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EEVC Working Group 12 Report

EEVC Recommended Requirements for the Development and Design of an Advanced Frontal Impact Dummy

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EEVC RECOMMENDED REQUIREMENTS FOR THE DEVELOPMENT AND DESIGN OF AN ADVANCED FRONTAL IMPACT DUMMY

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Abstract

In Europe, occupant protection in frontal impact has been a subject of research for many years. Regulatory bodies, research institutes and car manufacturers have been addressing biomechanics, crashworthiness and car design for quite some time. Only a couple of years ago, however, this has become subject for collaboration within the European Experimental Vehicles Committee (EEVC), especially in view of initiatives to establish a new European frontal impact regulation. The Steering Committee of the EEVC has directed a mandate to establish requirements for an advanced frontal dummy which should be used to assess injury risks in frontal impact. This mandate provided the start of the EEVC Working Group 12. In view of other research programmes in this area, especially the Advanced Anthropomorphic Test Device (AATD) development programme of the US Department of Transport - National Highway Traffic Safety Administration (NHTSA), and in view of the current worldwide situation in side impact, the EEVC has decided to focus on the development of a **worldwide acceptable frontal dummy**. The set of recommended requirements put forward in this report can be regarded as additions and comments to the NHTSA AATD development programme, taking into account European impact conditions.

Further enhancement of the biofidelity of frontal dummies is considered essential, especially improved interaction with the vehicle interior and various restraint systems are necessary. In relation to an improved biofidelity, improvements in measurement capabilities for frontal dummies are necessary. This will probably also imply a review of injury criteria in the future.

An advanced frontal dummy should at least allow reliable injury assessment of the head/face, thorax, abdomen and the lower extremities and certainly for these parts, improved biofidelity with respect to current frontal dummies is recommended. A full understanding of an occupant's response to frontal impact will, however, require more parts to be biofidelic and more measurements to be taken, particularly at the neck, lumbar spine and pelvis. Appropriate biofidelity and injury assessment by themselves are, however, insufficient to ensure that an advanced frontal dummy can successfully be applied to improve car occupant protection using regulatory test procedures. Requirements for an advanced frontal dummy's repeatability, reproducibility, durability, sensitivity and handling are therefore also recommended in this report.

The recommended requirements included in this report are established based on biomechanical data, experiences with current frontal dummies and knowledge of European accident conditions. Expectations are that further recommendations will be made by EEVC on the basis on experimental evaluation studies of (parts of) advanced frontal dummies.

Contents

1 Introduction

1.1 General

In view of the developments in occupant protection in crash conditions, the Steering Committee (SC) of the European Experimental Vehicles Committee (EEVC) directed a mandate to set up a working group to study requirements for an advanced frontal impact dummy. This mandate specifically expressed the wish to harmonize with frontal impact dummy development proceeding in the USA, where the National Highway Traffic Safety Administration (NHTSA) started the Advanced Anthropomorphic Test Device (AATD) development program [1][fm 1].

1.2 EEVC-WG12 Terms of Reference

The mandate mentioned in section 1.1 provided the start for EEVC Working Group 12, specified by the following terms of reference [2]:

"To achieve the development of a universally acceptable frontal dummy for passenger cars through co-operation with interested institutions worldwide. This work should include specifications and evaluation procedures for a frontal dummy".

To perform its task, EEVC-WG12 has been in close contact with the NHTSA [3]. The NHTSA has replied positively to this EEVC initiative and has provided regular briefings to WG12 and support in obtaining the prototype parts for evaluation. Furthermore, the NHTSA has been in direct contact with European laboratories performing evaluations of these parts.

1.3 Report Objectives

The objective of this report is to support the development of an advanced frontal impact dummy by recommending requirements for its design and performance. This report should be regarded as discussion document and reflects the expertise and opinions of the EEVC-WG12 members on developments of advanced frontal dummies. Throughout this report, as much as possible the terminology is used as proposed in the EEC biomechanics programme [4]. It is not the intention of this report to propose a complete set of response and design requirements for an advanced frontal dummy. It is merely an addition and review of reports on requirements for an advanced frontal dummy, especially those resulting from the NHTSA AATD development programme [1], [5], [6]. The literature review included in this report reflects the status until December 1995.

[fm 1] The numbers between brackets designate the references at the end of this document.

