top	4
Middle	11
Bottom	33
Maximum Load	45

The results of this test show that a rear facing wheelchair head and back restraint in an M3 vehicle should have sufficient strength to withstand loads of up to 45kN.

6.4.6 Occupant space requirements

This was not examined for M3 rear facing.

6.5 Conclusions

The principal findings for rear facing in M3 vehicles are provided in the following summary. A formal set of recommendations are given in Section 11.

Head and back restraint:

- The occupant should be rear facing against a head and back restraint.
- The head and back restraint should meet the M1 requirements for energy absorption and strength in Directive 74/408/EEC as amended by 96/37/EC for M1 vehicles.
- It is important that there is no gap between the wheelchair and the head and back restraint.
- The head and back restraint needs to be capable of withstanding a horizontal loading of 50kN, but care should be taken over mounting of the head and back restraint so that no unnecessary additional loads are placed on the occupant (for instance by horizontal bracing behind the occupant).

7 M3 (bus) rear facing normal transit

7.1 Scope

The Public Service Vehicles Accessibility Regulations 2000 allow a wheelchair user in a bus to travel unrestrained, in a rear facing position, against a back restraint or bulkhead. It is assumed that this configuration will adequately keep the wheelchair in the designated space during normal transit, and this is how many thousands of journeys take place without incident.

The regulations demand a method for restricting lateral movement of the wheelchair into the gangway. This 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 rail extending from the front of the wheelchair space. A range for the position of both these items within the wheelchair space is specified.

A series of trials were carried out to study the movement of an occupied wheelchair in normal transit on a bus that is compliant with the PSVAR.

7.2 Testing methodology

Previous research at TRL has demonstrated that lateral accelerations on low floor buses can reach 0.4g on bus routes selected as being difficult to negotiate. With this knowledge, an Optare Excel 11.5 was tested on the large central area of the TRL research track with a dummy seated in a wheelchair, to determine whether the wheelchair was displaced during manoeuvres that generated this level of lateral acceleration.

The Optare Excel is compliant with the PSVAR and is fitted with a cranked vertical stanchion (see Figure 34). This feature is to allow easier access into the wheelchair space and provides a more convenient hand hold position when compared with a purely vertical stanchion. It was necessary to test other possible systems, so the stanchion was also removed from the vehicle, and a rail fitted in the required position. It was not possible to obtain a production rail that was compliant with the PSVAR within the time scale of the project, so a mock up was used in its place.

Figure 34 Wheelchair space in Optare Excel

To generate the level of lateral acceleration required for the experiment the vehicle was driven at a constant velocity of 24-25 mph. A left turn was then executed, of 20 metres constant radius, while the speed was maintained.

This gave a repeatable test procedure suitable for the experiment. The acceleration at the wheelchair space was logged and downloaded for analysis.

The experiment was carried out with a Hybrid II 50th percentile dummy seated in a DDA reference wheelchair. The dummy and wheelchair were rear facing and unrestrained, with the brakes applied. The seat back of the wheelchair was in contact with the back restraint.

The stanchion was tested in three positions (see Figure 35). These were 400, 480 and 560 mm from the front end of the wheelchair space, measured at the base of the stanchion. Due to the difficulty in maintaining a constant speed whilst conducting the prescribed turn, each position was tested a number of times to ensure that the driver had been able to complete the manoeuvre successfully, with the correct level of lateral acceleration. In all, 12 test runs were completed.

For the retractable rail, a section of tubing of 34mm diameter was attached to the luggage pen of the vehicle, for convenience, and extended to a point 540mm from the front of the wheelchair space (see Figure 36). To comply with the PSVAR, the rail was initially fitted between 600 - 800 mm from the floor of the vehicle, and moved in intervals of 50 mm.

Figure 35 Wheelchair space fitted with stanchion

Figure 36 Wheelchair space fitted with rail

A VHS camera was fitted on board. This was used to record the wheelchair movement during the test and to assess the extent to which the wheelchair moves into the gangway. If the wheelchair was maintained within the wheelchair space and the dummy remained in the wheelchair during a turn that registered 0.4g on the logging equipment, then the stanchion or rail could be said to be performing satisfactorily.

7.3 Results

Both the stanchion and rail are designed to prevent movement of the wheelchair into the gangway, where it could become a hazard for the wheelchair passenger and standing passengers in the vicinity. This is necessary in the Optare Excel and similar vehicles, because as the bus turns left there is a weight transfer to the left of the wheelchair, adjacent to the gangway. This reduces the grip of the wheels on the right hand side of the wheelchair, beside the wall. The mass can then pivot about the vertical axis of the left rear wheel. This effect is exaggerated by the front wheels, which are on castors, and without brakes.

The film of the tests indicates that the motion described could occur when lateral acceleration reached 0.29 - 0.3g, although movement into the gangway did not occur unless levels of acceleration reached 0.33 - 0.34g. It is only possible to give an approximation of when the motion occurred as the accelerometer and video were not directly linked.

7.3.1 Wheelchair space fitted with a stanchion

The Public Service Vehicles Accessibility Regulations 2000 state that the base of the stanchion must be between 400 and 560mm from the front of the wheelchair space. During the tests with the stanchion at 400mm almost no wheelchair movement was observed, even when the lateral acceleration recorded in the vehicle reached 0.4g. The same was true when the stanchion was moved forward to 480mm. The wheelchair could not move, because there was only a short distance of approximately 50mm laterally, between the handrim on the left rear wheel and the stanchion. Therefore as the wheelchair begins to rotate about the vertical axis of the wheel, the handrim contacted the stanchion and the movement ceased.

When the stanchion was positioned at 560mm from the front of the wheelchair space greater movement occurred as the stanchion was ahead of the leading edge of the handrim. However the stanchion contacted the front edge of the wheel and tyre and further movement was prevented. At no time did the wheelchair cross the plane of the wheelchair space and move into the gangway. As the stanchion was seen to perform satisfactorily in these tests, whilst positioned at the extremes of the range allowable, it was not necessary to conduct further tests outside this range.

7.3.2 Wheelchair space fitted with a rail

A retractable rail is permitted in the PSVAR in the place of a stanchion. This must extend at least 540mm from the front of the wheelchair space and be at a height between 600 and 800mm from the floor. A mock up device was fitted in the bus and braced laterally so that it was capable of bearing the load required. The rail was initially positioned within the height range described above.

At 600mm the rail did not perform well in separate tests where the peak lateral acceleration reached 0.35 and 0.4g. The wheelchair rotated about the vertical axis of the left rear wheel but the rail did not restrain the wheelchair due to the gap in the armrest, see Figure 37. The left front wheel and foot plate partially intruded into the gangway. Further movement was only prevented when the rail contacted the dummy leg.

The test was repeated with the rail at a height of 650mm. At this position the wheelchair did not move when the acceleration was 0.4g, because the rail was at the same height as the padded armrest on the wheelchair. When the wheelchair began to move it quickly contacted the rail, which prevented any movement into the gangway. The rail was then raised to 700mm. This height exceeded any side structure on the wheelchair and during the test there was significant wheelchair motion into the gangway. The wheelchair rotated about the vertical axis of the left rear wheel and passed under the rail until it was arrested by contact with the forearm of the dummy, Figure 38. At this point, part of both the left front wheel and foot plate were outside the designated wheelchair space and in the gangway. The rail was then raised to 800mm from the floor, the maximum height allowed in the PSVAR. The wheelchair again rotated under the rail, this time resulting in the greatest excursion into the gangway of the vehicle. At the end of tests where peak lateral accelerations were in the range 0.33 - 0.4g, the entire left foot plate and the left front wheel were outside the wheelchair space.

Figure 37 Post test with rail at 600 mm above floor

Figure 38 Post test with rail at 700 mm above floor

The tests described above were carried out with the rail at a height that was compliant with the PSVAR. It was apparent during these experiments that the rail was not performing satisfactorily at most of the heights tested, in the range allowed. At 700mm or above the reference wheelchair could pass underneath the rail, therefore there was no benefit in conducting further tests above the 800mm upper limit. Instead, additional tests were carried out with the rail below the lower limit, at 550mm from the floor. During these tests the rail performed well, and prevented the wheelchair from rotating into the gangway. The rail was more effective at this height because as movement began the rail contacted the handrims and restrained the wheelchair from further movement.

7.4 Conclusions

The results have shown that the reference wheelchair will move when exposed to levels of lateral vehicle acceleration that are possible on bus routes. Furthermore the effectiveness of the available methods for restricting this movement is variable, and dependent on the location of the device.

During tests with a vertical stanchion, wheelchair movement was restricted in all tests, when the position of the stanchion was varied within the range allowed. The level of peak lateral acceleration exceeded 0.4g in some of these tests, but the wheelchair did not move into the gangway. The optimum position for a stanchion is ahead of the vertical axis of the rear wheel as the wheelchair tends to pivot around this axis at levels of acceleration that were approaching 0.35g. However it should not be forward of the leading edge of the rear wheel because it is desirable for the wheel handrim and stanchion to make contact.

The performance of the rail in these tests was of concern. The ability of the device to restrict wheelchair movement was highly dependent on its height. If the rail could interact with the side of the wheelchair after movement began then it could restrict the motion sufficiently to keep the wheelchair and dummy out of the gangway. However, when tests were carried out at different heights allowed by the PSVAR, the wheelchair was able to rotate underneath the rail when subjected to lateral vehicle accelerations of the magnitude possible on bus routes. Based on these findings, the use of a single bar horizontal rail is not recommended, although a design with depth or some form of adjustment may be acceptable.

The results can only be used to give an indication of the performance of the stanchion or rail with respect to the DDA reference wheelchair only. Caution should be exercised when drawing conclusions for other wheelchair types. For instance, the stanchion performed well due to its position in relation to the large rear wheel, enabling it to stop the pivoting action of the wheelchair. The results may have been different for an attendant controlled wheelchair or an electric wheelchair with smaller rear wheels. The ability of the rail to restrict wheelchair movement was highly dependent on its height from the floor of the bus. It is therefore difficult to make recommendations regarding the effectiveness of the device using a single wheelchair type.

The only movement observed was a pivoting about the vertical axis of the left rear wheel; at no time did the wheelchair move forward. The brake performance could have been a factor in the lack of forward excursion of the wheelchair. The brake mechanism of the reference wheelchair appears to be more robust than that of a standard manual wheelchair. In these tests, tyre pressure was set at the lower limit of the recommended inflation level. The action of the brake shoe pressing on the tyre makes correct inflation pressure important. In the real world wheelchair tyres may not be fully inflated. Furthermore, there are occasions when a vehicle is likely to be accelerating whilst executing a turn, for instance entering a roundabout. It was not appropriate to investigate the possible effects of vehicle acceleration during the manoeuvre, as this could not be done with sufficient repeatability. However, it is possible that there would be a weight transfer to the front of the wheelchair, reducing the grip of the rear wheels.

In summary, the vertical stanchion appeared to provide a better means of restraining the wheelchair, although this conclusion requires validation against other wheelchair types, especially those with smaller wheels. The performance of the moveable horizontal rail was very dependent upon the dimensions of the wheelchair involved, and it is hard to see how the situation could be improved. This type of restraint therefore gives rise for concern, although again, tests with other designs of wheelchairs should be carried out before any actions are decided upon.

8 Information for regulatory impact assessment

8.1 Whelchair users

It is estimated that there are around 1,200,000 wheelchair users in this country representing approximately 2% of the population. If wheelchair users have the same social need to travel and the same ability to do so then it would be reasonable to assume that in all modes of transport wheelchairs users may represent 2% of all travellers. There is insufficient information on which to compare the travel patterns of wheelchair users with that of the population as a whole, nor is it possible to identify the proportion of wheelchair users who may transfer to a vehicle seat when travelling. However, it is unlikely that wheelchair users as group travel to the same extent as the population as a whole and we can be certain that not all will travel seated in a wheelchair. Furthermore, the travel patterns of wheelchair users may change as more vehicles become wheelchair accessible. In the absence of any information to the contrary it is assumed that wheelchair users who travel seated in their wheelchair will be exposed to 50% of the transport risks compared to other road users (i.e. 1% of the population). On this basis the overall exposure to travel risks may be taken as being proportionate to that of other road users for any type of vehicle that may be wheelchair accessible.

8.2 Cars and taxis (M1)

Cars, taxis and private hire vehicles with no more than 8 passenger seats are all M1 category vehicles[1] . Accident data does not differentiate between these vehicles and therefore they must be considered as a whole. As such they are all referred to as cars. Whilst there may be only a small proportion of private hire vehicles that are wheelchair accessible, many taxis are wheelchair accessible and there is a growing supply of wheelchair accessible cars for private use, for patient transport and similar applications.

8.2.1 Accident data

For the year 2000 RAGB accident data shows 1,665 car drivers and passengers killed and 18,054 seriously injured. This is a slight improvement on both the 94-98 baseline average of 1,762 and 21,492, and the 96-2000 average of 1,730 and 20,071 respectively. If, in future, 1% of these are wheelchair users there is the potential for them to be involved in 180 serious injuries and 16 fatalities per year based on the data for the year 2000. The findings of this research project indicate that improvements are needed if wheelchair users are to be afforded an equivalent level of protection to that of other vehicle occupants. This suggests that making no changes is likely to result in a higher number of wheelchair user casualties than is estimated here. However, there is no evidence to suggest that such levels of injury are occurring at present. This suggests that either current travel patterns are lower than they are estimated to be in the future or other

[1] *Excludes special purpose M1 vehicles*

factors, such as the nature of the journeys undertaken or the wheelchair location in a vehicle, have an influence on the exposure to transport risks.

8.2.2 Vehicle design changes

M1 vehicles are already equipped with a means of securing a wheelchair and are fitted with a wheelchair occupant restraint. The significant additional factors recommended for future designs include the provision of a head and back restraint for rear facing occupants, technical requirements based on a more representative deceleration test pulse (see Section 2) and provision of an adequate space envelope in the vehicle. The recommendations may lead to a fundamental re-appraisal by industry on the design of wheelchair accessible vehicles particularly in the taxis sector where traditionally vehicles are designed for a rear facing wheelchair user.

In order to provide an equivalent level of protection to that of a seated passenger, a wheelchair user, when rearward facing, must be provided with a head and back restraint with a padded surface meeting requirements for energy absorption. In addition, there must be sufficient space for lower rear protrusions on the wheelchair to pass under the head and back restraint to allow the wheelchair seat back to come close the head and back restraint. Where a wheelchair user is forward facing a head and back restraint, although highly desirable, is not essential and is therefore not considered (see 11.1). For both forward and rearward facing wheelchair users additional protection can be provided for the lower limbs but this goes further than that provided for other seated occupants and is therefore excluded. In the case of vehicles designed for a particular individual for personal use, some relaxation of the space requirement is possible so that some of the smaller vehicles may continue to be used as effective personal transport for wheelchair users without compromising safety.

The deceleration test pulse used to evaluate the survivability of wheelchair users within this project will involve some strengthening of vehicle structures. This test pulse is not replicated in all legislation relating to M1 vehicles but is expected to be the minimum standard in the near future.

8.2.3 Annual production estimates

Wheelchair accessible vehicles (M1) (forward facing) 3,000.

Taxis (M1) (rear facing) 3,000.

8.2.4 Cost estimates

Estimated cost of a head and back restraint for a rear-facing wheelchair arrangement: £400 per vehicle.

Additional structural strength M1 (anchorages or bulkhead supporting head and back restraint): £ 20 per vehicle.

Additional cost of adjustable wheelchair occupant restraint: £5 per vehicle.

Total cost 3,000 (400 +20+5) + 3,000 (20+5) = 1,350,000 or 1.35 £m.

8.2.5 Casualty cost savings

From RAGB 2000 casualty costs are as follows: £1,144,890 per fatality, £128,650 per serious injury, and £9,920 per slight injury. The measures proposed are aimed at improving the level of survivability and reducing the severity of injuries in accidents. From the number of potential fatal and serious injuries it is expected that the measures taken may reduce fatal injuries to serious, and serious injuries to slight, however, these measures are an improvement over existing provisions and therefore the overall improvement is taken to be 20%. Therefore the potential cost savings are: (16(1144890 – 128650) + 180(128650 – 9920)) x 20% giving a total of £7,526,248 or £7.53m.

8.3 Minibuses (M2)

Vehicles of category M2 include vehicles with more than eight passengers but not exceeding 5 tonnes maximum mass. The majority of these vehicles are mass produced minibuses with 9 to 16 seats and usually less than 4 tonnes maximum mass. Vehicles of this type are popular in the community, Local Authority, health and voluntary transport sectors, many of which will be wheelchair accessible.

8.3.1 Accident data

For the year 2000 RAGB accident data shows 11 passengers killed and 94 seriously injured. This may be compared with both the 94-98 average of 8.6 and 129, and the 96-2000 average of 8.4 and 126.4 respectively. Annual casualty numbers fluctuate widely with no particular trend emerging. On this basis the 96-2000 average is taken to be representative of potential casualties. If, in future, 1% of these casualties are wheelchair users there is the potential for them to be involved in 0.084 fatalities and 1.264 serious injuries per year. The findings of this research project indicate that improvements are needed if wheelchair users are to be afforded an equivalent level of protection to that of other vehicle occupants. This suggests that making no changes is likely to result in a higher number of wheelchair user casualties than is estimated here.

8.3.2 Vehicle design changes

M2 vehicles are already equipped with a means of securing a wheelchair and are fitted with a wheelchair occupant restraint. The significant additional factors recommended for future designs include technical requirements based on a more representative deceleration test pulse (see Section 2) and potentially the need for more space in the vehicle.

The recommendations for M2 vehicles are the same as those for M1 vehicles. It would be unusual to find a rearward facing wheelchair arrangement in such vehicles at present and the recommendation for a head and back restraint would further discourage such an arrangement due to the constraints of space and access. The effect of a new regulatory proposal is therefore assessed for forward facing wheelchair users in line with current practice. As with M1 vehicles a head and back restraint and protection for the lower limbs is not considered to be essential.

The deceleration test pulse used to evaluate the survivability of wheelchair users within this project will involve some strengthening of vehicle structures. For M2 vehicles there is research evidence to suggest that this test pulse should be adopted, but it is a significant departure from current requirements. Additional structural strength is likely to bring additional costs although these will be less when engineered from the outset as for volume production vehicles or when part of a coach built structure. For the purpose of costs it is assumed that vehicles will usually have a flexible seating/ wheelchair arrangement and be capable of accommodating up to 6 wheelchairs.

8.3.3 Annual registrations

A total of 10,000 vehicles are estimated to be registered annually of which 2,000 are believed to be wheelchair accessible. It should be noted that these figures are based on M2 vehicles with no more than 16 passenger seats. The number of vehicles with more than 16 passenger seats within the M2 category is unknown but the number likely to be wheelchair accessible and be required to have seat belts for other passengers is thought to be small.

8.3.4 Cost estimates

Additional structural strength: £120 per vehicle.

Additional cost of adjustable wheelchair occupant restraint: £30 per vehicle.

Cost of proposals 2000 x (120+30) = £300,000.

8.3.5 Casualty cost savings

From RAGB 2000 casualty costs are as follows: £1,144,890 per fatality, £128,650 per serious injury, and £9,920 per slight injury. The measures proposed are aimed at improving the level of survivability and severity of injury accidents. From the number of potential fatal and serious injuries it is expected that the measures taken may reduce fatal injuries to serious, and serious injuries to slight with a 20% improvement over existing provisions. The potential cost are: (0.084(1144890 – 128650) + 1.264(128650 – 9920)) x 20% giving a total saving of £47,088.

8.4 Buses and coaches (M3)

Buses and coaches in this category are vehicles with more than 8 passengers and exceeding 5 tonnes maximum mass. In less than 20 years all such buses used to provide local or scheduled services are required to be wheelchair accessible.

Those that are designed to carry standing passengers are not required to be fitted with seat belts and it is widely accepted that the way in which such vehicles are used is satisfactory for a wheelchair user travelling rearward facing without any wheelchair or occupant restraint system (see Section 7). Regulations are already in place for these vehicles and nothing within the recommendations of this report is likely to add to vehicle costs.

For vehicles that do not carry standing passengers seat belts are required. In these vehicles a wheelchair user will normally travel forward facing and therefore the cost of complying with revised technical requirements are considered for this arrangement only.

8.4.1 Accident data

RAGB provides casualty data for large buses and coaches. This includes M2 vehicles with more than 16 passenger seats, although the number of such vehicles that are wheelchair accessible and required to be fitted with seat belts for passengers is considered to be small. This accident data is based on some 67,000 public service vehicles of which it is estimated 13,000 will be coaches. Previous data suggests that approximately half of passenger casualties relate to boarding or alighting. RAGB for the year 2000 shows 14 fatalities and 513 serious passenger injuries and compares to the 94-98 baseline average of 19 and 626, and the 96-2000 average of 13 and 546. Taking data for the year 2000 gives a potential of 7 fatalities and 257 serious injuries for moving vehicle injury accidents. However, not all such injury accidents will relate to coaches and not all coaches will be required to be wheelchair accessible based on current DfT regulations. If only 19% of vehicles are coaches, the potential casualties by this mode are reduced to 1.33 fatalities and 48.83 serious injuries. If, in future, 1% of these casualties are wheelchair users then there is the potential for them to be involved in 0.0133 fatalities and 0.4883 serious injuries per year. The findings of this research project indicate that improvements are needed if wheelchair users are to be afforded an equivalent level of protection to that of other vehicle occupants. This suggests that making no changes is likely to result in a higher number of wheelchair user casualties than is estimated here.

8.4.2 Vehicle design changes

The provisions are very similar to those for cars and minibuses but based on a deceleration test pulse that is identical that of European Directive 96/37/EC. The requirements are similar to PSVAR 2000 and Directive 2001/85/EC but the static test loads are higher and in the forward direction, and are more than 2 $^{1}/_{2}$ times current PSVAR requirements. On the plus side, the structural strength in the localised area of a wheelchair space may be easier to accomplish in the custom built body of a coach and therefore the overall effect of these changes is likely to be minimal.

