SAFETY OF WHEELCHAIR OCCUPANTS IN ROAD TRANSPORT

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ABSTRACT

The TNO Road-Vehicles Research Institute is involved in a long-term research programme on the transport of wheelchair occupants. The objective of this programme was to develop requirements regarding the safety and operation of wheelchair occupant protection systems. Many users and experts in this field had their doubts about the safety of these systems. Therefore normal and extreme driving manoeuvres were simulated to evaluate the strength and the stability of some presently used Dutch protection systems. In addition dynamic sled tests were carried out, simulating different types of crashes. The handling of the systems was also evaluated. The tests showed that even light impacts or sudden manoeuvres can induce failure of the used protection systems.

In this paper results of this experimental test programme will be presented and recommendations for future regulations in this field will be made. Guidelines for improved wheelchair occupant protection system design are also included.

INTRODUCTION

In 1983 the TNO Road-Vehicles Research Institute (IW-TNO) together with the Rehabilitation Research Institute (IRV) started a research programme on the transport of handicapped people. The programme centred on the safety of wheelchair occupants during their transportation in passenger cars or pick-up vans. The objective was to develop requirements for the wheelchair occupant protection systems, with respect to their safety and operation. There are many products specially designed for the wheelchair-bound disabled to provide for more possibilities of transport. In the past many organisations had their doubts about the quality of protection systems used in The Netherlands. In this country there is no legislation prescribing the use or quality of these systems.

The research programme started with a literature survey of existing regulations in this field. It appeared that in the past few years a lot of research work had been done resulting in the adoption of national standards or in the preparation of regulations in several countries. Most of these standards or regulations appeared to be design-restrictive or they required only the use of protection systems rather then providing guidelines for its quality. At present the existing standards or guidelines do relate to crash performance. Whilst the prescribed test methods are very different, the systems are in most cases required to withstand the forces of a 10-20 g's crash.

An inventory was made of the various protection systems used in the Netherlands, U.S.A., Canada, Sweden, Germany, U.K. and Australia. This showed there are many different systems available. These systems vary from relatively simple designs, like a leather webbing fixed to the wheel, to fairly complex constructions: with several anchors, bolsters and belts.

In the second phase of the programme a large number of transport companies was visited in order to evaluate the operation of Dutch systems. People who work with the systems daily were asked to show the operation of their protection system. The handling was recorded on a video-tape. This revealed that a number of systems were used wrongly: lap belts were used as diagonal belts, rail anchors were mounted in backwards, some parts were not used at all. Besides there were problems in finding the right attachment points on the wheelchair. Moreover, considerable differences were found in the force and time needed to lock and unlock the systems. It was concluded that instructions for encasing, use and emergency rescue should be supplied by the manufacturer, together with the protection system. Eight Dutch protection systems were selected for safety evaluations. On a test circuit the systems were submitted to normal and extreme driving manoeuvres. Next a series of dynamic sled tests was carried out to simulate crash situations. The test methods and the results of this experimental test programme will be discussed in detail in the present paper.

In the third phase of the programme TNO has formulated requirements and recommendations regarding instructions for use, design and durability of the systems. Meanwhile a working group of the Dutch Standardization Office ('Nederlands Normalisatie Instituut', NNI) has started preparations to transform this work into standards. Some recommendations and requirements will be included here. The IRV institute has made a video-film and a leaflet that inform about the correct use of Dutch protection systems. The Consumers' Organisation of Goods for the Handicapped ('Stichting Warenonderzoek Gehandicapten', SWOG) distributes the film and the leaflet [ref 1].

TNO is now developing test methods to evaluate requirements with respect to wheelchair occupant protection systems. Furthermore a project has been started concerned with the design of safe protection systems. Some aspects of both studies will also be incorporated in the present paper.

TEST METHODS

Introduction

From the literature survey mentioned above it was concluded that results of system evaluations conducted in other countries, could not be applied to the current Dutch systems, mainly due to the different design principles. Therefore it was decided to conduct a series of driving tests and crash simulation tests with a series of frequently used Dutch protection systems. These systems and the applied test methods will be described in the next sections.