1.4 Report Format

The recommended requirements put forward in this report are firstly based on European accident and injury data (chapter 2) to establish priorities for injury assessment capabilities of an advanced frontal dummy. The priorities are compared with those established in the AATD development programme.

To reflect the current state of technology, a short discussion is held on development of frontal dummies up to now (chapter 3). Specific attention is given to the limitations of existing dummies in order to provide guidance for the development of advanced frontal dummies.

Recommended requirements for advanced frontal dummies are split in general dummy characteristics (chapter 4) and characteristics per body part (chapter 5). These chapters form the main body of this report. The recommended requirements contained herein are established from experience gained with the use of current dummies in Europe, taking into account European accident conditions and reviewing the most recent biomechanical frontal impact data.

The discussion and main conclusions are presented at the end of this report (chapter 6). The conclusions are provided with a list of priorities of subjects that, to the view of the EEVC-WG12, need attention in the developments of an advanced frontal dummy currently taking place in the world.

2 European Accident and Injury Data

2.1 Introduction

In this chapter, an analysis of accident and injury data is presented, based on a literature review conducted by Rattenbury and Gloyns in 1993 [7][ftn 2] (section 2.2) and based on relevant documents of EEVC-WG12 (section 2.3). The most important conclusions are summarized at the end of this chapter (section 2.4).

A comment to technical literature of accident studies expressed in the literature study by Rattenbury and Gloyns [7] is also valid for the current analysis: an understanding of the samples is critical in assessing their relevance to the current specifications of an advanced frontal dummy design. Strictly speaking, only studies which are based on a representative sample of seriously and fatally injured belted front seat occupants in frontal impacts are directly relevant. There are few studies that meet this selection criterion precisely. Useful information can also be derived from less rigorously selected samples, as long as any possible bias introduced by the particular sample is recognized.

2.2 Conclusions from the Rattenbury and Gloyns Study

In 1993, Rattenbury and Gloyns conducted an extensive literature review on accident and injury data which included some 50 sources [7]. Those conclusions from this review relevant to the design of an advanced frontal dummy, are listed below.

- For car occupants, frontal impacts are still the major cause of severe and fatal injuries, even in countries with high seat belt use rates. In general, European data suggest that frontal impacts account for 40-66% of impacts causing severe or fatal injuries. Some variations between countries can be expected, but the general conclusion that frontal impacts are the single most important type of impact in serious and fatal accidents is unarguable.
- The car-to-car impact is the most frequent configuration in frontal impacts, varying from 45-66% in the analyzed literature. Variations in distributions of object struck in these studies may be due to sampling criteria or genuine differences between countries.
- Impacts were both longitudinal members play a significant part in absorbing energy probably account for less than 25% of accidents with severe and fatal injuries. In the majority of frontal impacts only one longitudinal member is involved, with some additional loading via the engine/bulkhead load path in a proportion of these impacts, implying non-longitudinal loading hence a 3-dimensional motion of the occupant can be expected.

[ftn 2] This review study is also referenced by the EEVC-WG11 (frontal impact test procedure).

- The most reliable European data suggests that a test speed of 50 kph[ftn 3] would address only a small proportion of the more severely injured casualties in frontal impacts. A test speed of 55 kph would still address less than half the casualties with injuries of AIS 3 or greater. A test speed of 60 kph would address about two-thirds of these casualties.
- When injuries of AIS 2 or more are considered, the head (including the face) is the most frequently injured area particularly for drivers.
- Head and facial injuries caused by contact with the steering wheel are probably the single most important issue in frontal impact protection. There are no requirements which deal with this issue at present in Europe. The use of a head injury criterion on instrumented dummies in a full scale crash test is necessary. Some caution is necessary here though, as recent work suggests the tolerance work on which HIC was based used very different loading conditions on the head to those which occur in steering wheel impacts.
- It is also clear that the use of HIC or some other head injury criterion is insufficient to address the problem of facial injuries, nor will it address the range of head impacts seen in real accidents. An additional component test is needed to address these or other issues.
- Chest and abdominal injuries are generally of lesser importance to belted drivers, though for fatally injured occupants they are still critical.
- For belted passengers, chest and abdominal injuries become relatively more important, though the head and face, and to a lesser extent the legs, must still be considered.