8.4.3 Annual registrations

Wheelchair accessible coaches in the M3 category are estimated to be 100 vehicles per annum. This is based on the requirements of the PSVAR which require all coaches used on local and scheduled services to be wheelchair accessible by 2020. This is some 18 years hence, however, there are some 1300 vehicles involved and it is likely that the replacement cycle for vehicles used on these services will be shorter. For the purpose of annual cost to industry it is anticipated that vehicles will be replaced over a 13 year period at the rate of 100 per annum. Only one wheelchair space per vehicle is assumed to be fitted.

8.4.4 Cost estimates

An estimate of £20 per vehicle for some additional strengthening in the localised area of the anchorages and assuming one wheelchair space per vehicle.

Additional cost of adjustable wheelchair occupant restraint: £5 per vehicle.

Cost: 100 x (20+5) = £2500.

8.4.5 Casualty cost savings

From RAGB 2000 casualty costs are as follows: £1,144,890 per fatality, £128,650 per serious injury, and £9,920 per slight injury. The measures proposed are aimed at improving the level of survivability and severity of injury accidents. From the number of potential fatal and serious injuries it is expected that the measures taken may reduce fatal injuries to serious, and serious injuries to slight with a 20% improvement over existing provisions. The potential costs are: (0.0133(1144890 – 128650) + 0.4883(128650 – 9920)) x 20% giving a total saving of £14298.

9 Discussion

Much discussion of the results is presented in Sections 5 to 8 along with conclusions specific to the vehicles represented by those sections. This section is therefore confined to a discussion of factors common to the whole study and observations of general and related interest.

The scope of the research was to compare the level of safety afforded to people seated in their wheelchairs with that of people seated in vehicle seats, in M category vehicles. The results indicated that concerns arise from this comparison of injury levels for wheelchair seated occupants by over extension of the neck. This was the particularly the case for rear facing occupants in all vehicles. It was demonstrated that the occupant neck kinematics can be significantly improved if the wheelchair is positioned against a head and back restraint, however the head and back restraint must meet the M1 requirements for energy absorption otherwise high head accelerations will result. In addition, there should be no gap between the wheelchair occupant and the head and back restraint for maximum protection. The benefits or disbenefits of a head and back restraint in 2 planes were not investigated within the scope of this project.

The relative merits of an upper anchorage location for the occupant restraint diagonal belt and a floor location were assessed for forward facing occupants in all vehicle categories. In all cases the floor mounted anchorage generated higher loads on the occupant's lumbar spine than the upper anchorage location, however this was usually still lower than the lumbar loads of the vehicle seated occupant. There are no injury criteria for lumbar loads and therefore it cannot be stated whether the occupant is at risk of spinal injury or not purely on the basis of the dummy readings. However, as far as is known, there is not a notable incidence of lumbar spine injury in accidents involving restrained, forward facing occupants, indicating that the vehicle seated occupant does not appear to be at a high level of risk. As the wheelchair seated occupant sees lower lumbar loads than the vehicle seated occupant, it could be argued that the wheelchair occupant is therefore unlikely to be at risk, whichever anchorage method is used.

The reason that the lumbar loads recorded in wheelchair seated occupants are lower than the vehicle seated occupant is due to compliance in the wheelchair structure, but wheelchairs are tending to become stiffer and stronger which is likely to increase lumbar loads significantly. The upper anchorage should therefore still be considered preferable. It should be noted that there is insufficient information on the performance of wheelchairs to draw any further conclusions at this time.

In the case of rear facing M1 vehicles it was necessary to go further than a comparison of the wheelchair and vehicle seated occupants as under some circumstances the vehicle seated occupants can be at risk of neck injury. The survivability of a wheelchair user was therefore taken as the objective.

The research also demonstrated that vehicle anchorages approved to automotive regulations would not be sufficient to withstand the forces generated by a wheelchair. Instead, a specific test would be required of the wheelchair anchorage system applying the forces derived from the dynamic tests. The anchorage test loads recommended as a result of this work are up to 30kN for forward facing passengers in M1 & M2 category vehicles and up to 20kN for M3 vehicles. This compares with equivalent loads ranging from 7 to 17kN for M3 and M2 vehicles respectively as required by Directive 2001/85/EC and PSVAR 2000. There is a lesser but still significant difference for rearward facing passengers. There are no static test loads specified in regulations for M1 vehicles.

The loads in the occupant restraints were found to be high (up to 7kN) in comparison to those of passengers in cars (See Table 3 and Table 20) and might be expected to cause injury in over 50% of fit adults. Some car manufacturers are known to limit the belt loads to 4 kN for this reason. While standard passenger seat belts would be expected to carry loads of this magnitude without failure, limitation of belt load is achieved at the expense of increased excursion and hence increased risk of contact injuries.

On the basis of the above, the objective of providing wheelchair seated passengers equivalent protection is achievable with the recommended changes in vehicle legislation.

Unfortunately, it is not possible to support these arguments with accident data concerning wheelchairs in vehicles as the current accident databases cannot identify whether the injured person was disabled. However, the disabled population is increasing and the DDA will require that their safety is fully considered when travelling in land based public transport.

In the longer term, there are areas outside the scope of this research that will need to be considered. For instance, the restraint of childrens' wheelchairs could raise other issues. Non-standard moulded seating systems in wheelchairs are frequently used and in these cases the child may sometimes be in a reclined position.

The carriage of luggage was also not considered in the current project although wheelchair users should not carry luggage at the rear of the wheelchair because it has been demonstrated that a gap between the wheelchair and head and back restraint should not be allowed.

It is also recognised that the research assumes the correct use of the restraint equipment. Misuse was not considered and would in any case be difficult to prevent through legislation - this could be more appropriately addressed through training or design.

Finally it had been decided that side impact would be excluded from the study although it is recognised that it may need to be considered for M1 vehicles in particular at a later date.

It should also be borne in mind that the Hybrid III series of dummies are essentially representative of 'fit' adults whereas many disabled and elderly wheelchair occupants may be at greater risk of injury than indicated by these dummies. Unfortunately, little data is available to address such differences and indeed there are some other important differences between the responses of these dummies and humans in accidents. One of these differences is that the spine representation used in frontal impact dummies (such as those used in this work) is less flexible than that of a human and hence may not respond in a truly biofidelic manner under impact loading. Furthermore, these dummies were designed to be forward facing and it could therefore be argued that their biofidelity may be compromised in the rear facing tests. However the arguments presented for the dummy selection in Section 2.1.5 are robust, and the comparative nature of the tests means the results can be used to give an indication of the difference in occupant loading as a result of different systems.

10 Conclusions

- Based on the research described in this report, wheelchair seated passengers are not currently provided with an equivalent level of safety as vehicle seated passengers.
- Changes in legislation are required to improve the safety of wheelchair seated passengers in all M category vehicles (except normal transit buses).
- For normal transit buses the limitations of this research is such that no conclusions can be reached regarding improvements to the current legislative requirements in Great Britain.
- The presence of a head and back restraint is essential for rear facing occupants and desirable for forward facing occupants to minimise neck injuries. There should be no gap between the wheelchair occupant and the head and back restraint.
- The diagonal part of the wheelchair occupant’s seat belt should be anchored to a third point at shoulder level to minimise lumbar spine loading and occupant excursion.
- There should be sufficient space in the vehicle to prevent occupant contact with the interior unless appropriate protection is provided (see recommendations for dimensions).
- Vehicle anchorages approved to automotive seat-belt regulations would not be sufficient to withstand the forces generated by a wheelchair and occupant where both are attached to a single anchorage. Instead a specific test would be required of the anchorages, applying the forces derived from the dynamic tests (see recommendations).

Recommendations for future research

- Future research should consider children. This could include an examination of the wide range of wheelchairs available to children and how they should be restrained.
- Only frontal impact was considered (for both forward and rear facing passengers) within the scope of the project. It may be desirable to investigate side impact in future research.
- Restraint misuse was also outside the scope of this project, however, it would be beneficial to reduce the potential for misuse. This could be achieved through engineering or educational means despite it being difficult to address through legislation as described earlier.

11 Recommendations

The following are the recommendations for vehicle requirements as concluded by TRL from the programme of numerical simulation and testing described in this report. A corresponding full set of specifications based on these recommendations (as developed by SAVE Transport Consultancy) are given in Appendix E.

11.1 M1 and M2 forward facing

Vehicle anchorages

It is recommended that four vehicle anchorages or an equivalent system is provided for each wheelchair location.

A four point anchorage system should comprise two for attachment at the front of the wheelchair and two at the rear of the wheelchair. Alternatively it is acceptable to provide a system with only two attachment points on the wheelchair, either for convenience or to permit self docking systems. In this case these should be provided to allow attachment towards the rear of the wheelchair and should be capable of sustaining the same forces as the anchorages of the four anchorage system. Part of a back restraint or other structure may act upon the wheelchair as part of the system in order to restrain the wheelchair in both the forward and rearward direction.

It is recommended that the strength of the vehicle anchorages be assessed in a static strength test:

- Each of the rear anchorages should be able to sustain a force of 30kN when applied forwards and upwards at an angle of 45° to the horizontal.
- Each of the front anchorages (where provided) should be able to sustain a force of 5kN when applied rearwards and upwards at an angle of 45° to the horizontal.
- 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.

The relative location of the vehicle anchorages should be in accordance with ISO 10542-2, although this standard only refers to 4 point tie-down systems. For other types of tie-down system the manufacturers recommendations should be followed.

While static strength requirements are recommended here based on the dynamic tests performed in this programme, an alternative dynamic strength test, based on the dynamic test for wheelchair tie-downs in ISO 10542-1 using a surrogate wheelchair and a 95th percentile adult male dummy, could be considered, although it was not part of this research programme to develop such a test.

Occupant restraint

It is recommended that the occupant restraint is provided by a lap and diagonal seatbelt. The lap belt part should be anchored to the floor. Due to their potential to cause compressive injuries to the spine, shoulder belts anchored to the floor are not normally recommended for vehicle seating positions. The research in this programme indicated that, although the lumbar spine forces for floor mounted shoulder belts were higher than for shoulder belts anchored at the upper location, they were still lower than for the dummy seated in the normal vehicle seat. On this basis, either upper anchorage mounted or floor mounted shoulder belts would be acceptable. However, the fact that lumber spine forces can be reduced by providing an upper anchorage it is recommended that, where possible, shoulder belts be provided with an effective upper anchorage to restrain the wheelchair occupant.

For strength requirements, it is recommended that the anchorages be assessed by a static strength test. The two lower anchorages should withstand, without failure, forces of 25kN applied forwards and upwards at an angle of 30° to the horizontal, for a minimum period of 0.2 seconds.

The upper anchorage should withstand a static force of 8kN applied at an angle of 45° forwards and downwards to the surface to which it is attached.

An alternative and more realistic static strength assessment could be made by applying a static force of 27kN via a body block, such as that described in BS 3254 Part 1 (1988) ‘seated’ on a surrogate wheelchair, through a standard three point seat belt attached to the anchorages. This could prove less demanding under some conditions than a test at a fixed angle of 30°, but this test procedure would require development.

Head and back restraint

The conventional seat used for comparison in assessing the potential benefits of a head and back restraint was a high backed seat with a headrest. While this would be expected to lead to a recommendation that wheelchair occupants would need a similar construction to provide an equivalent level of crash protection, it should be noted that most seats fitted to current M1 and M2 vehicles are already high backed, or have a head restraint fitted, even though this is not mandated. It is therefore recommended that forward facing wheelchair occupants in M1 and M2 vehicles be provided with head and back restraints to reduce the risk of neck injury under rebound and in rear impacts. However, it is appreciated that the provision of a vehicle-based head and back restraint could be difficult in some circumstances, for instance in multiple occupancy vehicles. If a head and back restraint is mandated, consideration should be given to the circumstances where exemptions may be necessary for practical reasons. Perhaps in the future, some consideration could be given to wheelchair-mounted head restraints under these circumstances.

Where head and back restraints can be provided, they should meet the following requirements:

Dimensions

The head and back restraint should be reclined rearwards at an angle of 6° ± 2° to the vertical. The lowest edge shall be 510 ±20mm from the floor level and the top shall be at least 1350mm from the floor level. There shall be a clear space behind the head and back restraint to a height of 500mm and width of 750mm to a depth of 400mm from the lower forward edge of the restraint. The width of the head and back restraint shall be a minimum of 240mm to at least 1350mm from the floor level and a maximum of 280mm up to a height of 1200mm.

Energy absorption

The head and back restraint shall comply with the energy absorption requirements set out in Annex 4 of ECE Regulation 21 where the contact zone shall be defined as the forward surfaces of the restraint, within the two vertical longitudinal planes 100mm either side of the mid vertical longitudinal plane of the back restraint and between the two horizontal planes which are 550mm and 1350mm from the floor. The head impact shall be applied perpendicularly to the back restraint surface.

Strength

The head and back restraint shall sustain a force of 10kN for a minimum of 0.2 seconds when applied via a block measuring 700mm high by 400mm wide, with 50mm radiussed edges. The block shall be aligned with the centre line of the back restraint and with its principal vertical axis aligned with the main torso line for the head and back restraint. The centre of the applied force shall be applied horizontally towards the rear of the vehicle at a height of 670mm above the floor level.

Occupant space

It is recommended that the space provided for a wheelchair and occupant shall be not less than 1300mm measured in the longitudinal plane of the vehicle and 750mm in the transverse plane of the vehicle, up to a height of 1500mm measured vertically from any part of the floor of the wheelchair space.

In addition, if it is wished to provide protection for the legs from unyielding and sharp surfaces, there should be a further space 750mm wide, 450mm long and to a height of 750mm ahead of the wheelchair space if there has not been adequate padding provided to any surface within this space liable to be contacted by the wheelchair occupant's legs, e.g. by ensuring that all contactable surfaces within that space comply with the energy absorption requirements of the headform impact test in ECE Regulation 21, Annex 4.

11.2 M1 and M2 rear facing

Vehicle anchorages

It would appear that the conventional 'Y' type wheelchair tie-down is sufficient provided that there is a head and back restraint in contact with the rear back of the wheelchair at the time of impact. The single anchorage for the ‘Y’ restraint should be capable of withstanding a force of 10kN applied rearwards and upwards at an angle of 45° above the horizontal.

Occupant restraint

It is recommended that the occupant restraint is provided by a lap and shoulder seatbelt to minimise the risk of ejection from the wheelchair. Standard ECE Regulation 16 seat belts and anchorages to the ECE Regulation 14 anchorage strength requirements would be suitable for this condition.

Head and back restraint

It is recommended that wheelchair occupants be provided with head and back restraints to reduce the risk of serious neck injury under frontal impact conditions. The head and back restraint should meet the following requirements:

Dimensions

The head and back restraint should be reclined forwards (in the vehicle frame of reference) at an angle of 6° ± 2° to the vertical. The lowest edge shall be 510 ±20mm from the floor level and the top shall be at least 1350mm from the floor level. To ensure that the wheelchair back restraint can be brought into contact with the head and back restraint, there shall be a clear space forward of the head and back restraint to a height of 500mm and width of 750mm to a depth of 400mm from the lower rearward edge of the restraint. The width of the head and back restraint shall be a minimum of 240mm to at least 1350mm from the floor level and a maximum of 280mm up to a height of 1200mm.

Energy absorption

The head and back restraint shall comply with the energy absorption requirements set out in Annex 4 of ECE Regulation 21 where the contact zone shall be defined as the rearward surfaces of the restraint (i.e. those liable to impact from the wheelchair and occupant), within the two vertical longitudinal planes 100mm either side of the mid vertical longitudinal plane of the back restraint and between the two horizontal planes which are 550mm and 1350mm from the floor. The head impact shall be applied perpendicularly to the back restraint surface.

Strength

The head and back restraint shall sustain a force of 100kN for a minimum of 0.2 seconds when applied via a block measuring 700mm high by 400mm wide, with 50mm radiussed edges. The block shall be aligned with the centre line of the back restraint and with its principal vertical axis aligned with the main torso line for the back restraint. The centre of the applied force shall be applied horizontally towards the front of the vehicle at a height of 670 mm above the floor level.

Occupant space

It is recommended that the space provided for a wheelchair and occupant shall not be less than 1300mm measured in the longitudinal plane of the vehicle and 750mm in the transverse plane of the vehicle, up to a height of 1500mm measured vertically from any part of the floor of the wheelchair space.

11.3 M3 forward facing

Vehicle anchorages

It is recommended that four vehicle anchorages or an equivalent system is provided for each wheelchair location.

A four point anchorage system should comprise two for attachment at the front of the wheelchair and two at the rear of the wheelchair. Alternatively it is acceptable to provide a system with only two attachment points on the wheelchair, either for convenience or to permit self docking systems. In this case these should be provided to allow attachment towards the rear of the wheelchair and should be capable of sustaining the same forces as the anchorages of the four anchorage system. Part of a back restraint or other structure may act upon the wheelchair as part of the system in order to restrain the wheelchair in both the forward and rearward direction.

It is recommended that the strength of the vehicle anchorages be assessed in a static strength test:

- Each of the rear anchorages should be able to sustain a force of 20kN when applied forwards and upwards at an angle of 45° to the horizontal.
- Each of the front anchorages should be able to sustain a force of 5kN when applied rearwards and upwards at an angle of 45° to the horizontal.
- 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.

The relative location of the vehicle anchorages should be in accordance with ISO 10542-2, although this standard only refers to 4 point tie-down systems. For other types of tie-down system the manufacturers recommendations should be followed.

While static strength requirements are recommended here based on the dynamic tests performed in this programme, an alternative dynamic strength test based on the dynamic test for wheelchair tiedowns in ISO 10542-1, using a surrogate wheelchair and a 95th percentile adult male dummy, could be considered, although it was not part of this research programme to develop such a test.

Occupant restraint

It is recommended that the occupant restraint is provided by a lap and diagonal seatbelt. The lap belt part should be anchored to the floor. Due to their potential to cause compressive injuries to the spine, shoulder belts anchored to the floor are not normally recommended for vehicle seating positions. The research in this programme indicated that, although the lumbar spine forces for floor mounted shoulder belts were higher than for shoulder belts mounted at the upper location, they were both lower than for the dummy seated in the normal vehicle seat. On this basis, either upper anchorage mounted or floor mounted shoulder belts would be acceptable. However, the fact that lumber spine forces can be reduced by providing an upper anchorage it is recommended that, where possible, shoulder belts be provided with an effective upper anchorage to restrain the wheelchair occupant.

For strength requirements, it is recommended that the seat belt anchorages be assessed by a static strength test. The two lower anchorages should withstand, without failure, forces of 16kN applied forwards and upwards at an angle of 30° to the horizontal, for a minimum period of 0.2 seconds. The upper anchorage should withstand a static force of 5kN applied forwards and downwards at 45° to the surface to which it is attached.

An alternative and more realistic static strength assessment could be made by applying a static force of 9kN via a body block, such as that described in BS 3254 Part 1 (1988) ‘seated’ on a surrogate wheelchair, through a standard three point seat belt attached to the anchorages. This could prove less demanding under some conditions than a test at a fixed angle of 30°, but this test procedure would require development.

Head and back restraint

It would be beneficial, but not essential, for wheelchair occupants, forward facing in M3 vehicles, to be provided with head and back restraints to reduce the risk of neck injury under rebound and in rear impacts. Where head and back restraints can be provided, they should meet the following requirements:

Dimensions

The head and back restraint should be reclined rearwards at an angle of 6° ± 2° to the vertical. The lowest edge shall be 510 ±20mm from the floor level and the top shall be at least 1350mm from the floor level. The requirement for a clear space behind the head and back restraint to allow the wheelchair to be restrained in close contact with the back restraint is not necessary for forward facing in M3 vehicles.

Energy absorption

The head and back restraint shall comply with the energy absorption requirements set out in Annex 4 of ECE Regulation 21 where the contact zone shall be defined as the forward surfaces of the restraint, within the two vertical longitudinal planes 100mm either side of the mid vertical longitudinal plane of the back restraint and between the two horizontal planes which are 550 and 1350mm from the floor. The head impact shall be applied perpendicularly to the back restraint surface.

Strength

Since the head and back restraint is not essential in this condition, no strength requirements are proposed.

Occupant space

It is recommended that the space provided for a wheelchair and occupant shall be not less than 1300mm measured in the longitudinal plane of the vehicle and 750mm in the transverse plane of the vehicle, up to a height of 1500mm measured vertically from any part of the floor of the wheelchair space.

In addition, if it is wished to provide protection for the legs from unyielding and sharp surfaces, there should be a further space 750mm wide, 300mm long and to a height of 750mm ahead of the wheelchair space if there is not adequate padding on any surface within this space liable to be contacted by the wheelchair occupant’s legs, e.g. by ensuring that all contactable surfaces within that space comply with the energy absorption requirements of the headform impact test in ECE Regulation 21, Annex 4.

11.4 M3 rear facing fitted with seat belts

This project considered the use of wheelchair users travelling rearward facing in coaches. Coaches are required to have seat belts fitted for all passengers and therefore an equivalent level of protection is to be afforded to a wheelchair user.

Vehicle anchorages

It would appear that the conventional ‘Y’ tie-down for the wheelchair is sufficient.

There is also a recommendation for the head and back restraint to be in contact with the back of the wheelchair at the time of an impact. The single anchorage for the ‘Y’ restraint should then be capable of withstanding a force of 5kN applied at an angle of 45° above the horizontal.

Occupant restraint

It is recommended that the occupant be restrained by a lap and diagonal seatbelt to avoid ejection from the wheelchair on rebound or in other accident circumstances. Standard ECE Regulation 16 seat belts and anchorages to the ECE Regulation 14 anchorage strength requirements, applicable to M3 vehicles, would be suitable for this condition.