Wheelchair occupant protection systems

A wheelchair occupant protection system consists of two main parts:
- the occupant restraint system that secures the occupant;
- the wheelchair fixation system that keeps the wheelchair fixed.

From the literature survey it was evident how many different types of wheelchair occupant restraint systems are existing. The occupant restraint system is in most cases either a lap belt, a three point belt or a harness system. These belts are either attached to the floor, walls or roof of the car, to the wheelchair fixation system or to the wheelchair. There are also occupant restraint systems that consist of safety bars or supports (figure 1). Some protection systems have no occupant restraint system: in these systems the occupant is not secured at all. Even more different types of wheelchair fixation systems were found. They consist for instance of additional bars or webbings that are attached to the wheelchair frame or to the wheels [ref 2]. Or simple constructions are used like a peg in a hole (see figure 2). Even an airbagsystem was proposed to restrain the wheelchair and its occupant [ref 3].

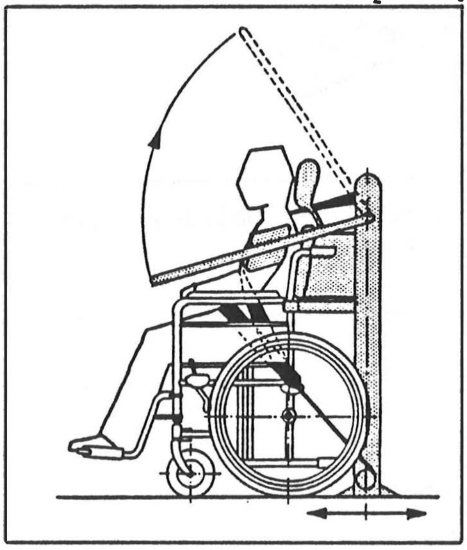

Figure 1.
An occupant restraint system with bars [ref 4].

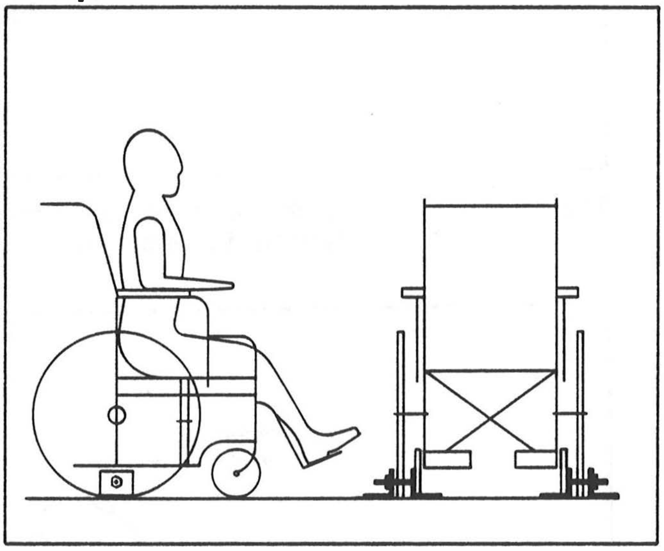

Figure 2.
A wheelchair fixation system based on a "peg in a hole" construction.

In the Dutch systems two main principles are applied for the fixation of the wheelchair:

- An anchor system or "Delta-support" that fixates the wheelchair via a vertical bar and a transverse tube or expander to a rail in the vehicle floor (figure 3). The expander is attached to the bar by means of a clamp. By adjusting the width of the expander the wheelchair is restrained at the vertical frametubes located at the back of the wheelchair. Five different versions of this system were tested, called "Anchor" 1 to 5. One of them had additionally a Y-shaped belt for restraining the front end of the wheelchair.
- A belt system that consists of three or four belts or cables that must be tensioned (figure 4). The belts are mostly connected to the wheelchair frame by hooks. Three versions of this type were tested, called "Belt" 1, 2 and 3.

In all selected systems a lap belt was used to restrain the occupant.