- Leg injuries are very important in real accidents, being probably the second most frequent type of injury. The use of the femur load criterion on instrumented dummies may help limit the risk of injury to the upper leg. But a significant proportion of the leg injury problem relates to the lower leg and is not addressed by this criterion. A criterion controlling intrusion would be appropriate in the medium term, as intrusion appears to be a major factor in injury causation in real accidents. In the future, the use of more sophisticated instrumentation in the dummy's lower leg could be used as well, although the problem of simulating bracing (a likely occurrence in real accidents) on the brake pedal may be difficult to solve. Correct assessment of the injuries caused by intrusion also requires that realistic belt slack is simulated to ensure the dummy interacts with intruding structures the same way as humans.
- The use of intrusion controlling criteria would also be beneficial in terms of reducing the risk of head, face and thorax injuries.

[ftn 3] kph = kilometre per hour

2.3 Analysis of Literature Presented to EEVC-WG12

In this section, first European accident and injury data are discussed as have been presented to the EEVC-WG12. This concerns two sources, presented under the headings *'Hannover'* and *'TRL'*. Secondly, some data from outside Europe are given that also have been presented to the EEVC-WG12 and were not included in the 1985 analysis of US accident and injury data to establish an injury priority rating (IPR). These data are presented under the headings *'GESAC'*, *'Monash'* and *'TRC'*. The latter two have specifically been included because no detailed European data on lower extremity injuries were available, while these injuries do appear frequently and may cause considerable suffering and treatment, which is not assessed using the AIS classification. Finally, the IPR, as established in the AATD development programme, is summarized to compare with the previously mentioned data; this under the heading *'NHTSA: IPR'*.

Hannover

Since 1985, the medical and technical staff of the Traffic Accident Research Unit of the Medical University of Hannover conducts on-the-spot accident investigations on a continuous basis. The resulting data are filed in a database. From this database (1985 to 1991), isolated frontal impacts at an impact angle of ± 30° involving passenger cars were analyzed [8], [9]. In these accidents, 87 belted frontal occupants were injured MAIS 3 or higher and in total suffered 781 injuries. Of the 87 front occupants, 64 were drivers and 23 were passengers. The injury severity distribution for the different injury causing structures of the car interior is shown in Table 1. The most frequently impacted structures are the steering wheel, the dashboard (instrument panel) and the legroom area. At these impact locations also the highest share of more severe injuries is observed. The distribution of injury severity over the body parts is shown in Table 2. Very severe injuries (AIS 5 and 6) tend to be located at the head and neck. AIS 3+ injuries are dominant in the abdomen, thorax, head and lower extremities. The distribution of the injury severity per type of tissue damaged is given in Table 3. With increasing injury severity, the injuries shift from bone and soft (superficial) tissues to the brain and organs.

Table 1: Injury Severity Distribution per Injury Causing Structure (values in %)

n = 781	total	Injury Severity						
		AIS1	AIS2	AIS3	AIS4	AIS5	AIS6	
Injury Causing Part	100.0	35.8	27.3	25.7	7.4	3.0	0.8	100.0
front	16.0	27.5	31.7	31.7	6.7	1.7	0.8	100.0
windscreen area	5.8	66.7	26.7	-	2.2	4.4	-	100.0
dashboard	16.9	41.7	18.2	31.1	3.0	5.3	0.8	100.0
steering wheel	20.0	35.7	20.1	27.9	12.3	3.2	0.6	100.0
legroom	11.1	35.6	40.2	24.1	-	-	-	100.0
side	4.7	40.5	29.7	21.6	5.4	2.7	-	100.0
roof	0.1	-	-	-	-	-	-	100.0
interior equipment	7.6	37.3	22.0	22.0	11.9	6.8	-	100.0
outside car	9.1	15.0	35.0	35.0	7.5	5.0	2.5	100.0
other	12.5	30.1	34.4	20.4	12.9	-	2.2	100.0

Table 2: Injury Severity Distribution per Body Region (values in %)

		Injury Severity						
n = 781	total	AIS1	AIS2	AIS3	AIS4	AIS5	AIS6	
Body Region	100.0	35.8	27.3	25.7	7.4	3.0	0.8	100.0
head	36.2	34.8	30.5	18.6	11.1	3.6	1.4	100.0
neck	2.4	47.1	17.6	11.8	5.9	5.9	11.8	100.0
thorax	16.5	30.2	25.4	28.6	11.9	4.0	-	100.0
upper extremities	10.9	53.6	31.0	15.5	-	-	-	100.0
abdomen	4.5	6.1	18.2	33.3	21.2	21.2	-	100.0
pelvis	2.3	27.8	44.4	27.8	-	-	-	100.0
lower extremities	26.8	38.3	23.9	36.4	1.4	-	-	100.0
other	0.3	-	-	-	-	-	-	100.0