Head and back restraint

It is recommended that wheelchair occupants be provided with head and back restraints to reduce the risk of serious neck injury under frontal impact conditions. The head and back restraint should meet the following requirements:

Dimensions

The head and back restraint should be reclined forwards (in the vehicle frame of reference) at an angle of 6° ± 2° to the vertical. The lowest edge shall be 510 ±20mm from the floor level and the top shall be at least 1350mm from the floor level. There shall be a clear space forward of the head and back restraint to a height of 500mm and width of 750mm to a depth of 400mm from the lower rearward edge of the restraint. The width of the head and back restraint shall be a minimum of 240mm to at least 1350mm from the floor level and a maximum of 280mm up to a height of 1200mm.

Energy absorption

The head and back restraint shall comply with the energy absorption requirements set out in Annex 4 of ECE Regulation 21 where the contact zone shall be defined as the rearward surfaces of the restraint, within the two vertical longitudinal planes 100mm either side of the mid vertical longitudinal plane of the back restraint and between the two horizontal planes which are 550mm and 1350mm from the floor. The head impact shall be applied perpendicularly to the back restraint surface.

Strength

The head and back restraint shall sustain a force of 50kN for a minimum period of 0.2 seconds when applied via a block measuring 700mm high by 400mm wide, with 50mm radiussed edges. The block shall be aligned with the centre line of the back restraint and with its principal vertical axis aligned with the main torso line for the back restraint. The centre of the applied force shall be applied horizontally towards the front of the vehicle at a height of 670 mm above the floor level.

Occupant space

It is recommended that the space provided for a wheelchair and occupant shall be not less than 1300mm measured in the longitudinal plane of the vehicle and 750mm in the transverse plane of the vehicle, up to a height of 1500mm measured vertically from any part of the floor of the wheelchair space.

11.5 Normal transit

Current regulations require forward facing wheelchairs on normal transit buses to be provided with a tie down system. This aspect has not been considered and does not form part of this report.

This project considered the use of wheelchairs travelling rearward facing in normal transit buses. Buses are not required to be fitted with seat belts and may also carry standing passengers. On this basis current regulations permit a wheelchair user to travel rearward facing without any tie-down system. A back restraint must be provided and suitable arrangements to keep the wheelchair from moving out of the wheelchair space under normal driving conditions. It is this latter aspect that this project has considered.

The vertical stanchion appeared to provide a better means of restraining the wheelchair than a horizontal rail, although this conclusion requires validation against other wheelchair types, especially those with smaller wheels.

The performance of the moveable horizontal rail was very dependent upon the dimensions of the wheelchair involved, and it is hard to see how the situation could be improved. This type of restraint therefore gives rise for concern, although again, tests with other designs of wheelchairs should be carried out before any actions are decided upon. Further tests with various designs of 'horizontal loop' type rails may also reveal an improved situation.

As a result, no firm recommendations can be made as regards the normal transit situation other than to observe that a vertical stanchion provides restraint against a wider variety of wheelchairs than a horizontal rail. However, it was apparent that the effectiveness of both systems was very dependent on the wheelchair geometry and as only one wheelchair was tested, a recommendation for changes to vehicle requirements cannot be made at this stage.

In view of the above no specification for normal transit in buses is provided in Appendix E.

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Appendix A: Injury criteria and associated performance limit values

Table A1 details the injury criteria and associated performance limit values for the HYBRIDIII family of dummies used in current legislation for a vehicle seated occupant. These values are generally only applicable to the 50th percentile dummy. Reference assessment values are given for the 5th and 95th percentile dummies for an acceptable level of the likelihood of injury. In addition, reference values are also given for injury criteria not currently included in legislation.

Table A2 shows the percentage of adults likely to suffer serious internal chest injury for a given peak diagonal belt load.

Table A1 Injury criteria and performance limits for HYBRIDIII dummies by body region

Injury criterion	*Legislative Performance Limit for 50th %tile HYBRIDIII dummy*	*Legislation / comment*	*Reference Injury Assessment Values for 5th and 95th percentile HYBRIDIII dummies*	
			5th %tile	*95th %tile*
Head				
HIC	1000	Frontal Impact Directive 96/79/EC	1113	957
HIC	500	Reg 80		
Accln 3ms exceedence	80g	Frontal Impact Directive 96/79/EC	N/A	N/A
Excursion	650 mm	Working document ISO/CD 7176/19-1	N/A	N/A
Neck				
Upper neck extension moment	57 Nm	Frontal Impact Directive 96/79/EC	31 Nm	78 Nm
Upper neck flexion moment	190 Nm	Not in legislation	104 Nm	258 Nm
Upper neck tension	Duration varying from 3.1kN for 0ms to 2.9kN for 35ms to 1.1kN for 45 ms	Frontal Impact Directive 96/79/EC	Duration varying from 2.2kN for 0ms to 1.934 kN for 31ms to 0.734kN for 40ms	Duration varying from 4.052 kN for 0ms to 3.561 kN for 37ms to 1.351kN for 40ms

Continued ....

Table A1 (Continued) Injury criteria and performance limits for HYBRIDIII dummies by body region

Injury criterion	*Legislative Performance Limit for 50th %tile HYBRIDIII dummy*	*Legislation / comment*	*Reference Injury Assessment Values for 5th and 95th percentile HYBRIDIII dummies*	
			5th %tile	*95th %tile*
Neck (Continued)				
Upper neck shear	Duration varying from 3.1kN for 0ms to 1.5 kN for 25 - 35 ms to 1.1kN for 45 ms	Frontal Impact Directive 96/79/EC	Duration varying from 2.068 kN for 0ms to 1.0kN for 20 - 29 ms to 0.734kN for 37 ms	Duration varying from 3.807 kN for 0ms to 1.842 kN for 28 - 39ms to 1.351kN for 50ms
Chest				
Compression	50 mm	Frontal Impact Directive 96/79/EC	41 mm	55 mm
Viscous criterion	1.0 m/s	Frontal Impact Directive 96/79/EC	1.0	1.0
Accln 3 ms excedence	30g	Reg 80	N/A	N/A
Accln 3 ms exceedence	60g	Not in legislation.	73g	54g
Lumbar				
Lumbar compression	N/A	Can only be used for comparative purposes	N/A	N/A

Continued ....

Table A1 (Continued) Injury criteria and performance limits for HYBRIDIII dummies by body region

Injury criterion	*Legislative Performance Limit for 50th%tile HYBRIDIII dummy*	*Legislation / comment*	*Reference Injury Assessment Values for 5th and 95th percentile HYBRIDIII dummies*	
			5th %tile	*95th %tile*
Pelvis				
Accln 3 ms exceedence	N/A	No limit but would not expect to be above 60-80g	N/A	N/A
Excursion H-point	N/A		N/A	N/A
Leg				
Excursion knee	375 mm	Working Document ISO/CD 7176/19-1	N/A	N/A

1 *Further criteria do exist in legislation for the leg such as femur load, knee slider, tibia loads and tibia index. However, these criteria are only applicable when the legs are loaded by, for example, a knee bolster, which is not the case for the test or modelling work conducted in this project.*

2 *HIC 1000 indicates a 20% risk of an injury ≥ AIS3, i.e. a serious injury.*

HIC 650 indicates a 5% risk of an injury ≥ AIS3 (Prasad and Mertz 1985 and Mertz et al. 1996).

3 *Chest compression 50 mm indicates 50% risk of an injury ≥ AIS3.*

Chest compression 22 mm indicates 5% risk of an injury ≥ AIS3 (Mertz et al. 1991).

4 *Viscous Criterion 1.0 m/s indicates 25% risk of an injury ≥ AIS4.*

Viscous Criterion 0.5 m/s indicates 5% risk of an injury ≥ AIS4 (Mertz et al. 1985).

5 *Notes 2,3 and 4 refer to 50th percentile adults only.*

Table A2 Percentage of adults likely to suffer internal chest injury with given peak diagonal belt load

Diagonal belt loading (kN)	*Percentage of adults likely to suffer internal chest injury*
4.0	10
5.0	20
6.5	45
7.5	60
8.0	70

Appendix B: Test results

The following pages contain a full set of impact test results for each of the 4 impact conditions investigated. The definition of each test is given in the relevant section of the main text.

B1 M1 and M2 forward facing test results

Test	*Dummy seating position*	*Wheel-chair restraint*	*Dummy*	*Diagonal belt anchor location*	*Head/ back restraint*	*Head*		*Upper neck shear load*		*Upper neck axial load*		*Upper neck moment*		*Chest*		*Lumbar comp kN*	*Pelvis res. 3ms g*	*Diag-onal belt kN*
						Res 3ms g	*HIC_{36}*	*Fore kN*	*Aft kN*	*Ten-sion kN*	*Comp kN*	*Flex-ion Nm*	*Exten-sion Nm*	*Res 3ms g*	*Dx peak mm*			
1	Vehicle seat	N/A	Hybrid III 50th	Upper	N/A	53.53	416	0.02	1.16	2.51	0.14	76.45	23.96	38.66	36.53	2.65	43.66	6.74
2	Manual wheel-chair	4 point webbing	Hybrid III 50th	Floor	No	49.8	399	0.26	1.23	2.16	0.01	98.73	36.71	33.58	54.16	1.58	45.83	7.23
3	Manual wheel-chair	4 point webbing	Hybrid III 50th	Upper	No	62.23	761	0.15	2.00	2.42	0.03	106.52	25.01	41.85	65.23	0.92	39.71	9.21
4	Manual wheel-chair	4 point webbing	Hybrid III 50th	Upper	Yes	49.40	495	0.08	1.64	1.99	0.09	95.06	35.53	41.64	*	1.36	47.38	8.34
5	Manual wheel-chair	4 point webbing	Hybrid III 50th	Upper	Yes with gap	76.61	579	0.11	1.87	2.32	0.41	91.22	49.92	41.30	*	0.13	32.60	7.34

** Transducer failure*

B2 M1 and M2 rear facing test results

						Head		Upper neck shear load		Upper neck axial load		Upper neck bending moment		Chest			
Test	Dummy seating position	Wheel-chair restraint	Dummy	Diagonal belt anchor location	Head/ back restraint	Res 3ms g	HIC_{36}	Fore kN	Aft kN	Ten-sion kN	Comp kN	Flex-ion Nm	Exten-sion Nm	Res 3ms g	Dx peak mm	Lumbar comp kN	Pelvis Res. 3ms g
1	Vehicle seat	N/A	Hybrid III 50th	Upper	N/A	77.86	648	1.26	0.82	2.08	2.64			32.91	18.1	5.9	65.67
2	Manual wheel-chair	2 point webbing	Hybrid III 50th	Upper	No	96.7	951	1.41	1.12	4.14	1.08			39.3	14.5	8.3	74.36
3	Surrogate wheel-chair	2 point	Hybrid III 50th	Upper	No	116.77	1051	1.01	0.26	3.73	2.25			29.09	11.19	12.2	55.57
4	Surrogate wheel-chair	2 point	Hybrid III 50th	Upper	No	133.45	1842	0.64	1.01	2.96	1.98			89.73	15.99	N/A	93.07
5	Manual wheel-chair	2 point	Hybrid III 50th	Upper	Yes	107.44	1116	0.32	0.27	2.44	1.03			35.12	26.19	8.8	72.15
6	Surrogate wheel-chair	2 point webbing	Hybrid III 50th	Upper	Yes	183.67	2590	0.86	0.44	0.86	3.22			26.51	11.85	14	71.75
7	Electric wheel-chair	2 point webbing	Hybrid III 50th	Upper	No	115.01	1139	0.79	0.29	0.77	2.59			152.04	*	N/A	93.07

Continued ....

B2 (Continued) M1 rear facing test results

						Head		*Upper neck shear load*		*Upper neck axial load*		*Upper neck bending moment*		*Chest*			
Test	*Dummy seating position*	*Wheel-chair restraint*	*Dummy*	*Diagonal belt anchor location*	*Head/ back restraint*	*Res 3ms g*	*HIC_{36}*	*Fore kN*	*Aft kN*	*Ten-sion kN*	*Comp kN*	*Flex-ion Nm*	*Exten-sion Nm*	*Res 3ms g*	*Dx peak mm*	*Lumbar comp kN*	*Pelvis Res. 3ms g*
8	Manual wheel-chair	2 point webbing	Hybrid III 50^{th}	Upper	Yes	51.00	193.4	0.72	0.35	3.09	1.03	64.94	60.29	59.92	*	4.29	43.50
9	Manual wheel-chair	2 point webbing	Hybrid III 50^{th}	Upper	With gap	110.3	1667	1.39	1.60	4.84	1.40	169.15	74.89	69.02	*	2.14	61.26

Tests 1 - 7 used LTi bodyshell

Tests 8 and 9 no bodyshell and modified Rescroft head and back restraint

** Transducer failure*

Shaded areas denote channel not measured

B3 M3 forward facing test results

Test	Dummy seating position	Wheel-chair restraint	Dummy	Diagonal belt anchor location	Head/back restraint	Head		Upper neck shear load		Upper neck axial load		Upper neck moment		Chest		Lumbar comp kN	Pelvis res. 3ms g	Diag-onal belt kN
						Res 3ms g	HIC_{36}	Fore kN	Aft kN	Ten-sion kN	Comp kN	Flex-ion Nm	Exten-sion Nm	Res 3ms g	Dx peak mm			
1	Vehicle seat	N/A	Hybrid III 50th	Upper	N/A	32.15	159	0.06	1.12	1.25	0.92			11.81	25.44	2.44	26.11	4.17
2	Surrogate wheel-chair	4 point webbing	Hybrid III 50th	Upper	No	23.78	87	0.43	0.90	0.88	0.10			12.12	27.54	2.57	27.40	4.44
3	Surrogate wheel-chair	4 point webbing	Hybrid III 50th	Floor	No	33.88	148	0.42	1.02	1.33	0.06			14.38	33.2	3.32	28.81	5.17
4	Manual wheel-chair	4 point webbing	Hybrid III 50th	Upper	No	23.18	77	0.15	0.94	0.97	0.09			12.09	27.32	1.40	22.32	5.17
5	Manual wheel-chair	4 point webbing	Hybrid III 50th	Floor	No	27.33	99	0.28	0.84	1.25	0.03			10.41	24.43	2.14	22.48	4.74
6	Manual wheel-chair	4 point clamps	Hybrid III 50th	Upper	No	22.06	74	0.17	0.89	0.76	0.11			11.17	29.77	1.39	22.74	5.61
7	Manual wheel-chair	4 point clamps	Hybrid III 50th	Floor	No	61.22	297	0.16	0.90	0.14	0.41			10.70	23.35	1.56	20.87	4.15

Continued ....

B3 (Continued) M3 forward facing test results

Test	Dummy seating position	Wheel-chair restraint	Dummy	Diagonal belt anchor location	Head/ back restraint	Head		Upper neck shear load		Upper neck axial load		Upper neck moment		Chest		Lumbar comp kN	Pelvis res. 3ms g	Diag-onal belt kN
						Res 3ms g	HIC_{36}	Fore kN	Aft kN	Ten-sion kN	Comp kN	Flex-ion Nm	Exten-sion Nm	Res 3ms g	Dx peak mm			
8	Surrogate wheel-chair	4 point webbing	Hybrid III 95^{th}	Upper	No	27.62	117	0.36	1.14	0.97	0.04			28.72	32.13	#	31.13	5.31
9	Surrogate wheel-chair	4 point webbing	Hybrid III 5^{th}	Upper	No	31.39	154	0.14	0.75	1.00	0.08			25.35	20.85	#	25.71	4.05
10	Manual wheel-chair	4 point webbing	Hybrid III 50^{th}	Upper	Yes	31.38	83	0.09	0.77	0.85	0.09	53.49	21.32	20.95	26.47	1.11	19.99	3.82
11	Manual wheel-chair	4 point webbing	Hybrid III 50^{th}	Upper	Yes with gap	21.94	64	0.08	0.74	0.84	0.20	49.69	14.53	41.30	*	0.85	21.36	3.86

 # Lumbar spine instrumentation not available for this dummy

** Transducer failure*

Shaded area denotes channel not measured

B4 M3 rear facing test results

Test	Dummy seating position	Wheel-chair restraint	Dummy	Diagonal belt anchor location	Head/ back restraint	Head: Res 3ms g	Head: HIC_{36}	Upper neck shear load: Fore kN	Upper neck shear load: Aft kN	Upper neck axial load: Ten-sion kN	Upper neck axial load: Comp kN	Upper neck bending moment: Flex-ion Nm	Upper neck bending moment: Exten-sion Nm	Chest: Res 3ms g	Chest: Dx peak mm	Lumbar comp kN	Pelvis Res. 3ms g
1	Vehicle seat	N/A	Hybrid III 50th	N/A	N/A	55.14	223	0.46	0.12	1.27	0.55			8.02	3.8		20.77
2	Manual wheel-chair	None	Hybrid III 50th	None	Yes	80.10	460	0.24	0.15	1.11	0.39			7.84	*		26.27
3	Surrogate wheel-chair	None	Hybrid III 50th	None	Yes	91.94	557	0.46	0.31	1.46	1.11			10.33	*		23.06
4	Manual wheel-chair	2 point webbing	Hybrid III 50th	Upper	Yes	43.38	214	0.28	0.20	1.37	0.21	18.48	13.27	24.72	*	2.06	23.25
5	Manual wheel-chair	2 point webbing	Hybrid III 50th	Upper	Yes with gap	58.50	437	0.56	0.37	2.56	0.98	51.89	13.27	41.86	*	2.31	27.48

Shaded area denotes channel not measured

** Transducer failure*

Appendix C: Simulation study

C1 Model description

C1.1 Wheelchair models

Three separate wheelchair models were developed to match the mass and rigidity of the three wheelchairs chosen for the investigations (manual, electric and surrogate wheelchairs). With the exception of the surrogate wheelchair all wheelchair dimensions used to develop the wheelchair models were measured directly from the wheelchairs. Dimensions for the surrogate wheelchair were taken from International Standard ISO/DIS 10542-1.

All the wheelchairs were dismantled as far as was practical and the individual components weighed in order to establish the correct distribution and centre of mass for the wheelchairs. A number of individual component masses were estimated from the combined mass of the attached weighed components. Calculations on the rotational inertia of the individual components were based on the rudimentary shapes of the components. It was anticipated that the inaccuracy in the model rotational inertia calculations was inconsequential to the model predictions as it was estimated that there would be limited rotation of the wheelchairs in the model runs.

Informed judgements had to be made on how the wheelchairs would respond and deform under loading and many of these characteristics of the wheelchairs were finalised in the validations of the wheelchair models. It was assumed that the frame and seat of the surrogate wheelchair would not deform under loading. In the case of the manual and electric wheelchairs, video footage from previous testing of wheelchairs to ISO 7176/19 were examined to establish the common points of failure and deformation of these wheelchairs under loading. However, it was not possible to determine the magnitude and form of loading which had caused these deformations to occur. To match the flexibility observed in the tests, alterations were made to the joint and spring stiffnesses connecting the rigid bodies of the wheelchair frames together. It was assumed in both the manual and electric wheelchairs that the FE seat pan and seat back have elastic properties and that they neither ripped nor broke away from the wheelchair frame under loading. Further work would be needed to establish the true modes of failure and deformations of these wheelchairs under loading to improve the performance/predictions of the wheelchair models.

Manual wheelchair model structure

Figure C1 presents a diagram of the modelled manual wheelchair. Rigid bodies have been used to form the wheelchair frame and joints and springs introduced between these rigid bodies to match those present in the actual wheelchair and to approximate the correct degree of wheelchair stiffness. All wheels in the model are able to rotate and this is true for all the wheelchair models. However, for all model runs all rear wheels in the wheelchair models were braked.

Figure C1 MADYMO model of the manual wheelchair

Finite elements have been used to accurately model the surface profile of the canvas seat back and seat pan. These are rigidly fixed at their peripheral edges to the rigid structures in the wheelchair model used to support the seat back and seat pan.

Electric wheelchair model structure

The fundamental structure of the electric wheelchair is similar to that for the manual wheelchair with the exception of some additional rigid features. Further to the manual wheelchair the electric wheelchair has two electric motors to drive the rear wheels, a battery pack and two small wheels protruding from the back of the wheelchair which prevent the chair from tipping over backwards when mounting obstacles such as kerbs. Furthermore, a rigid tubular section is fixed between the uprights that support the canvas seat back. This provides additional rigidity to the wheelchair when assembled for use. The electric wheelchair is illustrated in Figure C2.

Surrogate wheelchair model structure

Figure C3 provides an illustration of the surrogate wheelchair model. This was modelled as a rigid structure consisting of a rigid frame attached to which are rigid planes representing the seat pan, seat back, leg board and foot rest. Four wheels are attached to this rigid structure by joints, which allow the wheels to rotate.

Figure C2 MADYMO model of the electric wheelchair

Figure C3 MADYMO model of the surrogate wheelchair

C1.2 Dummy models

The MADYMO software is supplied with a family of validated Hybrid III dummy models (5th, 50th and 95th percentile). For the purposes of this modelling study, it was necessary to position these dummies in the modelled wheelchairs and also to fit the occupant restraints over the dummies.

Further to the family of Hybrid III dummy models, a 50th percentile human body model has recently been developed in MADYMO, which provides a more human-like biofidelic response than the Hybrid III dummy model. It would have been possible to use the human body model in this modelling study. However, use of the 50th percentile human body model would have prevented model predictions being compared directly with test results and would have invalidated the use of the injury criteria outlined in Appendix 1 to interpret model predictions. However, this is a useful reference for any future modelling studies requiring a more biofidelic human body model.

C1.3 Vehicle interiors

Rear facing taxi and bus interiors were developed for the modelling studies.

Measurements were taken directly from a purpose built taxi interior to develop the rear facing taxi interior model and establish the location of the wheelchair restraint and occupant tie-down points within the taxi.

The details of the modelled bus interior were taken from EC Directive 2001/85 and the dimensions of the wheelchair back restraint used in the bus were measured directly from a back restraint conforming to the Public Service Vehicles Accessibility Regulations (2000). These regulations do not require either the occupant or wheelchair to be restrained in the designated wheelchair space on large buses and so the model replicated this situation.