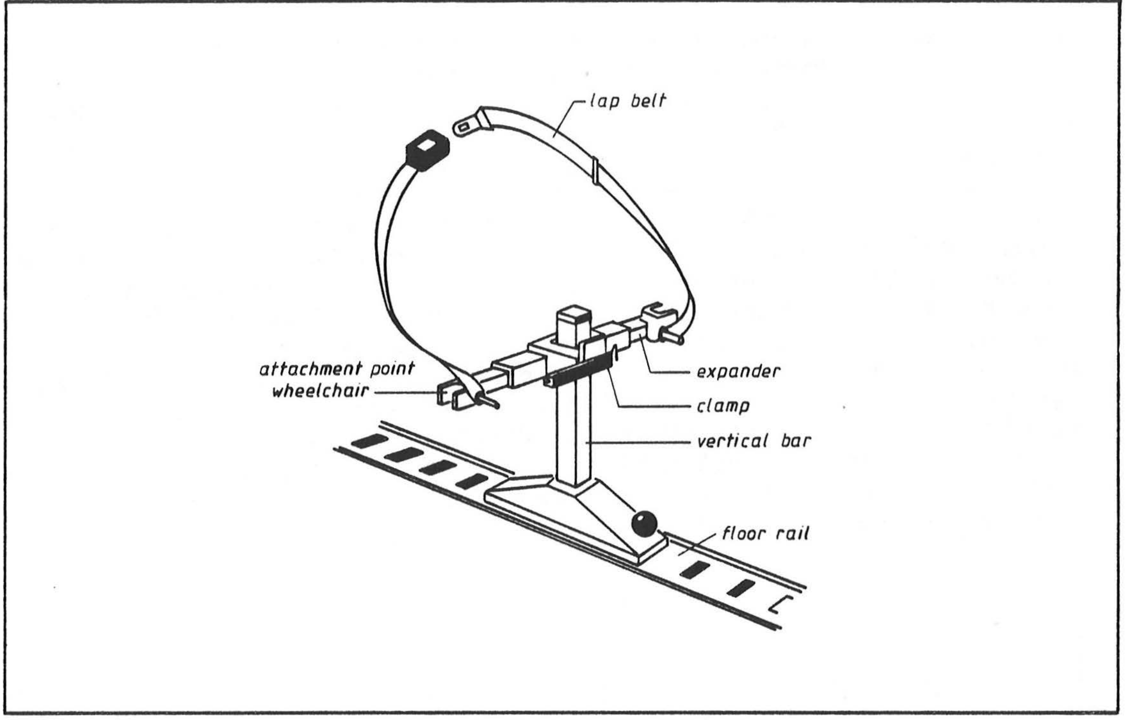

Figure 3. An example of an anchor system or "Delta-support", a typically Dutch protection system.