Table 3: Injury Severity Distribution per Tissue Type (values in %)

		Injury Severity						
n = 781	total	AIS1	AIS2	AIS3	AIS4	AIS5	AIS6	
Tissue Type	100.0	35.8	27.3	25.7	7.4	3.0	0.8	100.0
soft part	40.8	77.6	15.1	4.1	2.2	0.9	-	100.0
bone	41.9	8.7	40.8	41.4	7.2	0.9	0.9	100.0
organ	6.1	-	6.4	55.3	25.5	12.8	-	100.0
brain	7.4	1.7	34.5	25.9	22.4	10.3	5.2	100.0
vessels	1.5	-	30.0	30.0	10.0	30.0	-	100.0
ligament, tendon	0.8	-	50.0	50.0	-	-	-	100.0
other, unknown	1.3	-	22.2	44.4	11.1	22.2	-	100.0

Detailed analyses of the Hannover data show that contact with the steering wheel is a particular concern for facial skull and skin injuries, injuries to the skin, ribs and organs of the thorax and brain injuries. Steering wheel impacts to the face cause fractures and soft tissue injuries in almost all areas of the face. In the majority of all cases, isolated injuries occur. Only weak indications of combined injuries were observed: bone and soft tissue injuries to the face, bone injuries to the thorax and neck distortions, and facial injuries and neck distortions.

In [8], the influence of the ΔV on the injury severity is discussed. In frontal collisions with $\Delta V < 30$ kph, 62.4% of the car occupants remained uninjured. With $\Delta V > 50$ kph the injury severity increases rapidly. In the velocity range of 31 to 50 kph, only 4.8% are seriously or fatally injured (MAIS > 2), but in the velocity range of 51 to 70 kph, this number increases to 18.8%. Above 70 kph, this number further increases to 53.7%. Obviously, the injury severity per body part also increases with increasing ΔV. In the velocity range of 31 to 50 kph, 1.4% of the car occupants are seriously or fatally injured to the head (AIS > 2). For a ΔV between 51 and 70 kph, this number increases to 5.5% at for a $\Delta V > 70$ kph, this number is 43.9%. Similar trends are observed for the thorax and pelvis/abdomen area (AIS > 2): for 30 kph $< \Delta V <$ 50 kph, the numbers are 0.6% and 1.0% respectively, for 50 kph $< \Delta V <$ 70 kph, the numbers are 10.4% and 10.3% respectively.

TRL

The TRL in-depth accident database contains data from a continuous accident study, carried out by teams of the Institute for Consumer Ergonomics, Loughborough and the university of Birmingham. This data base has been analyzed for restrained drivers and restrained front seat passengers separately for front impacts (11 to 1 o'clock) [10], [11], [12], [13], [14]. The injury severity distribution per body part for both types of occupants are given in Tables 4 and 5.

Table 4: Injury Severity Distribution of Restrained Drivers; TRL Data Base (in %; n = 2445)

	Skeletal			Soft Tissue			Total		
	AIS≥3	AIS≥4	AIS≥5	AIS≥3	AIS≥4	AIS≥5	AIS≥3	AIS≥4	AIS≥5
face	1.4	0.3	0.0	0.3	0.0	0.0	1.7	0.3	0.0
head	3.4	1.7	0.1	9.2	4.5	2.5	12.5	6.2	2.7
neck	0.4	0.1	0.1	0.7	0.4	0.3	1.1	0.4	0.3
thorax	3.6	1.5	0.4	8.1	5.0	1.8	11.7	6.5	2.2
abdomen	-	-	-	2.4	1.8	1.2	2.4	1.8	1.2
pelvis	1.0	0.1	0.0	0.5	0.0	0.0	1.6	0.1	0.0
upper leg	4.7	0.0	0.0	0.1	0.0	0.0	4.8	0.0	0.0
lower leg	3.0	0.0	0.0	0.1	0.0	0.0	3.1	0.0	0.0