No interior models were developed for the forward facing M1 situation as no taxis have this arrangement. However, in order to give some idea of the possible confines of a forward facing M1 vehicle, a converted forward facing MPV (modified for personal use) was measured and the vehicle dimensions were used as boundary thresholds against which the dummy excursions were compared. Interior models were also not provided for M3 coaches as it was assumed that interaction with the vehicle interior would not occur in this type of vehicle.

The location of the tie-down points for the three point occupant restraints in the forward facing M1 vehicle and M3 coach were initially taken from the converted MPV. These were located behind and positioned laterally wider than the width of the wheelchair in order to allow access for the wheelchair occupant from the rear of the vehicle. However, this set-up did cause problems in the model runs in which the shoulder strap of the occupant restraint was attached to the floor. It was noticed in these model runs that the dummy failed to return back into the wheelchair seat following the impact. However, the results from an almost identical test conducted at Millbrook revealed that the dummy did return back into the seat following the impact. It was noticeable that one fundamental difference between the set-up of the Millbrook test and that of the model was that the floor attachment for the shoulder strap was positioned directly behind the connecting shoulder, rather than lateral to the width of the wheelchair as had been set up in the model. Replicating the same positioning of the shoulder strap floor tie-down in the model resulted in the dummy returning back into the wheelchair seat after impact. This difference in the positioning for the floor attachment of the seat belt is illustrated in Figure C4. Consequently, model runs in which the floor rather than the upper anchoarge was used positioned the floor tie-down attachment approximately behind the line of the connecting shoulder.

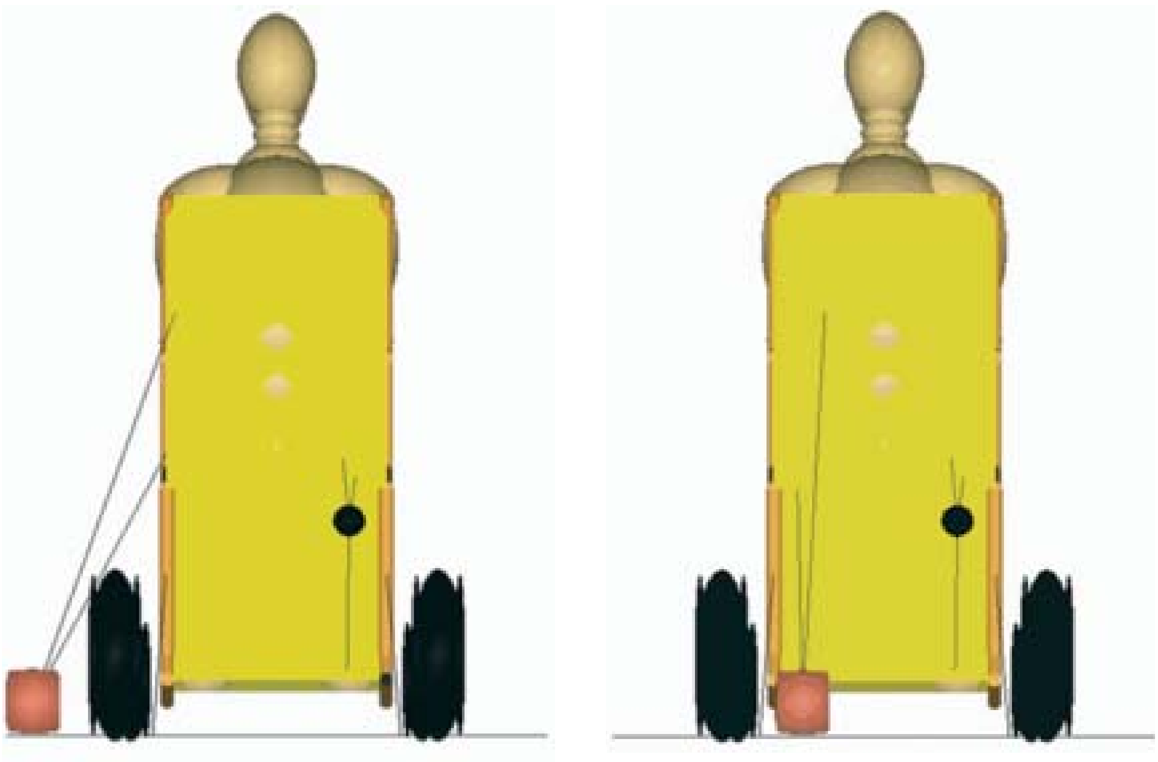

Figure C4 The original and modified tie-down position for the seat belt floor attachment

C1.4 Wheelchair and occupant restraints

Two types of wheelchair restraint systems were investigated in the modelling study, wheelchair tie-downs and clamps. The wheelchair tie-down characteristics/stiffnesses were established during the validation of the models presented in the following section.

Video analysis of sled tests in which clamps had been used to secure a low-mass surrogate wheelchair demonstrated that the frame of the wheelchair slid through the clamps under loading and relative rotational motion occurred between the wheelchair frame and the clamps. To replicate this response, each wheelchair clamp was modelled by attaching the upper end of a rigid body to the frame of the wheelchair via a translational and a spherical joint and rigidly fixing the lower end of the rigid body to the ground via a point constraint. To achieve the desired amount of translational and rotational motion between the clamp and the wheelchair frame stiffness, characteristics where introduced in these joints to limit the degrees of motion. The magnitudes of these stiffness values were determined during the validation presented in the following section. Occupant belt stiffnesses and other characteristics for the models were taken from a validated occupant vehicle model.

C1.5 Model validation

The responses of the wheelchair combined with that of the wheelchair tie-downs were validated against three forward facing sled tests carried out outside this project and undertaken at either TRL or Millbrook. The tests used HYBRID II dummies and all the wheelchairs were fixed to the sled by 4-point wheelchair tie-downs. A further sled test was used to validate the response of the wheelchair clamps. In this test a low-mass surrogate wheelchair weighing approximately 40 kg was used. To replicate this test set-up the mass of the surrogate wheelchair model was modified to match that used in the test. This was done for the purposes of this model validation run only.

In all the sled tests the dummies were forward facing and the occupant restraint had the shoulder strap attached to the upper location. Furthermore, all deceleration pulses and configurations of the occupant and wheelchair restraints were as defined in ISO/DIS 10542-1. For the model validation runs the deceleration pulses applied to the models were identical to those experienced in the tests. However, in contrast to the tests a HYBRID III dummy model was used in the model validation runs.

Model validation results

In all the validation runs visual inspection of the test videos confirmed that the kinematics of the model matched that observed in the tests. With the exception of the electric wheelchair, comparisons of model predictions and test results was limited to comparing the excursions of the wheelchair, head and knees as these were the only measured data taken from the tests (instrumented dummies had not been used). In addition to the excursions, the results from the sled test involving the electric wheelchair also included the trajectories of the wheelchair, head and knee of the dummy and provided additional results against which the model predictions could be compared.

Table C1 compares the wheelchair, head and knee excursions obtained from the tests and predicted by the models. Comparisons of the predicted and measured wheelchair and body segment trajectories obtained from the test involving the electric wheelchair are presented in Figure C5. As shown in all these results, there is satisfactory agreement between the model predictions and the test results.

Table C1 Validation results from the wheelchair models and their tie-downs

	Wheelchair excursion		*Head excursion*		*Knee excursion*	
Sled test	*Test*	*Model*	*Test*	*Model*	*Test*	*Model*
Manual chair with 4pt tie-downs	91	111	485	528	333	254
Electric with 4pt tie-downs	123	109	639	639	341	396
Surrogate with 4pt tie-downs	156	153	541	479	298	315
Surrogate with clamps	223	223	580	576	349	350

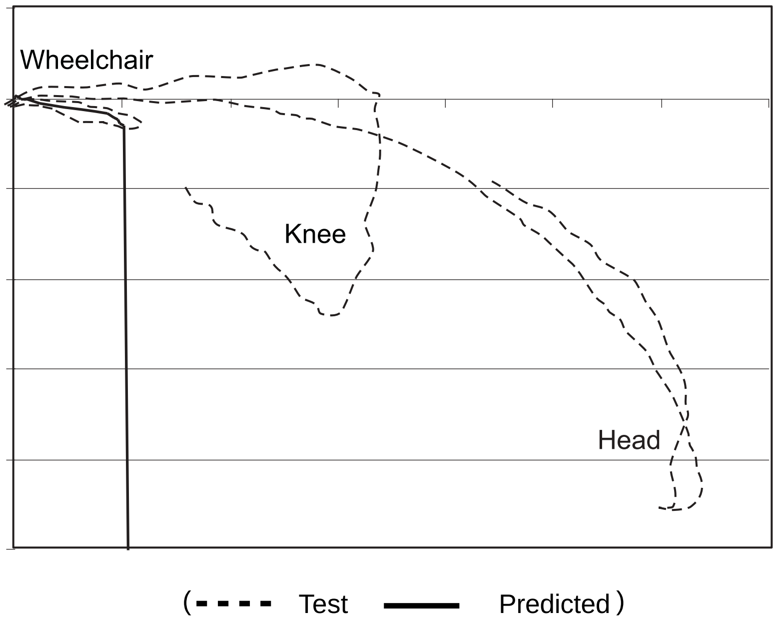

Figure C5 Wheelchair and dummy segment trajectories

Limitations of the model validation

A number of additional measurements from the sled tests would have been beneficial in improving the robustness of the validation process, including:

- Accurate descriptions of the dummy set-ups in the wheelchairs.
- Accurate details of the wheelchair locations on the sleds.
- The belt locations on the sled, wheelchair and dummy.
- The lengths of the belt runs.
- An instrumented dummy with head, thorax and pelvis accelerometers as a minimum.

The model validation has also been limited to testing the whole wheelchair and its tie-downs as one complete system. Additional benefits would have been achieved if components of the wheelchair such as the wheels and tyres, the wheelchair tie-downs and the occupant restraint systems were characterised individually in loading tests so that these could be represented more accurately in the complete model. As a consequence of these limitations, model predictions can only be relied upon to provide qualitative rather than quantitative interpretations of the expected outcome of vehicle accidents.

C2 M1 modelling results

Thirty four model runs were completed investigating the outcome of wheelchair users in taxi and minibus accidents. Within this number there were two fundamental groups of transported wheelchair occupants to investigate; rearward facing and forward facing exposed to a R44 pulse.

C2.1 Rearward facing taxi

Methodology

Figure C6 shows the wheelchair and 50th percentile HYBRIDIII dummy occupant located in the taxi. It was anticipated that the glass partition positioned behind the passenger's head would break during the impact and this fact was later confirmed in the dynamic tests. However, for the purposes of the modelling it was assumed that the glass remained intact in order to ensure that the wheelchair and occupant kinematics were representative of a bulkhead in which the glass partition was mounted higher and hence would not break. The wheelchairs were anchored to the taxi bulkhead by a single strip of belt material, which split to connect to the left and right rear sides of the wheelchair frame. Standard belt properties were used for this restraint.

For this rear facing configuration 12 model runs were made, all using the R44 deceleration pulse, modelling pulse 1, shown in Figure 1. The first three of these investigated the different response of each wheelchair, manual, electric and surrogate. The other runs were completed to investigate how the introduction and change in position and design of a head and back restraint might help in reducing injuries. Three designs of head and back restraint were investigated in conjunction with each wheelchair design. The head and back restraint designs were:

- i A head and back restraint matching the shape and position of that defined in ECE Regulation 17 and rigidly fixed adjacent to the bulkhead fascia of the taxi.
- ii A head and back restraint in which the back restraint is located at the same position as that in (i), but the head restraint is positioned approximately 90 mm closer to the occupant's head than that in (i).
- iii A head restraint only, located in the same position as that defined in (i)

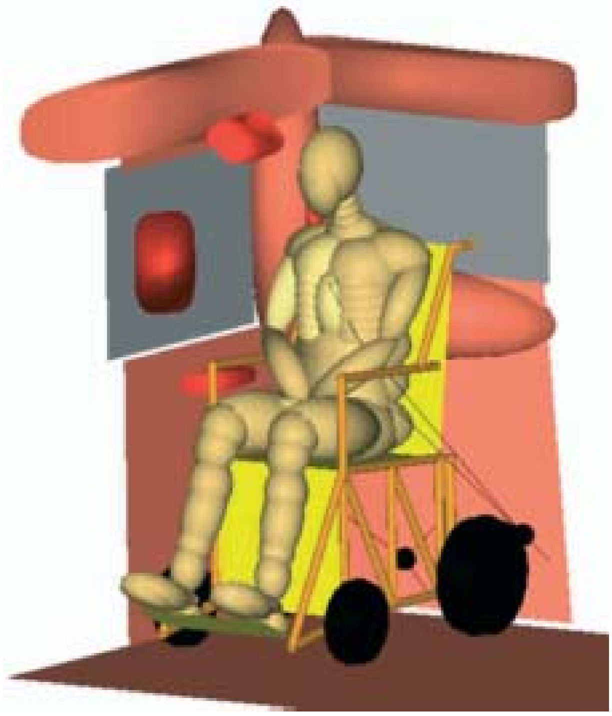

Figure C6 Modelled vehicle interior for the rearward facing taxi model runs

Results and discussion

The HYBRIDIII dummy injury criteria values predicted from the rearward facing taxi model runs are presented in Table C4. The injury criteria values that are above the performance limits detailed in section are highlighted in orange or red. Values highlighted in orange are where the model predictions are between 0 and 10 % greater than the performance limits and values highlighted in red where the predictions are more than 10 % above the performance limits. All non-highlighted values relate to the model predictions, which are below the injury criteria performance limits.

No back restraint

Examination of the results for the runs with no back restraint show that performance limits for the neck extension bending moment and chest and pelvis accelerations were exceeded for all wheelchair types. For the electric wheelchair the HIC and head 3 ms acceleration criteria limits were also exceeded. The explanation for the high neck bending moment is the absence of a head restraint, which allows excessive head rearward motion as shown in Figure C7.

The only realistic way to prevent this and lower neck bending moments to more acceptable levels is to introduce some form of head and / or back restraint to restrain this motion. A possible explanation for the high chest and pelvis accelerations could be that the taxi interior to wheelchair contacts were too stiff. Obtaining experimental quasi-static force displacement curves for these contacts would help to give a more accurate contact description and address this possible problem.

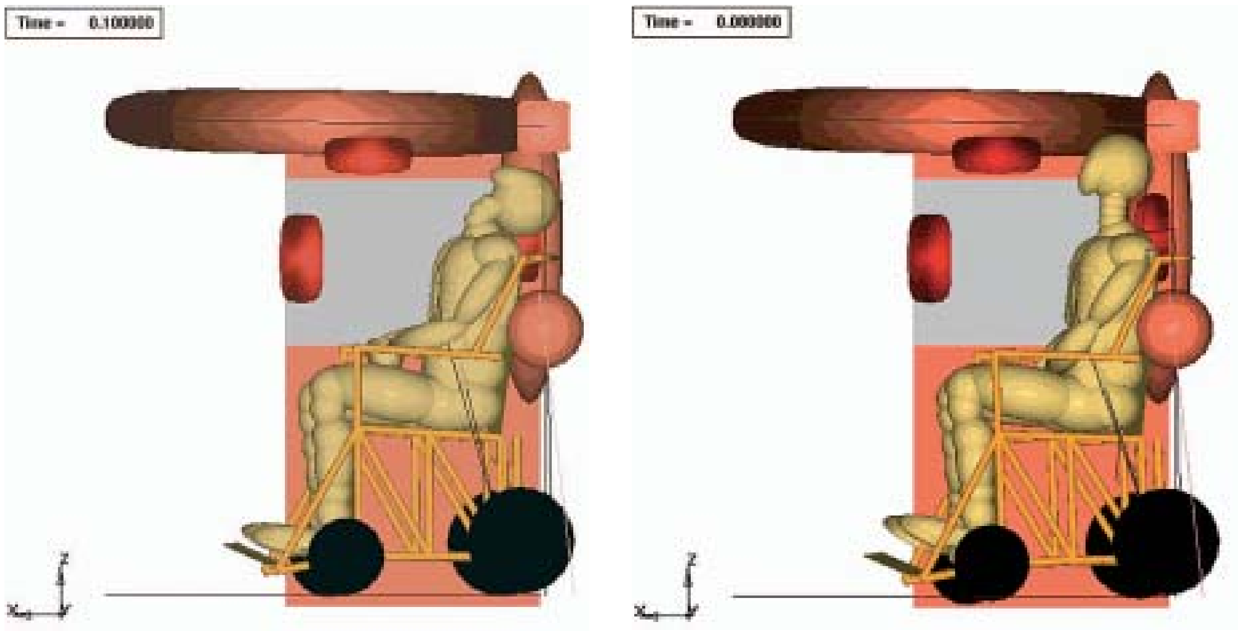

Figure C7 Limits of neck extension for the rearward facing taxi with no back restraint and with a full head and back restraint

Head and back restraint

In general, comparison of the results with and without a head and back restraint show that although the introduction of a head and back restraint is successful in reducing the neck bending moment, it substantially increases the HIC and head 3 ms exceedence values. The configuration of head and back restraint that gives the best overall improvement in neck bending moment is the back restraint with the head restraint positioned 90 mm closer to the occupant's head. The reason why the head and back restraint results in high head injury criteria values is that the head restraint bottoms out during the impact. Hence, to reduce both the neck and head injury criteria values below the performance limits the compliance, and possibly shape, of the head and back restraint would require optimisation.

C2.2 Forward facing taxi/minibus

Methodology

A matrix of twenty eight forward facing model taxi / minibus runs, shown in Table C2, was completed to investigate the effect of wheelchair type, dummy size, wheelchair restraint type, occupant restraint mounting and decreasing the deceleration pulse peak acceleration on dummy injury criteria values and wheelchair tie-down and occupant restraint loads.

Results and discussion

The HYBRIDIII dummy injury criteria values predicted from the forward facing taxi model runs are presented in Table C5 and Table C6 for the deceleration pulse 1 and pulse 2, respectively. Both deceleration pulses fall within the R44 defined corridors (see Figure 1) but pulse 1 has a peak

Table C2 Matrix of model runs completed to investigate forward facing taxi / minibus

Wheelchair type			*Dummy percentile size*			*Wheelchair restraint type*		*Occupant restraint mounting*		
Man	*Surr*	*Elec*	*5*	*50*	*95*	*Clamp*	*Web*	*Upper*	*Floor*	*Decel pulse*
■			■				■	■		Pulse 1
	■		■				■	■		Pulse 1
		■	■				■	■		Pulse 1
■				■			■	■		Pulse 1
	■			■			■	■		Pulse 1
		■		■			■	■		Pulse 1
■					■		■	■		Pulse 1
	■				■		■	■		Pulse 1
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	■			■					■	Pulse 2
		■		■					■	Pulse 2

acceleration of approximately 20g whereas pulse 2 has a peak acceleration of approximately 25g. The injury criteria values that are above the performance limits detailed in Section 0 are highlighted in orange or red as for the rearward facing taxi runs. Wheelchair tie-down and occupant restraint loads and lumbar spine loads are shown in Table C7 and Table C8, for deceleration pulses 1 and 2, respectively.

Upper / floor mounted occupant restraint

There are two basic types of wheelchair occupant restraint, one in which the belt is routed through an upper location and the other in which no upper location is present and the belt is routed directly from the floor to the wheelchair occupant's shoulder. This latter type is referred to as 'floor mounted'.

If the data in Table C5 are examined it is clearly seen that, in general, the head and neck injury criteria values for the are far higher for the floor mounted compared to the upper mounted restraint. In addition, far more injury criteria performance limits are exceeded for the floor mounted restraint. The reason for this is that the floor mounted restraint does not adequately restrain the occupant's upper body and allows it to rotate about the waist leading to the head impacting the knees as shown in Figure C8. This also explains why the chest injury criteria were lower for the floor mounted restraint. The upper and lower lumbar spine load cell compression values recorded are shown in Table C7. Examination of them shows that the lumbar compression is far higher for the floor mounted compared to upper mounted restraint. This indicates a higher likelihood of lumbar spine injury for the floor mounted restraint. However, this cannot be quantified, as there are no injury criteria for the lumbar spine.

Wheelchair type

There is no significant difference in the injury criteria predicted for the different wheelchair types (Table C5). However, in general, the surrogate wheelchair gives the lowest injury criteria values. This could be due to its higher mass resulting in greater forward motion in the impact leading to an increased ride down distance for the occupant.