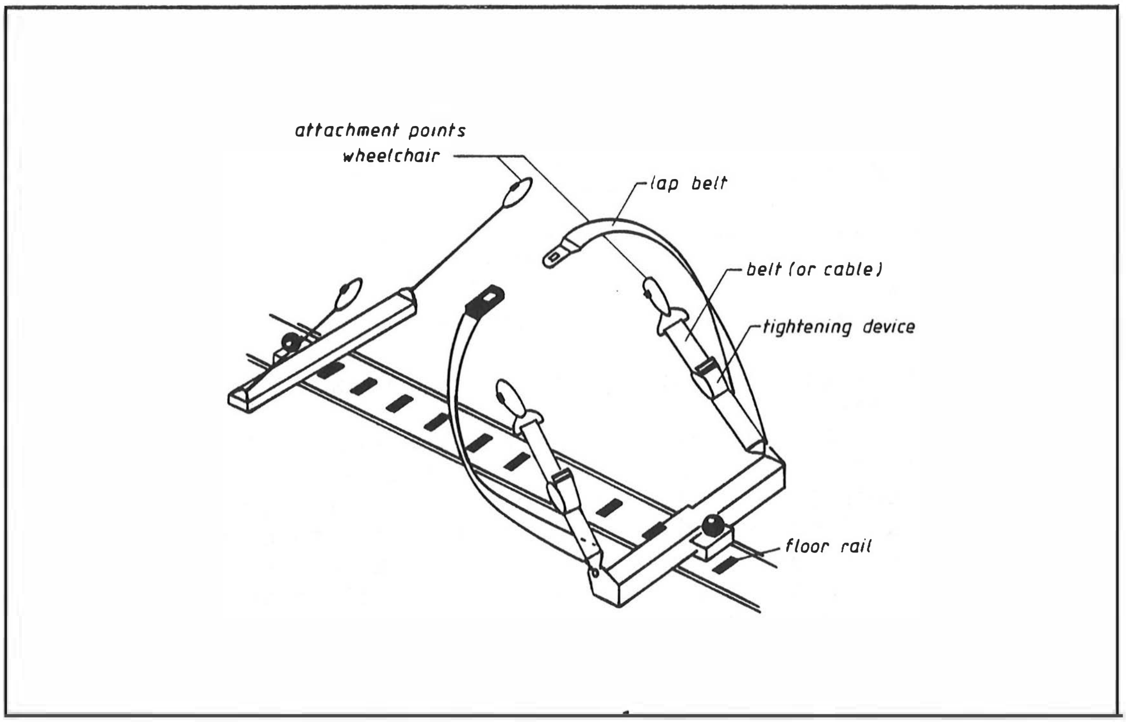

Figure 4. An example of a four-point belt system.

Driving manoeuvres simulation tests

The selected protection systems were installed in a minibus, where they were to restrain either an electrically-propelled wheelchair or a manually-propelled wheelchair, according to the specifications of the manufacturer. The approximate weight of these wheelchairs was 90 or 20 kg respectively. All wheelchairs were occupied by a 75 kg test dummy ('TNO-10'), facing the normal driving direction of the vehicle. On a test circuit the systems were submitted to normal and extreme driving manoeuvres. Table 1 summarizes the input conditions of the extreme tests. Normal driving was conducted between these tests. The test circuit has been covered three times with each system. The results of test 4, braking in a corner, will be omitted because the input conditions seemed not to be reproducible.

Table 1. Input conditions of driving simulation tests.

Test number	Type of Test	Loading Direction	Driving Velocity (km/h)	Acceleration in Loading Direction (g's)
1	Braking	Forward	50	0.9
2	Braking	Rearward	10	0.6
3	Slalom	Sideways	40	0.8
4	Braking	Forward/sideways	40	*)
5	Hobble	Upwards	10	1.3

*) no reproducible results

The vehicle floor accelerations and the relative movement of the wheelchair with respect to the floor were recorded in 3 directions. Furthermore high speed films were made during the extreme tests.

Crash simulation tests

An electric or manually-propelled wheelchair was installed on a sled and restrained by one of the selected protection systems. A PART 572 dummy with a weight of 75 kg was secured in the wheelchair. Additionally every wheelchair was secured with an emergency belt. This belt was looped loosely around the wheelchair in order to hold the combination if the protection system would fail. The test programme is summarized in table 2.

Relatively light and heavy crash situations in various directions were simulated. For frontal crashes the sled was moving at 30 km/h. The protection systems have been in succession exposed to a deceleration of 5, 10 and 15 g's until they failed. Also side impacts and rear impacts were simulated. For these tests the wheelchairs have been installed on the sled at an angle of 90 degrees or rearward facing respectively. Only a light crash with a deceleration of 5 g's and a

Table 2. Input conditions of the dynamic sled tests.

Type of test	Velocity (km/h)	Test number	Code System	Deceleration (g)	Type of Wheelchair
Frontal	30	1	Anchor 1	5	Manual
		2	Anchor 1	10	Manual
		3	Anchor 2	10	Manual
		4	Anchor 4	10	Manual
		5	Anchor 5	5	Powered
		6	Anchor 5	10	Powered
		7	Anchor 5	15	Powered
		8	Belt 1	5	Manual
		9	Belt 1	10	Manual
		10	Belt 2	5	Powered
		11	Belt 2	10	Powered
		12	Belt 3	10	Powered
Side	20	13	Anchor 3	5	Manual
		14	Anchor 4	5	Manual
Oblique	30	15	Anchor 1	10	Manual
Rear	20	16	Anchor 2 *)	5	Manual
		17	Belt 2	5	Powered

*) including a Y-belt on the wheelchair front

velocity of 20 km/h was simulated. One test, simulating an oblique crash, was performed with the sled moving at 30 km/h and a deceleration of 10 g's. The wheelchair was installed at an angle of 25 degrees from the sled deceleration direction.

The dummy was instrumented with triaxial accelerometers in the head, chest and pelvis. The sled deceleration was measured through two uniaxial accelerometers. Belt force transducers were mounted on the lap belt. High speed films were made in order to analyse the motion of the wheelchair and dummy during the impact test. Belt slip and displacements of system components have been measured after each test.

TEST RESULTS

Introduction

The results of the driving simulation tests and the crash simulation tests will be presented in the following sections. The analysis is limited to the data of the motion and displacements of the wheelchair-occupant combination, and particularly the crasworthiness of the eight selected systems.

Results of the driving simulation tests

In general the selected protection systems appear to be strong enough to keep the wheelchair combination fixed. Only one anchor system failed: in test number 3, the slalom, the expander came off the wheelchair-tubes because the spring mechanism inside the expander is not locked by the clamp in this system. No problems with respect to safety were observed in the other systems.

However, considerable differences were found in stability of the anchored wheelchairs. Consequently, the driving comfort of the wheelchair occupant varied widely. Maximum horizontal displacements up to five cm of the wheelchair relative to the vehicle floor were observed. Vertical displacements up to three cm were found in test number 5, the hobble. In test number 3 the wheelchair was inclined up to five degrees in lateral direction, causing the wheels to get off the floor.

Results of the crash simulation tests

In general most of the protection systems failed in a 5-g or 10-g frontal impact. Table 3 summarizes the test results. Systems were damaged and components broke. The anchor systems failed because the forces acting on the clamp which connects the expander to the vertical bar were too high: the expanders of the anchor systems slided off the vertical bar (see figure 5). The expander-bar connections were established through friction, for instance by a rubber block compressed between bar and clamp. However, in test number 5 and 6 the wheelchair with dummy remained restrained, although the vertical bar suffered large deformations. The relatively low centre of gravity of the electric wheelchair minimizes the vertical component of the force on the clamp. The maximum horizontal wheelchair and dummy's head displacement in test number 6 were 12 cm and 75 cm respectively. This anchor system slided off in the 15-g test.

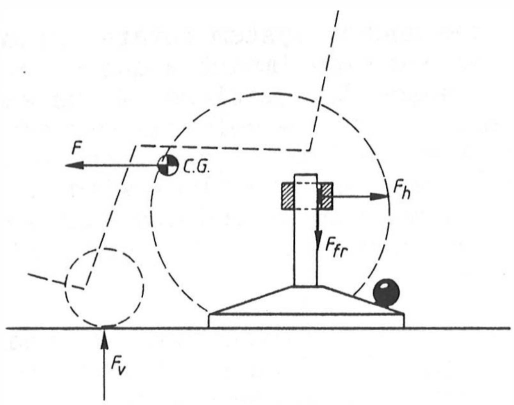

Figure 5. Forces acting on the wheelchair and clamp which slides off the vertical bar of an anchor system.

Table 3. Results of crash simulation tests.

Test number	Type of system	Deceleration (g)	Type of wheelchair	Results
1	Anchor 1	5	Manual	Slides off
2	Anchor 1	10	Manual	Slides off
3	Anchor 2	10	Manual	Slides, and breaks
4	Anchor 4	10	Manual	Slides off
5	Anchor 5	5	Powered	Restrained
6	Anchor 5	10	Powered	Restrained, deformations
7	Anchor 5	15	Powered	Slides off, deformations
8	Belt 1	5	Manual	Restrained
9	Belt 1	10	Manual	Restrained, deformations
10	Belt 2	5	Powered	Restrained, deformations
11	Belt 2	10	Powered	Connection breaks
12	Belt 3	10	Powered	Connection breaks
13	Anchor 3	5	Manual	Restrained, severe deformations
14	Anchor 4	5	Manual	Restrained, severe deformations
15	Anchor 1	10	Manual	Slides off, wheel breaks
16	Anchor 2	5	Manual	Restrained, wheelchair fails
17	Belt 2	5	Powered	Restrained, wheelchair fails

Components broke off in the 10-g tests of one anchor system and of two belt systems, resulting in free movement of the wheelchair and occupant. Figure 6 illustrates the final position of the dummy and wheelchair after such a test. One belt system passed a 10-g test, but it suffered large permanent deformations of some components. The maximum horizontal head displacement of 87 cm occurred in this test.