Tie-downs / clamps

The model runs in which clamps were used to fix the wheelchair in position result in approximately similar injury criteria predictions to the equivalent runs completed with tie-downs used to fix the wheelchair to the taxi floor (Table C5). However, the wheelchair does move substantially further forward when restrained by clamps, about 200 mm for clamps compared to 50 mm for tie-downs. The peak loads sustained by each clamp for these model runs were between 7.3 and 12.4 kN with the higher loads coincident with the use of the 95 % dummy (Table C7)

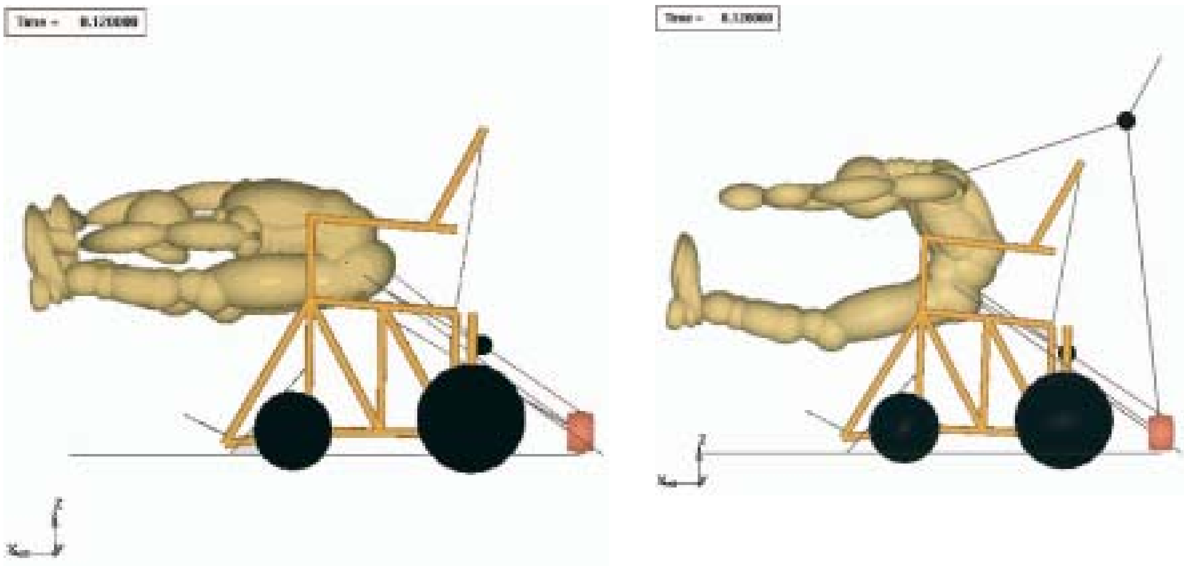


Figure C8 Comparison of dummy response when the seat belt is attached to the floor and to the upper location

Dummy size

In general the larger the dummy, the greater the forward excursion (Table C5). For example, the knee excursions for all the runs with a 95th percentile dummy exceed the performance limit. This is obviously caused by the larger mass of the larger dummies. The predicted injury criteria values are usually slightly higher for the larger dummies. However, for all injury criteria for which the performance limit varies with dummy size, with the exception of HIC, this is offset by the fact that the performance limits are higher for the larger dummies.

Deceleration pulse

Comparison of the equivalent runs for the two deceleration pulses shows that the injury criteria values are lower for the deceleration pulse with the lower peak deceleration, as expected (Table C5 and Table C6). However, the percentage reduction in the injury criteria values is much less than the percentage reduction in the peak deceleration.

C3 Bus modelling results

The 50th percentile dummy occupant was positioned in a manual wheelchair in the bus interior with the rear of the wheelchair just in contact with the head and back restraint structure. As previously mentioned, (Section C1.3 – vehicle interiors), the details of the bus interior were taken from EC Directive 2001/85.

Methodology

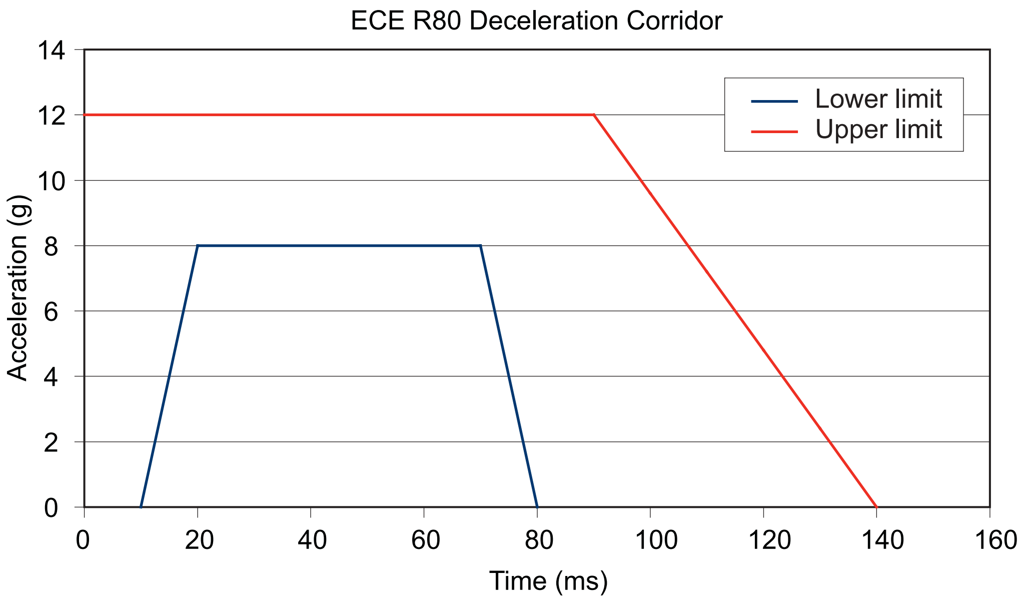
Six modelling runs were performed to investigate the different response of the manual and surrogate wheelchairs and for each wheelchair design to investigate how the interaction of the wheelchair handles and rear wheels of the wheelchair affected the model predictions. The series of runs completed for each wheelchair design were:

i Interaction of the wheelchair back with the bus head and back restraint only.

ii Interaction of the wheelchair back with the bus head and back restraint and the rear wheelchair wheels interacting with the bus structure.

iii Interaction of the wheelchair back with the bus structure and the rear wheelchair wheels and wheelchair handles interacting with the bus structure.

The R80 deceleration pulse shown in Figure 2 was applied to the model for all of the simulations.



Results and discussion

Injury criteria values

The predicted injury criteria values are shown in Table C9. As before, the values are highlighted in orange or red if the performance limits are exceeded. It should be noted that the HYBRIDIII dummy was derived for forward facing frontal impacts and it is not particularly biofidelic for rear impacts and hence injury criteria values measured in rear impact should be treated with caution. Examination of Table C9 shows that none of the performance limits were exceeded for the manual wheelchair. In fact, the injury criteria values were generally substantially below the performance limits. However, for the surrogate wheelchair the neck bending and chest acceleration performance limits were exceeded in a number of cases. The reason for increased neck bending with the surrogate wheelchair is that the stiff wheelchair structure holds the dummy's back away from the head and back restraint hence allowing more relative rearward motion between the head and the shoulders.

Head and back restraint loads

Allowing the wheelchair to interact with the bus structure leads to increases in the head loading of approximately 0.5 kN. Use of the bus structure to support the wheelchair during an impact does help to reduce the loading on the head and back restraint, lowering the peak loading response by as much as 6 kN in the manual wheelchair and 38 kN in the surrogate chair. Loading through the bus structure peaks at values of 23 and 34 kN for the model runs involving the manual and Surrogate wheelchairs respectively.

C4 M3 forward facing modelling

C4.1 Coaches

This set of runs were essential identical to a proportion of the forward taxi runs with the excerption that the deceleration pulse was identical to that used in the Bus runs. Table 14 details the runs that were completed.

Methodology

A matrix of ten modelling runs, shown in Table C3, was completed to investigate the effect of wheelchair type, occupant size and wheelchair restraint type on dummy injury criteria values and wheelchair tie-down and occupant restraint loads. The effect of using floor mounted occupant restraints as opposed to upper ones was investigated as part of the dynamic testing study. All the modelling runs used the R80 deceleration pulse shown in Figure 2. No vehicle interior was modelled as it was

Table C3 Matrix of model runs for coach study

Wheelchair type			*Dummy percentile size*			*Wheelchair restraint type*		*Occupant restraint mounting*		
Man	*Surr*	*Elec*	*5*	*50*	*95*	*Clamp*	*Web*	*Upper*	*Floor*	*Decel pulse*
X			X				X	X		R80
	X		X				X	X		R80
		X	X				X	X		R80
X				X			X	X		R80
		X		X			X	X		R80
X					X		X	X		R80
	X				X		X	X		R80
		X			X		X	X		R80
X			X			X		X		R80
X					X	X		X		R80

assumed that the dummy would not interact with the interior. However, excursion measurements were taken.

Results and discussion

Injury criteria predictions

As shown in Table C10 there was only one instance in which the injury criteria predicted by the coach models exceeded the performance limit, but by less than 3 percent. In general the injury criteria values were substantially below the performance limits indicating a low likelihood of serious injury for this type of impact.

Tie-downs / clamps

Comparison of the predicted injury criteria values for the equivalent runs for wheelchair tie-downs and clamps show no little difference and hence indicate that clamps are as effective as tie-downs in constraining the manual wheelchair in this type of impact.

Table C11 shows that wheelchair clamps were required to support loads approximately 1 kN to 2 kN greater than the rear wheelchair tie-downs in the equivalent model runs for the 5 and 95 occupant dummies, respectively.

C5 Full modelling results

C5.1 Taxi – rear facing

Table C4 Rear facing taxi HYBRIDIII injury criteria measurements

	Head			*Neck*				*Chest*			*Pelvis*		*Knee*
	HIC	*3ms Ac (m/s2)*	*Excur (mm)*	*Shear+ (kN)*	*Shear- (kN)*	*Tension (kN)*	*Bending (Nm)*	*Comp (mm)*	*VC $.10^{-3}$ (m/s)*	*3ms Ac (m/s2)*	*Excur (mm)*	*3ms Ac (m/s2)*	*Excur (mm)*
No backrest													
Manual	614	735	-340	1.6	-0.93	2.26	-122.6	14	56.81	987.9	-132.6	777.9	-135
Electric	1095	894.9	-470	1.24	-0.37	3.92	-67.6	17.3	156.5	1509.1	-205.3	927.3	-221
Surrogate	729.7	710.7	-448	1.4	-0.7	1.95	-101.4	18	39.5	800.8	-110	768.7	-110
Full backrest													
Manual	2998	1892	-239	0.87	-0.79	3.74	-91.2	13.1	24.83	579.1	-113	739.7	-120
Electric	9394	2936	-330	0.87	-1.6	9.82	-67.6	11.6	35.14	760.6	-166.9	737.8	-194
Surrogate	6006	2550	-322	1.22	-1.33	6.81	-74.9	19	51.3	685.3	-116	729.7	-116
Forward head													
Manual	2058	1642	-81.5	0.26	-1	3.17	-23.5	12.9	23.56	583.9	-113.2	729.3	-120
Electric	9046	3000	-195	0.34	-2.67	10.78	-67.6	9.5	35.09	759.9	-166.9	737.8	-194
Surrogate	6274	2612	-207	0.27	-1.36	8.29	-52.6	18	48.2	720	-116	721.6	-116
Head rest only													
Manual	1439	1404	-253	1.6	-1.12	2.45	-79.8	15.2	56.81	987.9	-132.6	777.7	-135
Electric	9488	2970	-327	1.24	-1.59	9.82	-47.5	17.3	156.5	1509.1	-205.4	927.3	-220
Surrogate	4918	2295	-339	1.4	-1.76	4.16	-116	16	37	800.8	-110	768.7	-110

Table C4 *(Continued)* Rear facing taxi HYBRIDIII injury criteria measurements

Yellow	between 0-10% greater than injury criteria
Red	Greater than 10 % above injury criteria

Injury criteria used (details in Appendix 1)

HIC - 5% = 1113, 50% = 1000, 95% = 957

Head accl - all dummys = 80g

Head excursion - all dummys = 650 mm

Neck shear - all dummies = 3.3 kN

Neck Tension - all dummies = 3.1 kN

Neck extension - 5% = 31Nm, 50% = 57 Nm, 95% = 78 Nm

Chest comp - 5% = 41 mm, 50% = 50 mm, 95% = 55 mm

Viscous criteria - all dummies = 1000 mm/s

Chest accel - 5% = 73g, 50% = 60g, 95% = 54g

Pelvis accel - all dummies = 60g

Knee excursion - all dummies = 375 mm

C5.2 Taxi / minibus - forward facing

Table C5 Forward facing taxi HYBRIDIII injury criteria measurements for model runs with R44 deceleration pulse 1 (peak acceleration ~25g)

	Head			Neck				Chest			Pelvis		Knee
	HIC	*3ms Ac (m/s2)*	*Excur (mm)*	*Shear+ (kN)*	*Shear- (kN)*	*Tension (kN)*	*Bending (Nm)*	*Comp (mm)*	*VC $.10^{-3}$ (m/s)*	*3ms Ac (m/s2)*	*Excur (mm)*	*3ms Ac (m/s2)*	*Excur (mm)*
B-pillar													
Manual-05	1749	971	710	0.13	-1.66	2.91	-40.5	65	591	590	-786	685	315
Manual-50	855	694.1	723	0.33	-1.64	2.75	-57.2	48	241.3	452.1	-506	686.9	315
Manual-95	1089.1	754.8	744	0.18	-1.93	3.3	-48.9	49	184	494	-532	633	410
Electric-05	1024	682	593	0.21	-1.31	2.03	-30.8	62	506	538	-365	658	329
Electric-50	700.2	639.2	679	0.45	-1.64	2.43	-35.6	52	234	451.4	-794	566.7	354
Electric-95	1021	691.8	656	0.28	-2.39	2.65	-53.7	50	168	444	-998	594	445
Surrogate-05	698	630	576	0.22	-1.15	1.92	-30.1	61	481	525	-152.7	642.6	326
Surrogate-50	566.8	536.1	616.3	0.29	-1.5	2.15	-35.3	48	206.2	477.4	-118	621.3	355.6
Surrogate-95	663.5	651.8	671	0.1	-1.48	2.96	-48	48	166	468	-610	584	423
Floor													
Manual-05	1013	840	898	0.13	-1.43	2.36	-59.7	49	496	459	-185	719	301
Manual-50	16852	860.4	966	5.28	-1.38	3.64	-75.1	34	194	307.9	-1	753.7	328
Manual-95	519	602.4	1261	0.11	-1.06	2.64	-89.3	43	170	403	-457	674	412
Electric-05	28828	867	835	5.23	-1.11	2.67	-49	47	468	433	-113	949	3.17
Electric-50	45348	997	931	6.16	-1.5	5.33	-88	39	211	416.7	-107	619.7	371
Electric-95	4629	774.4	976	1.73	-1.34	3.46	-73	39	190	432	-156	1089	463
Surrogate-05	31665	772	814	5.66	-0.88	2.4	-67	45	445	399	-86	735	315
Surrogate-50	25204	762.8	848	6.83	-1.19	3.26	-83	35.8	190	325.7	-103	674.4	362
Surrogate-95	14373	582.9	910	6.46	-1.1	2.78	-107	45	204	368	-38	657	426

Table C5 ***(Continued)*** **Forward facing taxi HYBRIDIII injury criteria measurements for model runs with R44 deceleration pulse 1 (peak acceleration ~25g)**

	Head			*Neck*				*Chest*			*Pelvis*		*Knee*
	HIC	*3ms Ac (m/s2)*	*Excur (mm)*	*Shear+ (kN)*	*Shear- (kN)*	*Tension (kN)*	*Bending (Nm)*	*Comp (mm)*	*VC .10^{-3} (m/s)*	*3ms Ac (m/s2)*	*Excur (mm)*	*3ms Ac (m/s2)*	*Excur (mm)*
B-pillar & clamps													
Manual - 05	1484	965	710	0.21	-1.59	2.84	-50	65	582	538	-815	641	326
Manual - 95	910.3	667.8	748	0.24	-1.88	2.89	-48	49	177	483	-616	619	410
Floor & clamps													
Manual - 05	4246	702	884	0.74	-1.19	2.02	-52.1	53	500	485	-267	697	327
Manual - 95	1512.3	723.3	992	0.24	-1.42	3.12	-76.9	46	219	423	-838	624	419.3

Table C6 Forward facing taxi HYBRIDIII injury criteria measurements for model runs with R44 deceleration pulse 2 (peak acceleration ~20g)

	Head			*Neck*				*Chest*			*Pelvis*		*Knee*
	HIC	*3ms Ac (m/s2)*	*Excur (mm)*	*Shear+ (kN)*	*Shear- (kN)*	*Tension (kN)*	*Bending (Nm)*	*Comp (mm)*	*VC .10^{-3} (m/s)*	*3ms Ac (m/s2)*	*Excur (mm)*	*3ms Ac (m/s2)*	*Excur (mm)*
B-pillar													
Manual	694.6	652.3	704	0.18	-1.49	2.62	-51	45	218.3	409.5	-452	560.7	295
Electric	459.2	488.6	599	0.2	-1.34	1.95	-33.5	44	182.1	406.6	-103	528.2	333
Surrogate	562.2	567.7	660	0.42	-1.5	2.11	-34.2	48	211	390.1	-769	520	331
Floor													
Manual	14227	811.8	957	4.45	-1.17	3.9	-72	35	157	304.9	-147	589.5	312
Electric	18660	676.7	841	5.31	-1	2.91	-71	30	163	280.9	-95	565.1	340
Surrogate	39729	853.6	924	6.17	-1.21	4.21	-74.9	38	209	379.7	-106	545.3	347

Table C7 Forward facing taxi, wheelchair tie-down and belt loads and HYBRIDIII injury criteria measurements for model runs with R44 deceleration pulse 1 (peak acceleration ~25g)

	Wheelchair tiedown loads				*Belt loads*		*Upper lumbar*			*Lower lumbar*		
	Front L (kN)	*Front R (kN)*	*Rear L (kN)*	*Rear R (kN)*	*Shoulder (kN)*	*Lap (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*
B-pillar												
Manual-05	4.04	2.88	5.23	5.2	8.42	6.5	3.65	-0.83	3.75	-4.15	0.88	0.88
Manual-50	6.36	4.14	5.77	5.69	11.05	9.54	4.44	-0.84	4.57	-4.09	1.48	1.48
Manual-95	5.15	5.81	7.15	7.2	12.58	12.94	7.37	-1.38	7.58	-5.97	1.37	1.37
Electric-05	4.37	5.49	9.08	9.52	8.14	7.29	3.92	-1.34	3.97	-4.01	1.63	1.63
Electric-50	6.2	5.62	9.32	9.05	11.17	10.53	6.7	-1.4	700	-3.89	1.38	1.38
Electric-95	7.65	6.66	9.81	9.47	12.33	13.86	10.87	-1.44	10.94	-4.95	2.06	2.06
Surrogate-05	6.44	6.59	13.63	13.61	7.83	8.17	4	-1.31	4.06	-4.15	1.61	1.61
Surrogate-50	9.31	9.31	13.44	13.44	10.4	10.86	4.93	-2.07	4.99	-3.24	2.42	2.42
Surrogate-95	7.48	7.08	14.58	14.59	13.15	14.37	10.7	-3.44	11	-11.29	3.85	3.85
Floor												
Manual-05	3.15	5.21	5.54	5.49	6.67	6.66	7.85	-1.31	7.91	-8.19	1.72	1.72
Manual-50	5.08	6.84	6.06	6.02	6.91	9.44	6.24	-3.21	6.35	-6.4	3.47	3.47
Manual-95	8.06	8.57	6.92	7.29	10.52	12.09	10.68	-1.69	11.08	-6.9	4.11	4.11
Electric-05	4.2	4.28	9.63	9.54	6.26	7.17	9.45	-2.23	9.45	-9.57	2.54	2.54
Electric-50	9.81	8.68	9.68	9.06	7.24	10.32	6.72	-2.91	7.16	-6.31	3.42	3.42
Electric-95	14.76	14.67	9.79	9.59	11.21	13.26	8.73	-2.8	8.9	-5.41	4.23	4.23
Surrogate-05	5.76	6.21	13.7	13.68	5.67	7.66	6	-3.31	6.05	-5.98	3.15	3.15
Surrogate-50	6.09	6.72	13.43	13.44	6.23	11.19	6.59	-5.19	7.71	-8.88	5.12	5.12
Surrogate-95	5.78	6.74	14.3	14.3	11.44	13.77	14.33	-5.77	14.48	-9.86	5.76	5.76

Table C7 ***(Continued)*** **Forward facing taxi, wheelchair tie-down and belt loads and HYBRIDIII injury criteria measurements for model runs with R44 deceleration pulse 1 (peak acceleration ~25g)**

	Wheelchair tiedown loads				*Belt loads*		*Upper lumbar*			*Lower lumbar*		
	Front L (kN)	*Front R (kN)*	*Rear L (kN)*	*Rear R (kN)*	*Shoulder (kN)*	*Lap (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*
B-pillar & clamps												
Manual - 05	8.15	7.35	0	0	8.31	7.46	5.08	-0.83	5.16	-5.5	0.89	0.89
Manual - 95	11.85	11.87	0	0	12.45	12.35	4.99	-4.51	5.15	-4.64	3.35	3.35
Floor & clamps												
Manual - 05	7.8	7.7	0	0	7	7.67	10.3	-1.98	10.8	-1.98	10.6	10.6
Manual - 95	12.4	12.4	0	0	9.7	11.8	7.3	-4.6	7.4	-5.26	5.5	5.5

Table C8 Forward facing taxi, wheelchair tie-down and belt loads and HYBRIDIII injury criteria measurements for model runs with R44 deceleration pulse 2 (peak acceleration ~20g)

	Wheelchair tiedown loads				*Belt loads*		*Upper lumbar*			*Lower lumbar*		
	Front L (kN)	*Front R (kN)*	*Rear L (kN)*	*Rear R (kN)*	*Shoulder (kN)*	*Lap (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*
B-pillar												
Manual	4.92	3.6	5.36	5.26	10.11	8.25	4.09	0.806	4.21	-3.76	1.56	4.34
Electric	7.25	7.29	10.2	10.17	9.37	9.44	4.05	-1.56	4.12	-3.38	1.84	4.83
Surrogate	5.6	5.8	7.56	7.39	10.04	9.08	6.34	-2.69	6.64	-3.06	1.16	6.72
Floor												
Manual	4.45	5.88	5.4	5.33	6.4	8.2	5.57	-3.31	5.72	-5.57	3.4	6.51
Electric	5.48	5.89	10.7	10.71	5.79	9.67	6.11	-4.49	7.2	-8.48	4.64	9.77
Surrogate	8.41	7.51	7.67	7.28	7	9.45	5.95	-2.72	6.36	-5.37	3.36	7.3

C5.3 Large buses

Table C9 Large bus injury criteria measurements for model runs with R80 deceleration pulse