In the oblique test the anchor system rotated around the vertical bar and slided off. In the 5-g side impact a quick release appeared to be impossible due to permanent deformations of the expander or of the floor rail. The movement of the wheelchair was severe; rotation around the vertical bar resulted in lateral displacements up to 30 cm. Furthermore the wheels came off the floor with an inclination angle up to 14 degrees. However, wheelchair and occupant remained restrained, partly caused by the emergency belts that were activated by the large wheelchair displacement.

In the 5-g rear impacts the wheelchair was the weakest part: in both tests the backrests broke. See figure 7 for the position of the wheelchair and dummy after the dynamic test.

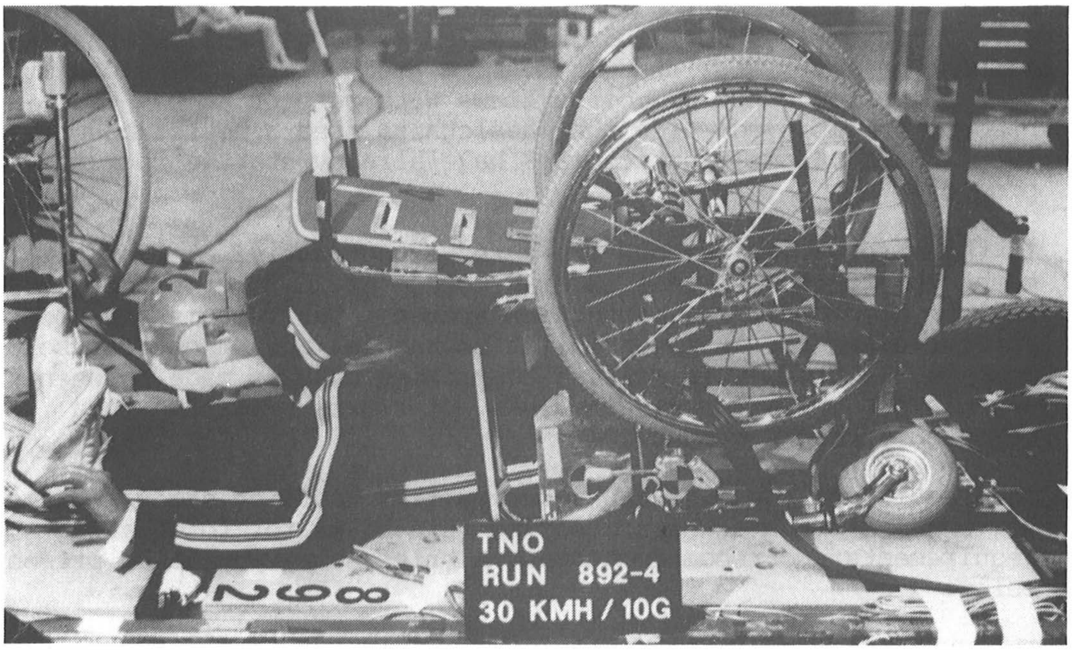

Figure 6. Final position after a 10-g frontal impact test.

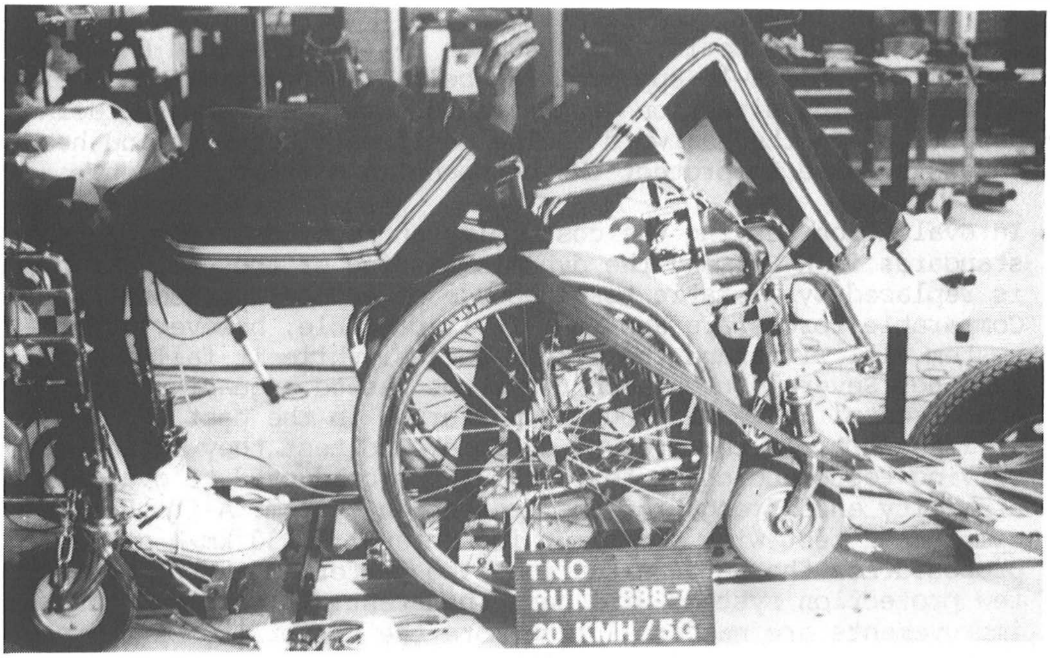

Figure 7. Final position after a 5-g rear impact test.

DISCUSSION AND CONCLUSIONS

Eight Dutch wheelchair occupant protection systems were selected for safety evaluations. Driving simulation tests as well as crash simulation tests were conducted. From these tests it was concluded that the performance of most systems with respect to the crash safety need to be improved. Also the wheelchairs need a better adaptation to the fixation. Some manufacturers have already started to improve their products.

If the safety requirements are based on automotive standards which means they must hold in a 50 km/h impact of 20-30 g's, complex designs will be needed for the protection systems. The systems will be expensive and fairly inconvenient to handle. So, an optimal solution must be resorted. This means a compromise must be made between safety aspects and operation requirements. Of course resulting in a reasonably priced product.

The results of the literature survey, the handling study and the driving and the crash tests served as a basis for formulating requirements and recommendations. A brief summary will be presented below.

The protection systems should in principle consist of two parts: the occupant restraint system and the wheelchair fixation system. Their performance should be tuned to each other to avoid loading of the wheelchair onto the occupant. Also the occupant should not load the wheelchair. This can be accomplished by using the same vehicle anchor points for both systems. An anchor system with a connection based on friction is not strong enough to withstand the forces that occur in a 5-g or 10-g impact. The fixation of the wheelchair should not be attached to the wheels. The occupant restraint system should at least consist of an ECE-16 approved lap belt. The occupant should face the normal driving direction of the vehicle or the rearward facing direction. In the rearward facing position a backrest and headrest should be used to protect the occupant in a frontal crash.

In evaluation testing the costs play an important role. In the DIN standards in W-Germany the dynamic testing of the protection systems is replaced by a static test because of economic reasons [ref 5]. Comparable forces are applied. It is possible, however, that an anchor system will withstand the static forces, while it fails in the dynamic testing. Several Dutch anchor systems passed a quasi-static test, with a horizontal force of 16000 N, performed in the past by the Ministry of Transport. In the present dynamic sled test they failed completely. Driving tests and crash tests should be conducted to evaluate the stability and strength of the protection system. A frontal crash simulation test with a maximum input level of 30 km/h and 10-15 g's is proposed for the Dutch situation. The performed tests have shown that few protection systems will pass this test. It is clear that design improvements are needed. Furthermore the durability of the protection systems should be evaluated with respect to wearing properties and environmental influences.

A safe transportation of wheelchair occupants can only be obtained through safe restraints. But the presence of safe restraints alone is not enough: they must be used and they must be used correctly. And a protection system will be used when it is easy and comfortable. The design should not allow misuse or a 'half-closed' position of clamps and lockings. Operation should be light and possible to be carried out with one hand only, allowing the free hand to manipulate the wheelchair. In the handling tests only fastening and loosening of the systems was regarded. When designing a good protection system a wider view must be taken. Also the loading and discharging must be easy and this means also the vehicle must be considered.