	Head			*Neck*				*Chest*			*Pelvis*		*Knee*
	HIC	*3ms Ac (m/s2)*	*Excur (mm)*	*Shear+ (kN)*	*Shear- (kN)*	*Tension (kN)*	*Bending (Nm)*	*Comp (mm)*	*VC .10^{-3} (m/s)*	*3ms Ac (m/s2)*	*Excur (mm)*	*3ms Ac (m/s2)*	*Excur (mm)*
Head and back restraint													
Manual	118.9	391.4	-204.4	0.35	-0.11	0.71	-47.8	3	1.84	234.2	-106	239.5	-116.6
Surrogate	121.3	366.6	-317.9	0.96	-0.19	1	-64.4	8.2	33.5	743	-96.4	437	-97.4
Head and back restraint + wheels													
Manual	191.5	464.5	-238.7	0.38	-0.23	1	-56.1	3.9	3.24	286.4	-109	402.9	-116.3
Surrogate	271	554.4	-358.5	0.56	-0.12	1.22	-45.1	3.3	2.12	288	-93.9	251.2	-96.7
Head and back restraint + wheels + Handles													
Manual	211.6	486.3	-235.9	0.37	-0.25	1.03	51.4	3.7	2.97	260.2	-104	465.2	-108.5
Surrogate	220.2	479.2	-365	0.53	-0.192	0.863	-58	4.53	5.68	322.6	-80.9	383.5	-82.9

C5.4 Coaches

Table C10 Coach injury criteria measurements for model runs with R80 deceleration pulse

	Head			*Neck*				*Chest*			*Pelvis*		*Knee*
	HIC	*3ms Ac (m/s2)*	*Excur (mm)*	*Shear+ (kN)*	*Shear- (kN)*	*Tension (kN)*	*Bending (Nm)*	*Comp (mm)*	*VC .10⁻³ (m/s)*	*3ms Ac (m/s2)*	*Excur (mm)*	*3ms Ac (m/s2)*	*Excur (mm)*
B-pillar													
Manual-05	362	442	562	0.19	-1.08	1.21	-27.7	41	350	316	-55	373	213
Manual-50	119.5	291.4	541	0.17	-1	1.13	-19.8	32	143.7	260.1	0	329	207
Manual-95	127.3	301.4	554	0.24	-1.11	1.22	-25	30	105	256	-49	334	266
Electric-05	209	374	440	0.26	-1.1	0.96	-23.6	38	279	289	0	343	218
Electric-50	99.8	256.8	510	0.15	-1.02	0.94	-25.4	32	139.8	268.1	-23	294.5	226
Electric-95	102.4	243.7	494	0.22	-1.08	0.87	-26.6	28	81.4	233	-0.1	270	279
Surrogate-05	131	306	428	0.021	-0.86	0.87	-18	38	279	292	-39	330	223
Surrogate-95	64.3	229.6	478	0.29	-0.92	0.95	-21.6	29	85	209	-53	273	274
B-pillar & clamps													
Manual - 05	316	463	562	0.064	-0.93	1.28	-34.3	42	330	297	-85	339	221
Manual - 95	116.4	297.3	570	0.21	-1.07	1.22	-28.2	30	92	230	-68	276	265

Table C11 Coach, wheelchair tie-down and belt loads and HYBRIDIII injury criteria measurements for model runs with R80 deceleration pulse

	Wheelchair tiedown loads				*Belt loads*		*Upper lumbar*			*Lower lumbar*		
	Front L (kN)	*Front R (kN)*	*Rear L (kN)*	*Rear R (kN)*	*Shoulder (kN)*	*Lap (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*	*Comp (kN)*	*Tension (kN)*	*Resultant (kN)*
B-pillar												
Manual-05	1.96	1.23	3.06	3.04	4.51	3.4	1.59	-0.24	1.68	-1.8	0.2	1.87
Manual-50	2.38	4.97	3.24	3.18	5.57	4.56	.2.16	-0.293	2.35	-1.8	0.54	2.27
Manual-95	3.31	2.68	5.08	5.13	6	5.7	4.23	-0.4	4.32	-3.68	0.133	4.54
Electric-05	2.85	2.29	4.31	4.39	4.38	3.78	1.51	-0.53	1.52	-1.61	0.6	1.62
Electric-50	3.78	2.88	4.48	4.6	5.53	4.68	3.05	-0.384	3.21	-1.46	0.25	3.16
Electric-95	3.75	3.2	4.7	5.06	5.93	5.65	5.22	-0.65	5.25	-2.74	0.296	5.33
Surrogate-05	2.81	2.95	5.01	5.01	4.31	4.29	1.8	-0.3	1.86	-1.75	0.25	1.83
Surrogate-95	4.53	4.72	5.36	5.6	6.33	6.31	3.82	-1.1	3.87	-2.36	0.91	3.79
B-pillar & clamps												
Manual - 05	4.22	4.24	0	0	4.59	3.83	2.85	-0.39	2.93	-3.06	0.68	3.11
Manual - 95	7.32	6.75	0	0	6	5.19	3.58	-0.56	3.6	-3.27	0.162	3.76

Appendix D: Surrogate wheelchair specifications

D1 General

Design, dimensional, material, and performance specifications are provided for a surrogate wheelchair (SWC) that produces representative loading and seating conditions of a powered wheelchair for testing WTORS to the requirements of this standard[2].

D2 Specifications

The surrogate wheelchair shall:

a be of rigid durable construction, such that there is no permanent deformation of the frame, seat surface, or seatback in a 48 km/h, 20 g frontal impact test with a 76.3 kg ATD positioned and restrained in the SWC;

b have a total mass of 85 kg $\pm$ 1 kg;

c conform with the dimensions shown in Figures D1 through D4,

d allow for adjustment to accommodate components and end fittings of different types of tiedown systems;

e provide two front securement points and two rear securement points for four-point strap-type tiedowns at the locations indicated in Figure D1 and with the geometry specified in Figure D4;

f provide pelvic restraint anchor points on both sides of the surrogate wheelchair located as shown in Figure D1;

g have a centre of gravity located 142 mm $\pm$ 25 mm forward of the rear axle and 287 mm $\pm$ 25 mm above the ground plane for the range of frame-to-floor clearance adjustments allowed;

h have a rigid, flat seat surface with dimensions shown in Figures D3 that is oriented at an angle of $4^{o} \pm 1.5^{o}$ to the horizontal (front end up), as shown in Figures D1 and D3, when the SWC tyres are inflated in accordance with (m) and (n) and are resting on a flat horizontal surface;

i have a rigid seatback with height and width dimensions indicated in Figures D2 and D3 that is oriented at $8^{o} + 1.5^{o}$ to the vertical when the tyres of the SWC are resting on a flat horizontal surface and inflated in accordance with (m) and (n);

j have a 20-mm to 30-mm thick firm (i.e., shore-A hardness = 60 to 80) rubber pad with height and width dimensions indicated in Figures D1 and D2 fixed to the front surface of the rigid seatback;

2 Details for the design, fabrication, and maintenance of a suitable surrogate wheelchair are available in SAE 2252 - Surrogate wheelchair drawing package and maintenance manual.

k have a detachable, but rigid, mounting plate for placement of a side-view target at the location of reference point P outboard of tiedown and restraint system components on either side of the SWC;

l have pneumatic front tyres that, when inflated to 320 + 30 kPa with the unoccupied surrogate wheelchair resting on a flat horizontal surface, have a diameter of 230 mm + 10 mm, a width of 75mm + 10 mm, and a sidewall height of 54 mm + 5 mm;

m have pneumatic rear tyres that, when inflated to 320 kPa + 30 kPa with the unoccupied surrogate wheelchair resting on a flat horizontal surface, have a diameter of 325 mm ± 10 mm, a width of 100 mm ± 10 mm, and a sidewall height of 70 mm ± 5 mm.

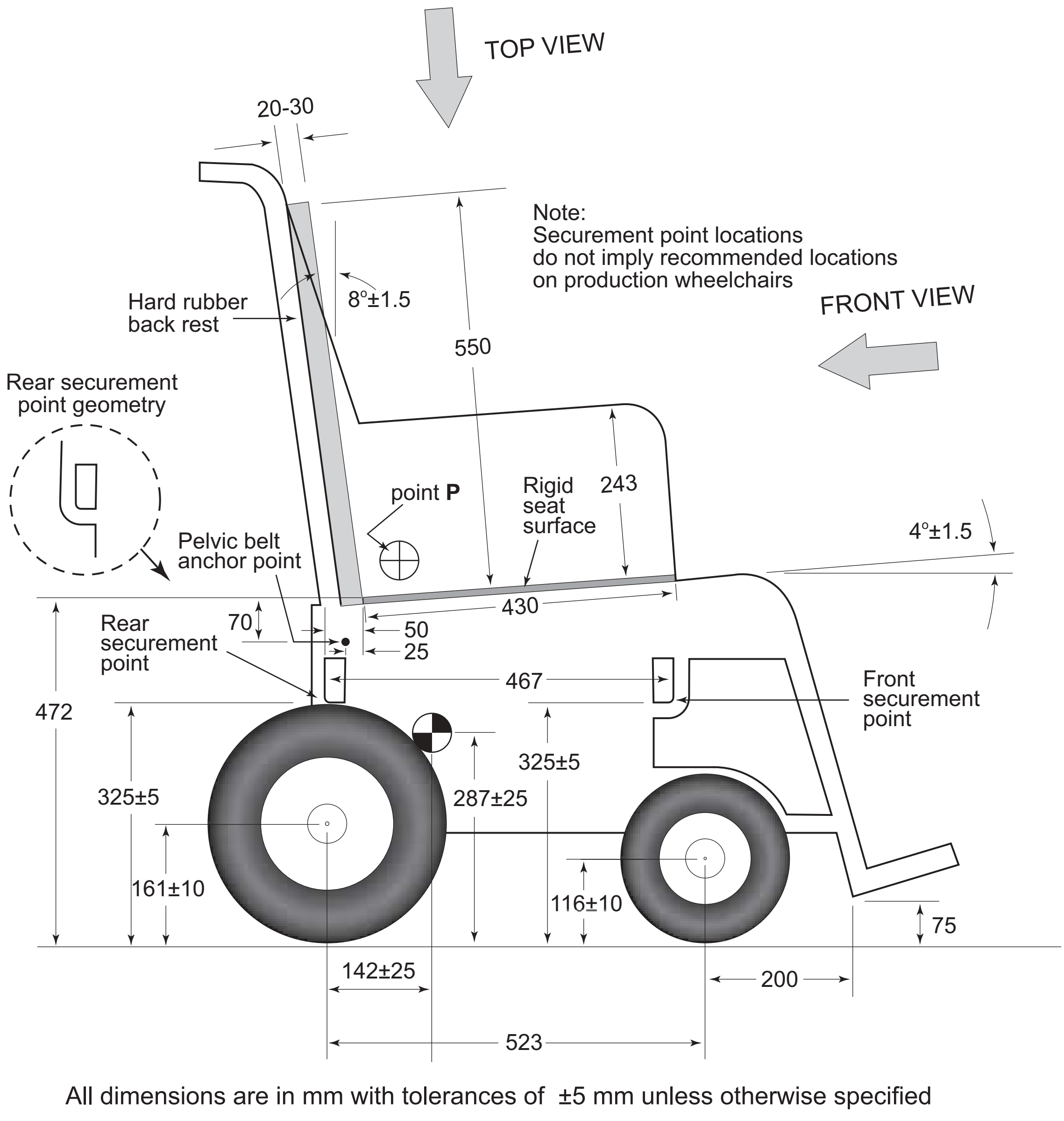
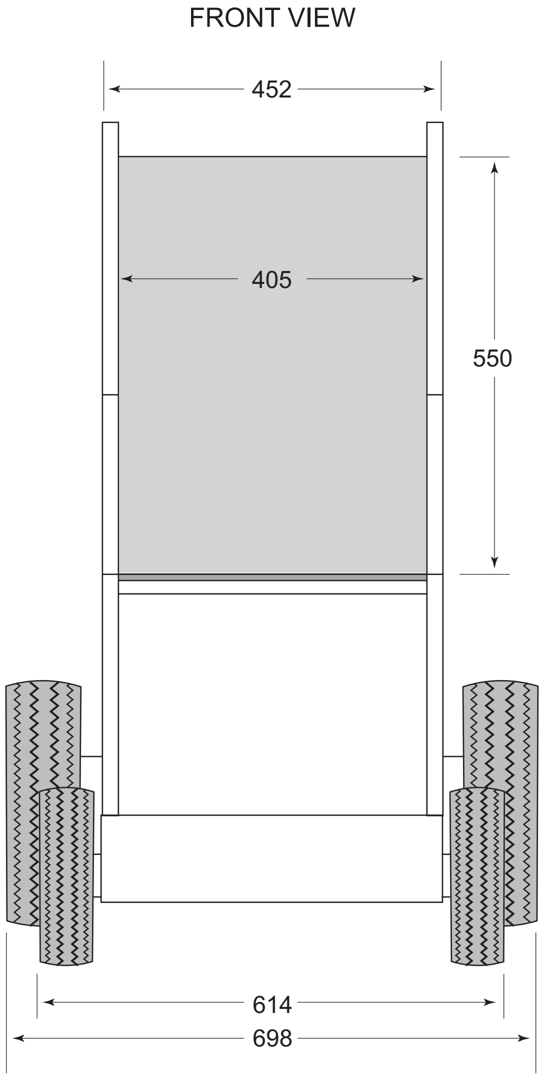


Figure D1 Side-view drawing of the surrogate wheelchair



All dimensions are in mm with tolerances of ±5 mm unless otherwise specified

Figure D2 Front-view drawing of the surrogate wheelchair

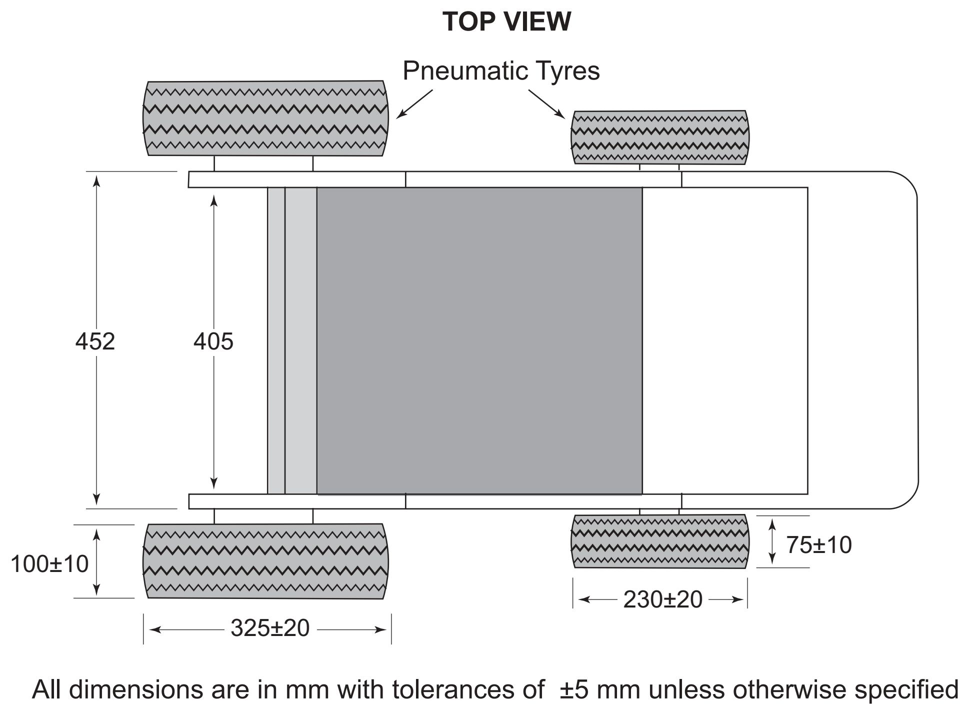


Figure D3 Top-view drawing of the surrogate wheelchair

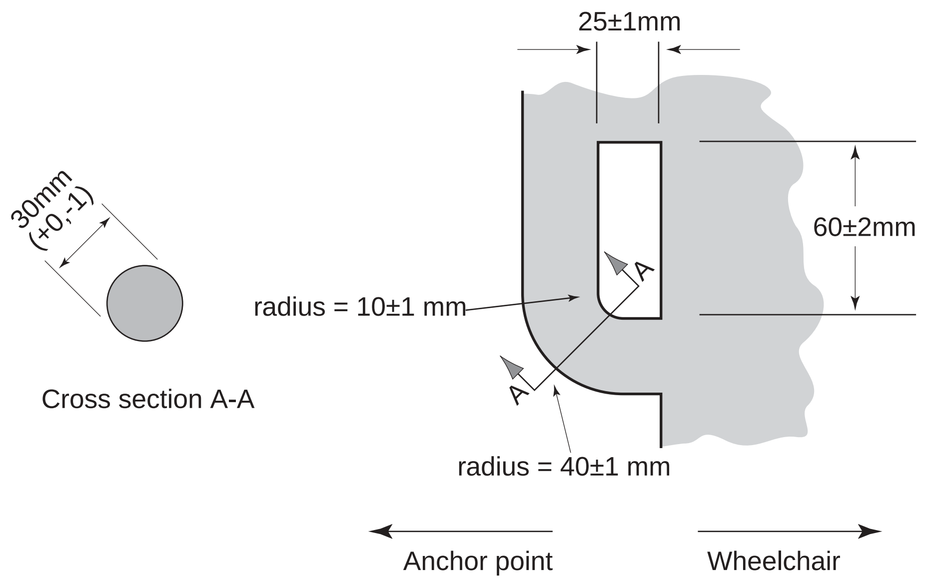


Figure D4 Dimensions of wheelchair securement points on surrogate wheelchair showing required engagement geometry for securement-point end fittings of four-point strap-type tiedowns

Appendix E: Vehicle specifications for safe carriage of wheelchair users

E1: Forward facing wheelchairs in M1/M2 category vehicles

1 Any wheelchair space shall comply with the following requirements:

a A wheelchair space shall not be less than:

i 1300mm measured in the longitudinal plane of the vehicle;

ii 750mm measured in the transverse plane of the vehicle; and

iii 1500mm measured vertically from any part of the floor of the wheelchair space.

b A wheelchair space shall allow the carriage of a wheelchair and a wheelchair user facing the front of the vehicle.

c A wheelchair space shall be fitted with a wheelchair tie down system and a wheelchair user restraint system suitable for a wheelchair user situated centrally in the transverse plane of the wheelchair space.

2 A wheelchair tie down system shall meet the following requirements:

a If a four point (two front and two rear) webbing system is fitted:

i each of the two rearmost anchorages must be able to withstand a force of 30kN applied at an angle of 45 degrees upwards and towards the front of the vehicle relative to a horizontal plane representing the floor of the wheelchair space. The force shall be maintained for at least 0.2 seconds;

ii each of the two foremost anchorages must be able to withstand a force of 5kN applied at an angle of 45 degrees upwards and towards the rear of the vehicle relative to a horizontal plane representing the floor of the wheelchair space. The force shall be maintained for at least 0.2 seconds;

iii wheelchair tie-down devices shall, as a minimum, meet the same performance requirements as the anchorage to which it is to be attached. Where different tie-down devices are used for the forward and rearward direction the attachment point to the vehicle must be so designed that it is not possible to attach the tie-down to the wrong anchorage point. This does not apply if the devices are permanently attached to the appropriate anchorage point or clearly labelled to indicate their suitability for a particular application;

iv the rear anchorages shall be positioned at the rearmost end of the wheelchair space and the forward anchorages not less than 1220mm forward of the rear anchorages measured in the longitudinal plane of the wheelchair space;

v the front and rear anchorages shall be positioned between 300mm and 600mm apart and equi-distant on either side of the longitudinal centreline of the wheelchair space;

vi the webbing at both the front and rear shall be easily adjustable. The front and rear webbing shall be adjustable between 300 and 750mm measured from the surface of the wheelchair space at the intersection of the vertical axis of the anchorage point to the vehicle floor and the farthest point of any wheelchair to which it might be attached;

vii as an alternative to the requirements in (i) the tie down system may be subject to a dynamic test in accordance with ISO 10542 Part 2.

b Where a tie down system, not being a four-point webbing system, is fitted the manufacturer shall provide such information as may be necessary to demonstrate that the system provides an equivalent level of protection to requirements described in (a). If the vehicle is intended for public transport use the system must be suitable for general wheelchair application.

3 A wheelchair user restraint system shall comprise a minimum of a three-point anchorage system (lap and diagonal):

a The lower anchorages shall be fitted at a position between 50mm forward or 50mm rearward of the rear transverse plane of the wheelchair space and not below or more than 50mm above the floor level of the wheelchair space. This does not apply if the lower anchorage is adjustable in a plane parallel to the longitudinal axis of the wheelchair space and in at least one position adjustment meets this requirement. The anchorages must be between 300mm and 700mm apart equi-distant on either side of the longitudinal centreline of the wheelchair space.

b The upper diagonal belt anchorage may be attached to the floor such that the belt may pass up and over the shoulder of the wheelchair user and down to the floor or via an upper webbing guide point or attached to a suitable higher anchorage point. All attachment points must be on the same side of the longitudinal centreline of the wheelchair space as that of the shoulder of the wheelchair user over which the webbing will pass. An anchorage shall be positioned at least 150mm measured in the transverse plane of the wheelchair space from the longitudinal centreline.

c The effective upper anchorage must, except when floor mounted, lie within the zone specified in Figure E1 and be adjustable in height. The height shall be adjustable at least between 800mm and 1050mm above the floor. If a head and back restraint is fitted the zone specified in Figure E1 shall not extend forward of a transverse plane 100mm forward and parallel to the padded surface of the head and back restraint.

d a force of 25kN shall be applied to each of the floor anchorages in a forward and upward direction at an angle of 30 degrees to the horizontal. The force shall be maintained for at least 0.2 seconds.

e The effective upper anchorage must be able to withstand a force of 8kN applied forward and downward at an angle of 45 degrees to the horizontal. Where the upper anchorage is attached to the floor a webbing guide shall be arranged in the approximate position of the shoulder of a wheelchair user for the purpose of this test.

f The restraint system shall comply with the requirements of ECE Regulation 16.

g any wheelchair user restraint or wheelchair tie down system fitted to a wheelchair space shall be capable of being easily released in the case of an emergency.