Riding comfort is important. A 'rigid' fixation to the vehicle floor is a nuisance, because all high-frequency vibrations of the vehicle are transferred, whereas an 'elastic' fixation leads to large wheelchair motions. Measurements and calculations conform ISO 2631 that were performed recently, have indicated that the comfort of a wheelchair occupant is considerably lower than the comfort of a front seat passenger in the same vehicle [ref 6]. This means that a driver should adapt his driving style to the circumstances of his passengers in the wheelchairs.

Until now there are no standards in relation to the transportation safety for the wheelchair. Standards are difficult to establish because of the many types of wheelchairs available and of the often contradictory requirements. A start could be made by standardisation of the parts to which fixation systems can be attached. If only these parts are made recognizable - through a specific colour or mark - this will attribute to the correct use and the safety of the wheelchair occupant protection system.

FUTURE PROGRESS

In several countries standards concerning the safety of wheelchair occupants in road transport have been or are being developed. Standards relate to the protection system and to the vehicle. Also in The Netherlands a working group of the Dutch Standardisation Office has started the preparations to transform the available knowledge into standards. In future hopefully also the design of the wheelchair will be subject to standardisation in this respect. Parallel to this TNO is developing quality guidelines for the design and use of protection systems. Test procedures will be further developed. A standard, rigid, test wheelchair is being developed to replace the weak wheelchair in the dynamic sled test.

Recently TNO has started a project concerned with the development of a new protection system based on the knowledge obtained from the previous phases of the research programme. In order to get more quantitive information and to understand more about the weak points in current protection systems and of forces acting on the system, mathematical simulations were made with the crash victim simulation model MADYMO. An anchor system was simulated in a 30 km/h crash test with a deceleration of 10 g's. Figure 8 shows the motion of the

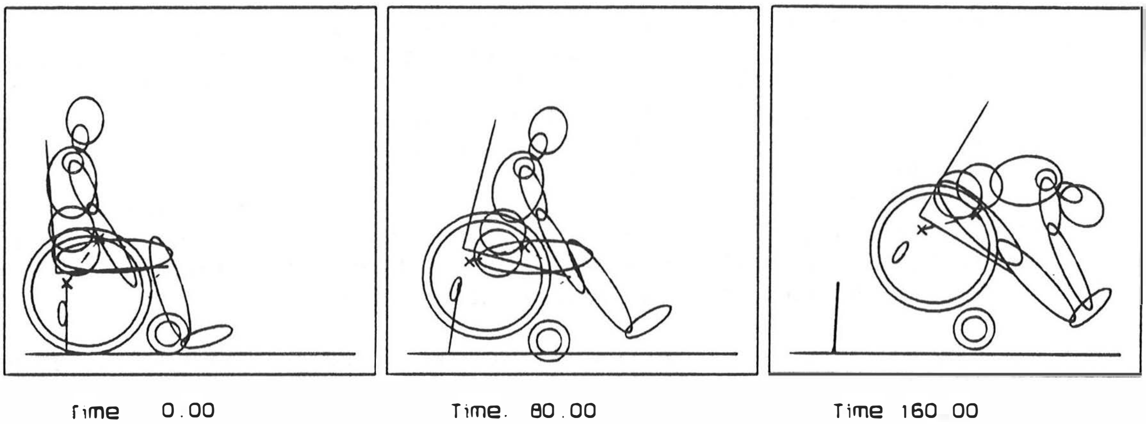

Figure 8. Mathematical simulation of a 10-g frontal impact test with an anchor system.

occupant and the manually-propelled wheelchair. It is illustrated that the clamp slides off the bar in the vertical direction and the wheelchair with the occupant turns over. In the simulation the clamp mechanism was modelled through a simple contact with defined friction properties.

Regulations, improved product design and product-specific information, to be provided by the manufacturer, will hopefully lead to improved protection of wheelchair occupants in road transport in the near future.

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