4 A head and back restraint, if fitted, shall comply with the following requirements (see Figure E2):

a The head and back restraint shall be fitted to the rear of the wheelchair space, transverse to the longitudinal plane of the wheelchair space.

b A padded surface, forming a single and continuous plane, must be provided and facing the front of the vehicle.

c The lower edge shall be at a height of not less than 490mm and not more than 530mm measured vertically from the floor and its forward edge not less than 350mm and not more than 400mm forward of the rear of the wheelchair space.

d The top edge shall be at a height of not less than 1350mm measured vertically from the floor of the wheelchair space.

e The width, measured in the transverse plane of the wheelchair space, must be not less than 240mm at any point and not more than 280mm at any point below a height of 1200mm measured vertically from the floor of the wheelchair space.

f A head and back restraint shall be fitted at an angle of not less than 4° and not more than 8° to the vertical with the lower edge positioned closer to the front of the vehicle than the top edge.

g The forward lower edge must not be less than 350mm and not more than 400mm forward of the rear of the wheelchair space.

h There shall be a clear space to the rear of the lower forward edge of the back and head restraint measuring at least 400mm rearward of that point, at least 500mm from the floor of the wheelchair space and for a width of 750mm equally spaced each side of the back and head restraint.

i The padded surface shall pass the energy absorption test according to annex 4 to ECE Regulation 21. This shall apply to the area bounded by two vertical planes extending 100mm on either side of the vertical centreline and between two horizontal planes 550mm and 1350mm above the floor.

j The head and back restraint must be capable of withstanding a force of 10kN for a minimum of 0.2 seconds applied via a block measuring 700mm in height and 400mm in width applied horizontally and centrally in the rearward direction at a height of 670mm above the floor. The corners of the block may have a radius not exceeding 50mm.

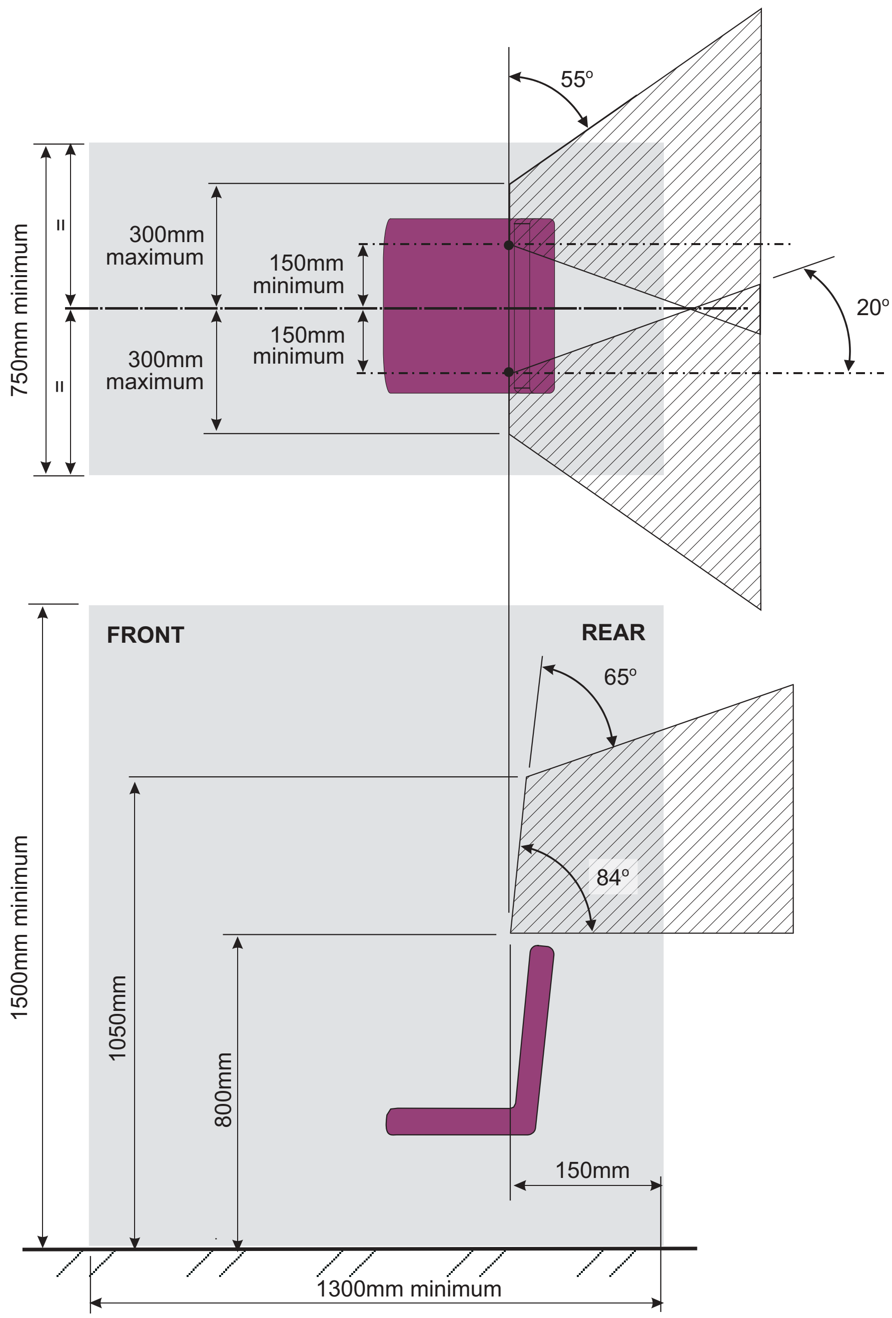


Figure E1 Upper anchorage forward facing

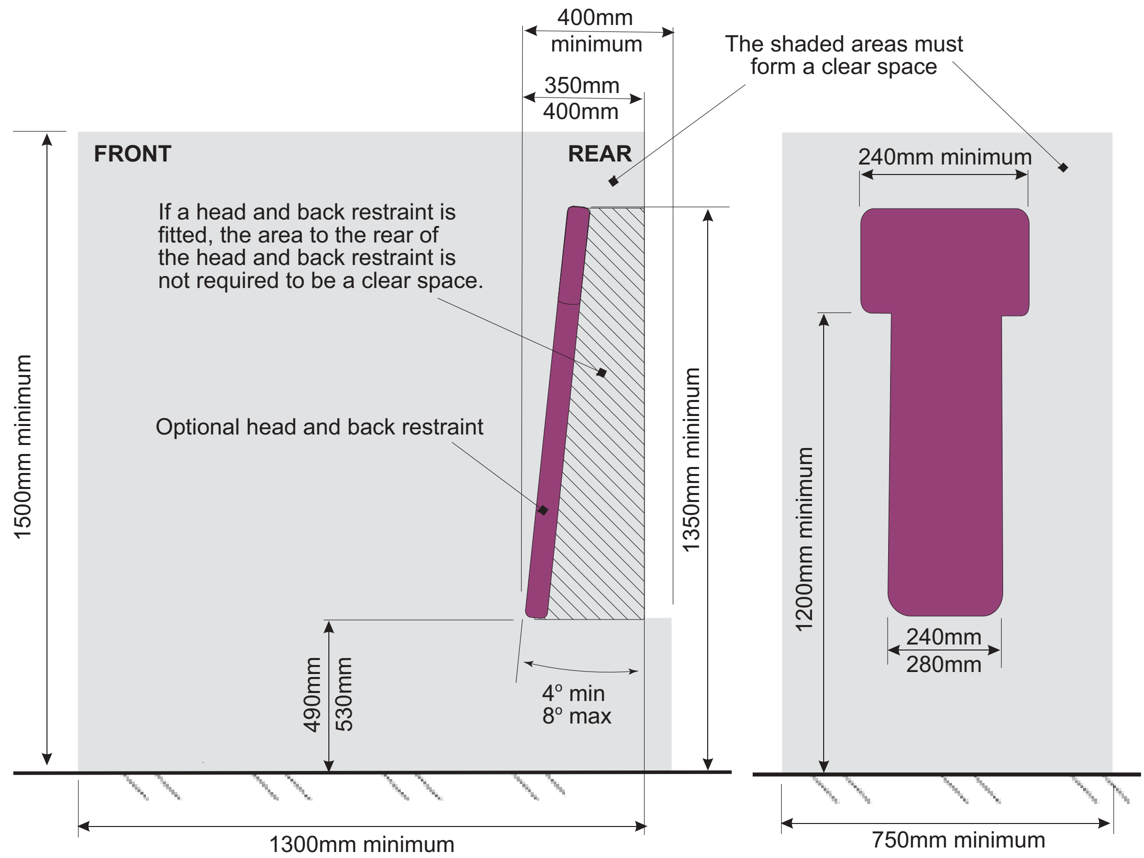


Figure E2 Wheelchair space – forward facing

E2: Rearward facing wheelchairs in M1/M2 category vehicles

1 Any wheelchair space shall comply with the following requirements:

- a Be not less than:
  - i 1300mm measured in the longitudinal plane of the vehicle;
  - ii 750mm measured in the transverse plane of the vehicle; and
  - iii 1500mm measured vertically from any part of the floor of the wheelchair space.
- b Shall allow the carriage of a wheelchair and a wheelchair user facing the rear of the vehicle.
- c Shall be fitted with a wheelchair tie down system and a wheelchair user restraint system suitable for a wheelchair user situated centrally in the transverse plane of the wheelchair space.
- d Shall be fitted with a head and back restraint at the forward end (relative to the vehicle) of the space.

2 A wheelchair tie down system shall meet the following requirements:

a A tie down system shall, subject to sub-paragraph (b), consist of a webbing system comprising two separate straps or a system with two attachment points on the wheelchair and a single attachment point to the vehicle and meeting the following requirements:

i the anchorage or combined anchorages must be able to withstand a force of 10kN applied at an angle of 45 degrees upwards and towards the rear of the vehicle relative to a horizontal plane representing the floor of the wheelchair space. The force shall be maintained for at least 0.2 seconds;

ii the wheelchair tie-down system shall, as a minimum, meet the same performance requirements as the anchorage to which it is to be attached;

iii the anchorage(s) shall be positioned at floor level at the forward end of the wheelchair space.

iv If a single anchorage is fitted it must be on the central longitudinal centreline of the wheelchair space and if two anchorages are fitted they must be between 300mm and 600mm apart and equi-distant on either side of the longitudinal centreline of the wheelchair space;

v the webbing shall be easily adjustable between 300mm and 750mm measured from the surface of the wheelchair space at the intersection of the vertical axis of the anchorage and the farthest point of any wheelchair to which it might be attached.

b Where an alternative wheelchair tie down system is fitted the manufacturer shall provide such information as may be necessary to demonstrate that the system provides an equivalent level of protection to requirements described in (a). If the vehicle is intended for public transport use the system must be suitable for general wheelchair application.

3 A wheelchair user restraint system shall comprise a minimum of a three-point anchorage system (lap and diagonal) complying with the following:

a The lower anchorages shall be fitted at a position between 50mm forward and 50mm rearward of the formost transverse plane of the wheelchair space and not below or more than 50mm above the floor level of the wheelchair space. This does not apply if the lower anchorage is adjustable in a plane parallel to the longitudinal axis of the wheelchair space and in at least one position adjustment meets this requirement. The anchorages must be between 300mm and 700mm apart equi-distant on either side of the longitudinal centreline of the wheelchair space.

b The effective upper diagonal belt anchorage must be attached to a suitable anchorage point and on the same side of the longitudinal centreline of the wheelchair space as that of the shoulder of the wheelchair user over which the webbing will pass. An anchorage shall be positioned at least 150mm measured in the transverse plane of the wheelchair space from the longitudinal centreline.

c The effective upper anchorage must lie within the zone specified in Figure E3 and be adjustable in height. The height shall be adjustable at least between 800mm and 1050mm above the floor. The zone specified in Figure E3 shall not extend rearward of a transverse plane 100mm rearward and parallel to the padded surface of the head and back restraint.

d A force of 5kN shall be applied to each of the floor anchorages in a rearward and upward direction at an angle of 30 degrees to the horizontal. The force shall be maintained for at least 0.2 seconds.

e The effective upper anchorage must be able to withstand a force of 2kN applied rearward and downward at an angle of 45 degrees to the horizontal. Where the upper anchorage is attached to the floor a webbing guide shall be arranged in the approximate position of the shoulder of a wheelchair user for the purpose of this test.

f The restraint system shall comply with the requirements of ECE Regulation 16.

g Any wheelchair user restraint or wheelchair tie down system fitted to a wheelchair space shall be capable of being easily released in the case of an emergency.

4 A head and back restraint shall be fitted complying with the following requirements (see Figure E4):

a The bottom edge of the head and back restraint shall be at a height of not less than 490mm and not more than 530mm measured vertically from the floor of the wheelchair space.

b The top edge of a back and head restraint shall be at a height of not less than 1350mm measured vertically from the floor of the wheelchair space.

c The width shall be not less than 240mm at any point and not more than 280mm at any point up to a height of 1200mm measured vertically from the floor of the wheelchair space.

d A back and head restraint shall be fitted at an angle of not less than 4° and not more than 8° to the vertical with the bottom edge of the back and head restraint positioned closer to the rear of the vehicle than the top edge.

e The lower rearmost edge of the head and back restraint shall be 350mm to 400mm to the rear of the forward edge of the wheelchair space.

f There shall be a clear space forward of the lower rearmost edge of the head and back restraint measuring at least 400mm forward of that point, at least 500mm above the floor of the wheelchair space and for a width of 750mm equally spaced about the longitudinal centreline of the wheelchair space.

g The surface of the back and head restraint shall be padded and form a single and continuous plane facing the rear of the vehicle. The padded surface shall pass the energy absorption test according to annex 4 to ECE Regulation 21. This shall apply to the area bounded by two vertical planes extending 100mm on either side of the vertical centreline and between two horizontal planes 550mm and 1350mm above the floor.

h The head and back restraint must be capable of withstanding a force of 100kN for a minimum of 0.2 seconds applied via a block measuring 700mm in height and 400mm in width applied horizontally and centrally in the rearward direction at a height of 670mm above the floor. The corners of the block may have a radius not exceeding 50mm.

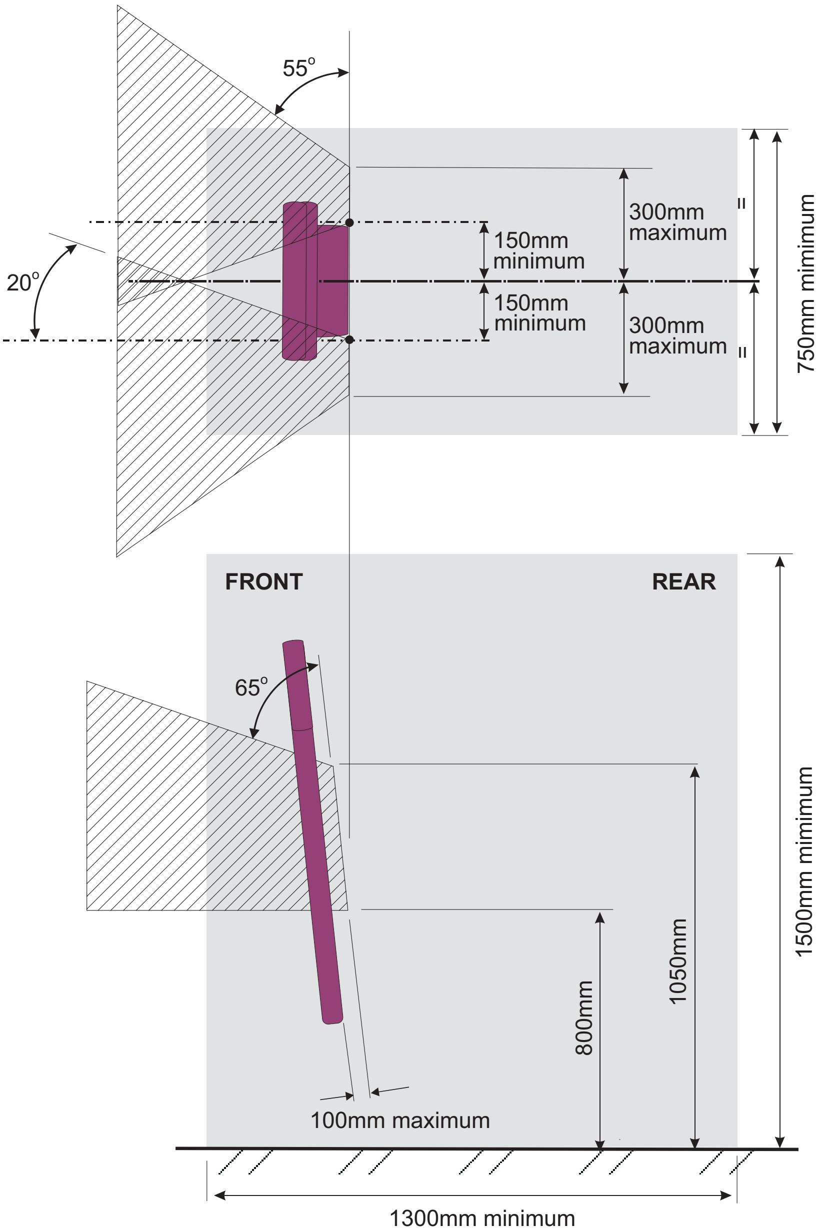


Figure E3 Upper anchorages rearward facing

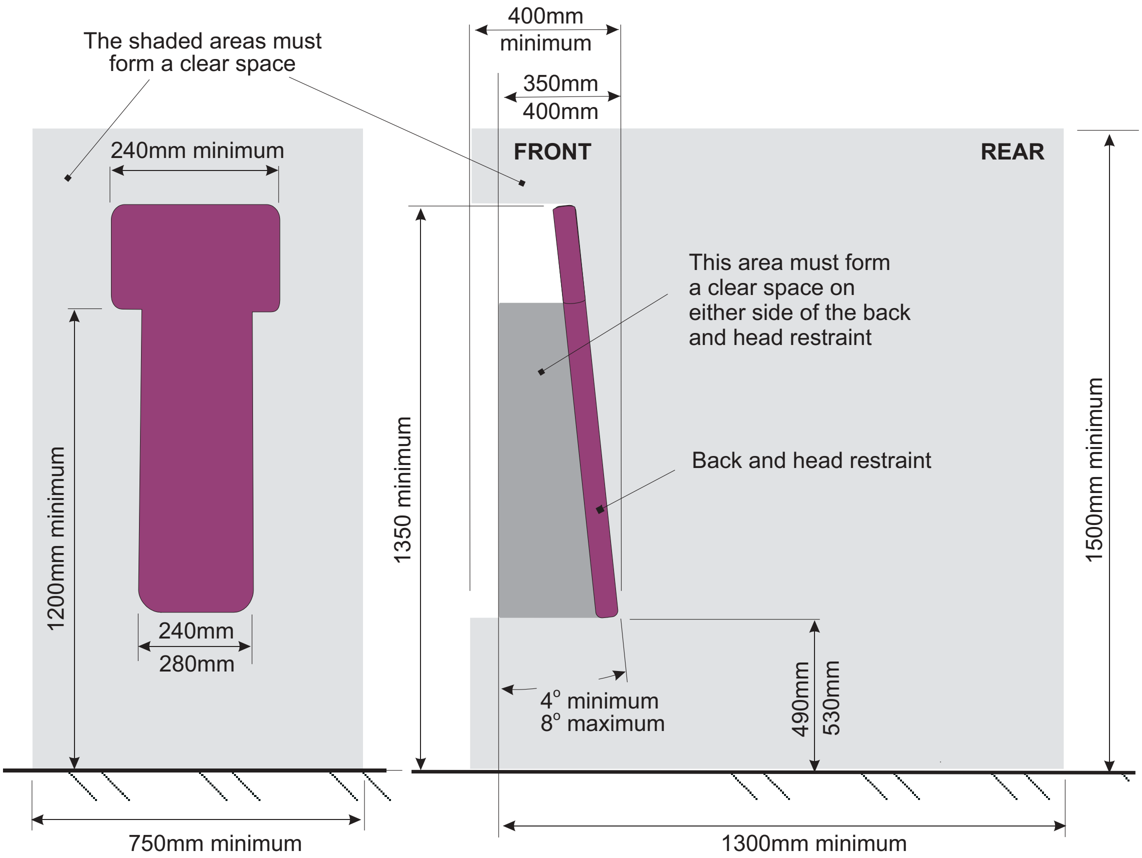


Figure E4 Wheelchair space – rearward facing

E3: Forward facing wheelchairs in M3 category vehicles

1 Any wheelchair space shall comply with the following requirements:

a A wheelchair space shall not be less than:

i 1300mm measured in the longitudinal plane of the vehicle;

ii 750mm measured in the transverse plane of the vehicle; and

iii 1500mm measured vertically from any part of the floor of the wheelchair space.

b A wheelchair space shall allow the carriage of a wheelchair and a wheelchair user facing the front of the vehicle.

c A wheelchair space shall be fitted with a wheelchair tie down system and a wheelchair user restraint system suitable for a wheelchair user situated centrally in the transverse plane of the wheelchair space.

2 A wheelchair tie down system shall meet the following requirements:

a If a four point (two front and two rear) webbing system is fitted:

i each of the two foremost anchorages must be able to withstand a force of 5kN applied at an angle of 45 degrees upwards and towards the rear of the vehicle relative to a horizontal plane representing the floor of the wheelchair space. The force shall be maintained for at least 0.2 seconds;

ii each of the two rearmost anchorages must be able to withstand a force of 20kN applied at an angle of 45 degrees upwards and towards the front of the vehicle relative to a horizontal plane representing the floor of the wheelchair space. The force shall be maintained for at least 0.2 seconds;

iii wheelchair tie-down equipment shall, as a minimum, meet the same performance requirements as the anchorage to which it is to be attached. Where the different tie-downs are used for the forward and rearward direction the fittings must be designed so that it is not possible to attach the tie-down to the wrong anchorage;

iv the rear anchorages shall be positioned at the rearmost end of the wheelchair space and the forward anchorages not less than 1220mm forward of the rear anchorages measured in the longitudinal plane of the wheelchair space;

v the front and rear anchorages shall be positioned between 300mm and 600mm apart and equi-distant on either side of the longitudinal centreline of the wheelchair space;

vi the webbing at both the front and rear shall be easily adjustable. The front and rear webbing shall be adjustable between 300and 750mm measured from the surface of the wheelchair space at the intersection of the vertical axis of the anchorage and the farthest point of any wheelchair to which it might be attached.

b Where a tie down system that is not a four-point webbing system is fitted the manufacturer shall provide such information as may be necessary to demonstrate that the system provides an equivalent level of protection to requirements described in (a) and, if the vehicle is intended for public transport use, that it is suitable for general wheelchair application.

3 A wheelchair user restraint system shall comprise a minimum of a three-point anchorage system (lap and diagonal):

a The lower anchorages shall be attached to the floor at a position between 0mm and 400mm forward of the rear of the wheelchair space and between 300mm and 700mm apart and equi-distant on either side of the longitudinal centreline of the wheelchair space.

b The upper diagonal belt anchorage may be attached to the floor such that the belt may pass up and over the shoulder of the wheelchair user and down to the floor or via an upper webbing guide point or attached to a suitable higher anchorage point. All attachment points must be on the same side of the longitudinal centreline of the wheelchair space as that of the shoulder of the wheelchair user over which the webbing will pass. An anchorage shall be positioned at least 150mm measured in the transverse plane of the wheelchair space from the longitudinal centreline and in the case of an upper anchorage or webbing guide not forward of the padded surface of the head and back restraint.

c The effective upper anchorage must, except when floor mounted, lie within the zone specified in Figure E5 and be adjustable in height. The height shall be adjustable at least between 800mm and 1050mm above the floor. If a head and back restraint is fitted the zone specified in Figure E5 shall not extend forward of a transverse plane 100mm forward and parallel to the padded surface of the head and back restraint.

d a force of 16kN shall be applied to each of the floor anchorages in a forward and upward direction at an angle of 30 degrees to the horizontal. The force shall be maintained for at least 0.2 seconds.

e The effective upper anchorage must be able to withstand a force of 5kN applied forward and downward at an angle of 45 degrees to the horizontal. Where the upper anchorage is attached to the floor a webbing guide shall be arranged in the approximate position of the shoulder of a wheelchair user for the purpose of this test.

f any wheelchair user restraint or wheelchair tie down system fitted to a wheelchair space shall be capable of being easily released in the case of an emergency.

4 A head and back restraint may be fitted to the rear of the wheelchair space meeting the following requirements (see Figure E6):

a The bottom edge of the head and back restraint shall be at a height of not less than 490mm and not more than 530mm measured vertically from the floor of the wheelchair space.

b The top edge of a head and back restraint shall be at a height of not less than 1350mm measured vertically from the floor of the wheelchair space.

c The width shall be not less than 240mm at any point and not more than 280mm at any point up to a height of 1200mm measured vertically from the floor of the wheelchair space.

d T head and back restraint shall be fitted at an angle of not less than 4° and not more than 8° to the vertical with the bottom edge of the back and head restraint positioned closer to the front of the vehicle than the top edge.

e The surface of the head and back restraint shall be padded and form a single and continuous plane facing the front of the vehicle. The padded surface shall pass the energy absorption test according to annex 4 to ECE Regulation 21. This shall apply to the area bounded by two vertical planes extending 100mm on either side of the vertical centreline and between two horizontal planes 550mm and 1350mm above the floor.

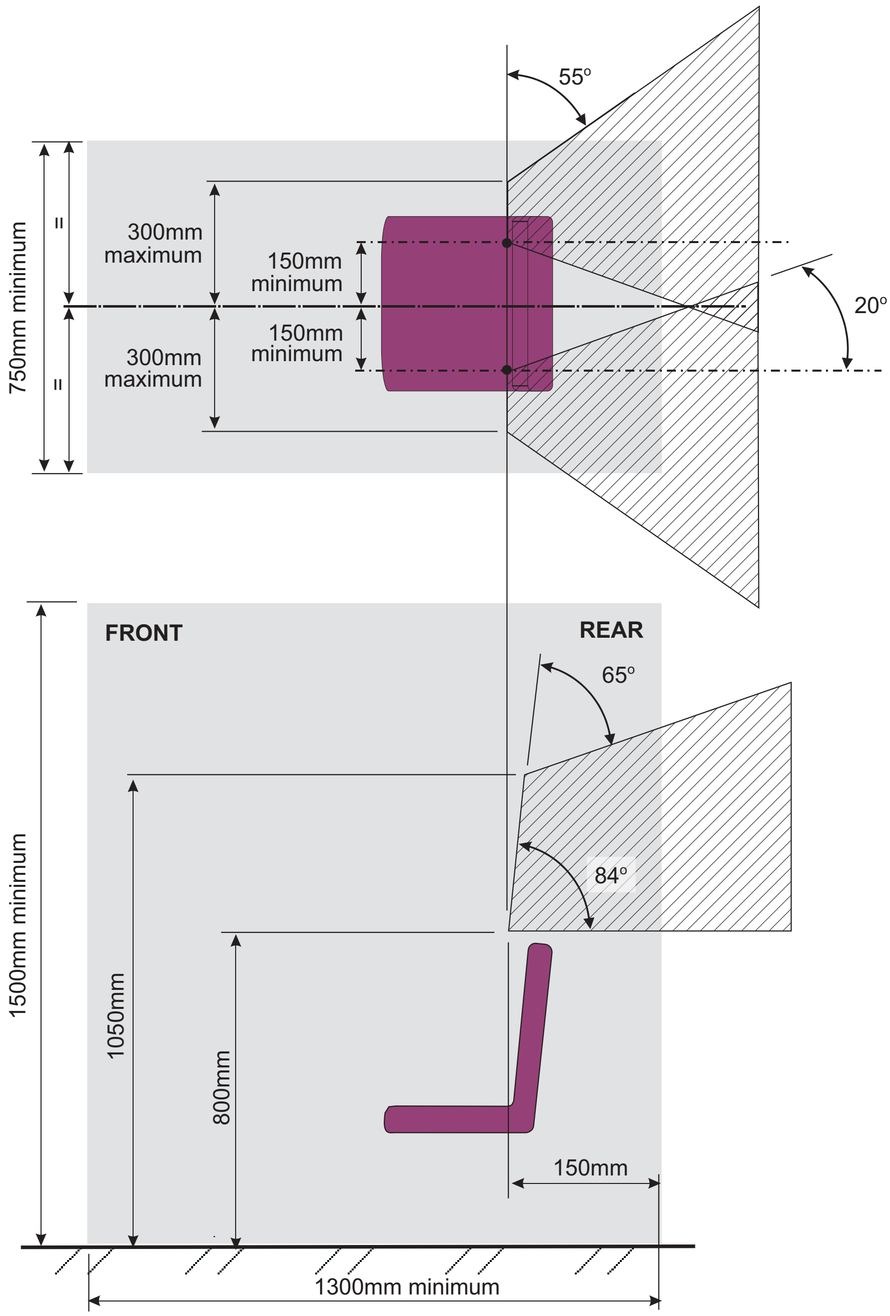


Figure E5 Upper anchorage – forward facing

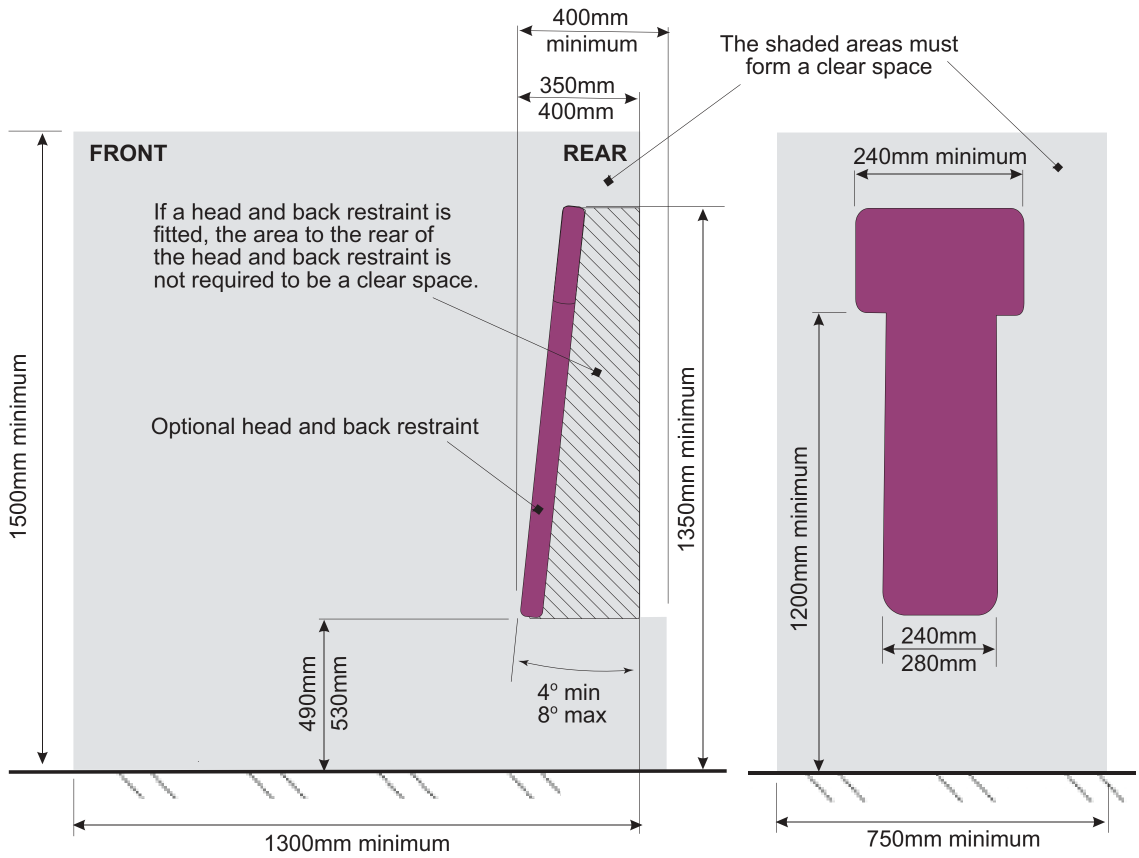


Figure E6 Wheelchair space – forward facing

E4: Rearward facing wheelchairs in M3 category vehicles fitted with passenger seat belts

1 Any wheelchair space shall comply with the following requirements:

a Be not less than:

i 1300mm measured in the longitudinal plane of the vehicle;

ii 750mm measured in the transverse plane of the vehicle; and

iii 1500mm measured vertically from any part of the floor of the wheelchair space.

b Shall allow the carriage of a wheelchair and a wheelchair user facing the rear of the vehicle.

c Shall be fitted with a head and back restraint at the forward end (relative to the vehicle) of the space.

2 A wheelchair tie down system, if fitted, shall comply with the following requirements:

a A tie down system shall, subject to sub-paragraph (b), consist of a webbing system comprising two separate straps or a system with two attachment points on the wheelchair and a single attachment point to the vehicle and meeting the following requirements:

i The anchorage or combined anchorages must be able to withstand a force of 5kN applied at an angle of 45 degrees upwards and towards the rear of the vehicle relative to a horizontal plane representing the floor of the wheelchair space. The force shall be maintained for at least 0.2 seconds;

ii the wheelchair tie-down system shall, as a minimum, meet the same performance requirements as the anchorage to which it is to be attached;

iii the anchorage(s) shall be positioned at floor level at the forward end of the wheelchair space;

iv If a single anchorage is fitted it must be on the central longitudinal centreline of the wheelchair space and if two anchorages are fitted they must be between 300mm and 600mm apart and equi-distant on either side of the longitudinal centreline of the wheelchair space;

v the webbing shall be easily adjustable between 300and 750mm measured from the surface of the wheelchair space at the intersection of the vertical axis of the anchorage and the farthest point of any wheelchair to which it might be attached.

b Where an alternative wheelchair tie down system is fitted the manufacturer shall provide such information as may be necessary to demonstrate that the system provides an equivalent level of protection to requirements described in (a). If the vehicle is intended for public transport use the system must be suitable for general wheelchair application.

3 A wheelchair user restraint system shall comprise a minimum of a three-point anchorage system (lap and diagonal) complying with the following:

a The lower anchorages shall be fitted at a position between 50mm forward and 50mm rearward of the foremost transverse plane of the wheelchair space and not below or more than 50mm above the floor level of the wheelchair space. This does not apply if the lower anchorage is adjustable in a plane parallel to the longitudinal axis of the wheelchair space and in at least one position adjustment meets this requirement. The anchorages must be between 300mm and 700mm apart equi-distant on either side of the longitudinal centreline of the wheelchair space.

b The effective upper anchorage must be attached to a suitable anchorage point and be on the same side of the longitudinal centreline of the wheelchair space as that of the shoulder of the wheelchair user over which the webbing will pass. An anchorage shall be positioned at least 150mm measured in the transverse plane of the wheelchair space from the longitudinal centreline.

c The effective upper anchorage must lie within the zone specified in Figure E7 and be adjustable in height. The height shall be adjustable at least between 800mm and 1050mm above the floor. The zone specified in Figure E7 shall not extend rearward of a transverse plane 100mm rearward and parallel to the padded surface of the head and back restraint.

d A force of 3kN shall be applied to each of the floor anchorages in a rearward and upward direction at an angle of 30 degrees to the horizontal. The force shall be maintained for at least 0.2 seconds.

e The effective upper anchorage must be able to withstand a force of 1kN applied rearward and downward at an angle of 45 degrees to the horizontal. Where the upper anchorage is attached to the floor a webbing guide shall be arranged in the approximate position of the shoulder of a wheelchair user for the purpose of this test.

f The restraint system shall comply with the requirements of ECE Regulation 16.

g any wheelchair user restraint or wheelchair tie down system fitted to a wheelchair space shall be capable of being easily released in the case of an emergency.

4 A head and back restraint shall be fitted complying with the following requirements (see Figure E8):

a The bottom edge of the head and back restraint shall be at a height of not less than 490mm and not more than 530mm measured vertically from the floor of the wheelchair space.

b The top edge of a back and head restraint shall be at a height of not less than 1350mm measured vertically from the floor of the wheelchair space.

c The width shall be not less than 240mm at any point and not more than 280mm at any point up to a height of 1200mm measured vertically from the floor of the wheelchair space.

d It shall be fitted at an angle of not less than 4° and not more than 8° to the vertical with the bottom edge positioned closer to the rear of the vehicle than the top edge.

e There shall be a clear space forward of the lower rearmost edge of the head and back restraint measuring at least 400mm forward of that point, at least 500mm above the floor of the wheelchair space and for a width of 750mm equally spaced about the longitudinal centreline of the wheelchair space.

f The surface of the back and head restraint shall be padded and form a single and continuous plane facing the front of the vehicle. The padded surface shall pass the energy absorption test according to annex 4 to ECE Regulation 21. This shall apply to the area bounded by two vertical planes extending 100mm on either side of the vertical centreline measured in the transverse plane and between two horizontal planes 550mm and 1350mm above the floor.

g The head and back restraint must be capable of withstanding a force of 50kN for a minimum of 0.2 seconds applied via a block measuring 700mm in height and 400mm in width applied horizontally and centrally in the rearward direction at a height of 670mm above the floor. The corners of the block may have a radius not exceeding 50mm.

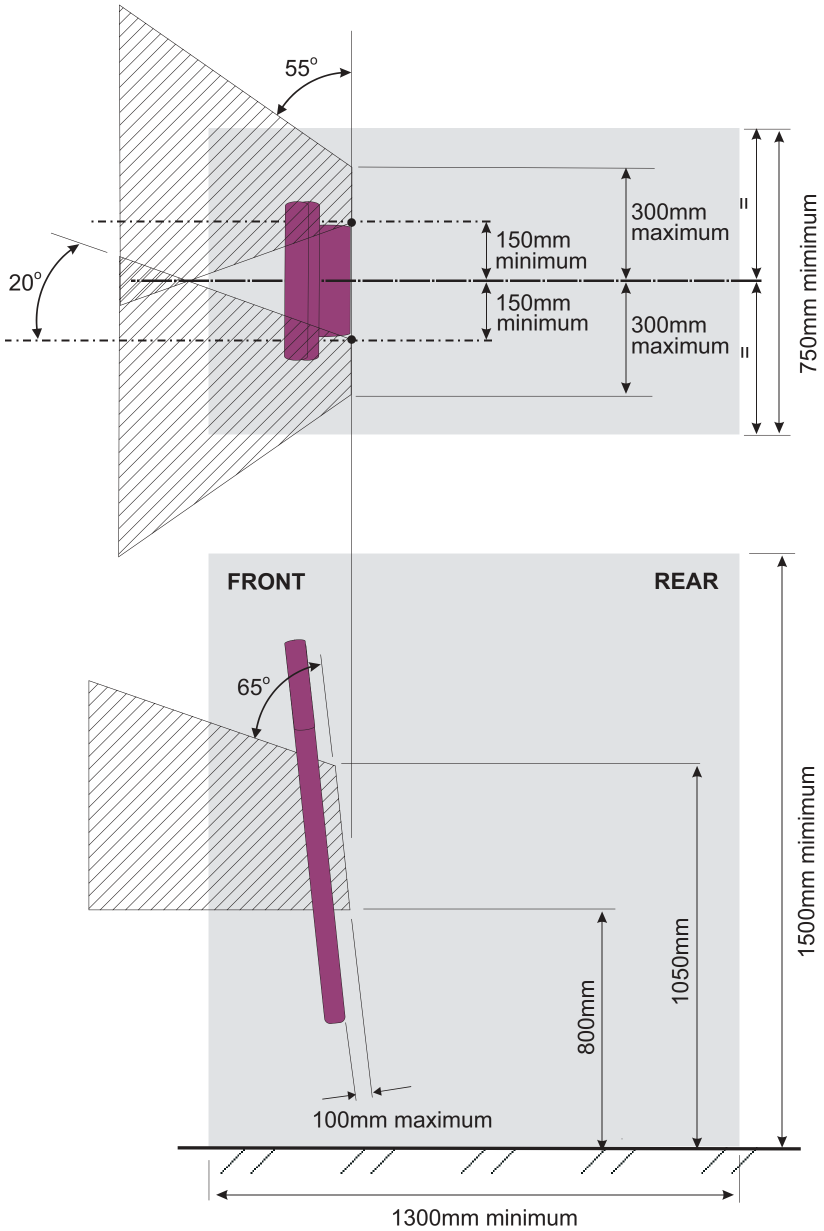


Figure E7 Upper anchorages – rearward facing

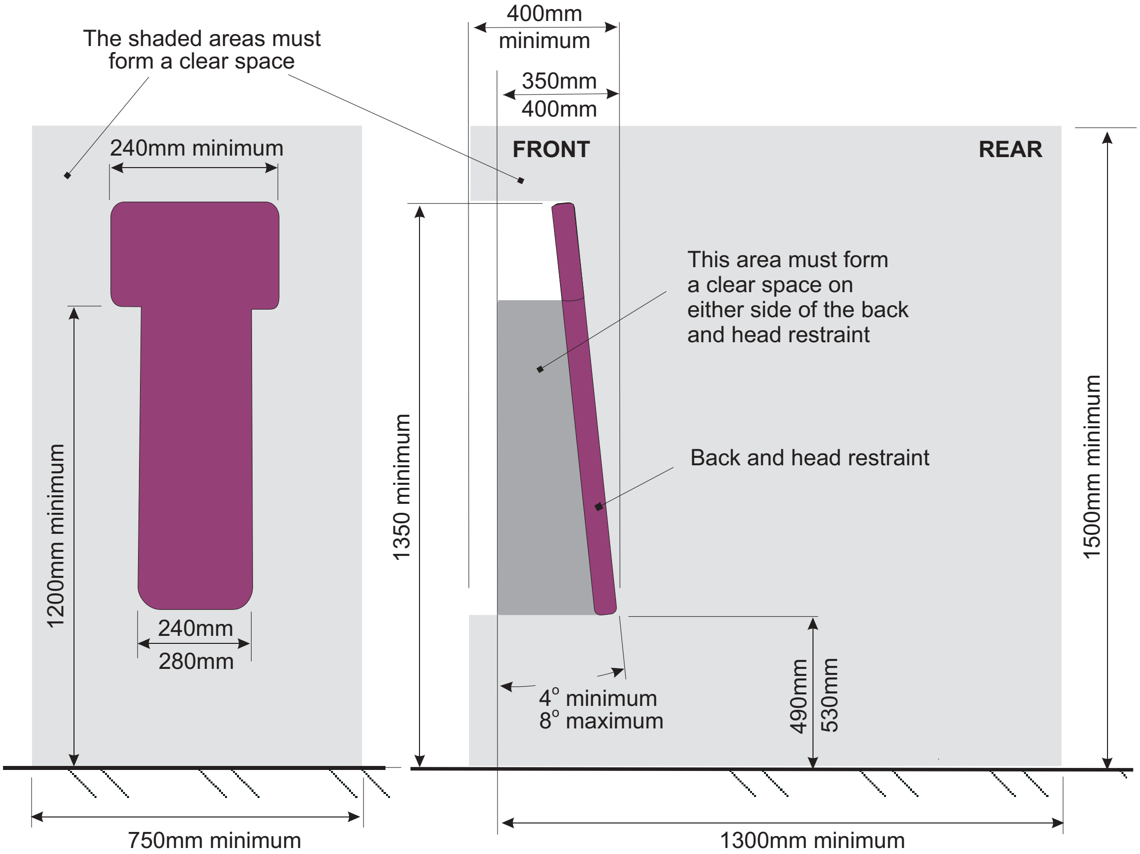


Figure E8 Wheelchair space – rearward facing