Table 5: Injury Severity Distribution of Restrained Front Seat Passengers; TRL Data Base (in %; n = 979)

	Skeletal			Soft Tissue			Total		
	AIS≥3	AIS≥4	AIS≥5	AIS≥3	AIS≥4	AIS≥5	AIS≥3	AIS≥4	AIS≥5
face	0.4	0.1	0.0	0.3	0.0	0.0	0.7	0.1	0.0
head	2.2	0.9	0.0	5.4	3.0	1.7	7.6	3.9	1.7
neck	0.5	0.4	0.4	0.5	0.2	0.1	1.0	0.6	0.5
thorax	3.1	0.4	0.2	8.2	5.3	1.6	11.3	5.7	1.8
abdomen	-	-	-	2.9	2.1	0.8	2.9	2.1	0.8
pelvis	0.8	0.1	0.0	0.2	0.0	0.0	1.0	0.1	0.0
upper leg	3.5	0.0	0.0	0.0	0.0	0.0	3.5	0.0	0.0
lower leg	2.1	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0

The TRL data base includes information on the contact considered to be the direct cause of the injury. Only few skeletal injuries were found to be attributable to seat belts; more frequently, soft tissue injuries to the thorax and abdomen resulted from seat belt contact.

Tables 6 through 9 provide more detail of more serious and severe injuries in frontal accidents from the TRL data base. The most frequent thorax injuries are fractured ribs, followed by lung contusions and lacerations. For the more severe injuries (AIS ≥ 5), injuries to the heart and aorta predominate (Table 6).

Table 6: Details of Thorax Injuries (AIS ≥ 3) to Restrained Front Seat Occupants (> 14 years) in Frontal Impacts; TRL Data Base

area	injury description	AIS	number
whole area	massive crush	6	6
heart	contusion	3	14
	contusion/laceration	4/5	42
	complex laceration	6	7
aorta	laceration/tear	4	4
	major laceration, incomplete transection	5	20
arteries/veins	laceration/tear	3/4	10
	segmental loss	6	2
ribs	fractures - stable	3/4	133
	flail chest - unstable	4/5	26
thoracic cavity	pneumo/hemo thorax/mediastinum	3/4	55
trachea/lungs	contusion/laceration (one lobe)	3	68
	contusion/major laceration	4	43
	major laceration	5	3
diaphragm	laceration	3	5

Injuries to the abdomen are (obviously) soft tissue injuries which tend to be rather severe once they occur (Table 7). Note than in this data base, half of the spleen injuries and more than half of the liver injuries are of severity AIS 5.

Table 7: Details of Abdomen Injuries (AIS ≥ 3) to Restrained Front Seat Occupants (> 14 years) in Frontal Impacts; TRL Data Base

area	injury description	AIS	number
stomach, duodenum and pancreas	laceration	3	2
	laceration with tissue loss	4/5	4
spleen	contusion/laceration	3	5
	severe laceration	5	5
liver and gall bladder (1 case)	laceration	3/4	25
	severe laceration	5	30
intestine (jejunum to colon)	laceration	3	4
	severe laceration	4/5	7
kidney	contusion/laceration	3	4
	severe laceration	5	3
bladder	laceration	4	2
retroperitoneal	haemorrhage/haematoma	3	5
perineum	laceration	3	1

Injuries to the pelvic bones do not often exceed AIS 3 and most common are fractures of the pelvic bones, but surprising is the high number of pubic symphysis separations (Table 8).

Table 8: Details of Pelvic Bone Injuries (AIS ≥ 3) to Restrained Front Seat Occupants (> 14 years) in Frontal Impacts; TRL Data Base

area	injury description	AIS	number
bony pelvis	open/displaced/comminuted	3	13
	crush	4	3
	sacroiliac	3	1
	symphysis pubis separation	3	12

The most frequent severe leg injuries (AIS ≥ 3) are femur fractures. A lot of leg fractures (e.g. to the lower leg) are classified AIS 2 and do not appear in Table 9, but it should be kept in mind that the AIS classification does not reflect the importance of injuries in terms of treatment, which for a number of leg injuries is known to be quite substantial.

Table 9: Details of Lower Extremity Injuries (AIS ≥ 3; except ankle dislocations) to Restrained Front Seat Occupants (> 14 years) in Frontal Impacts; TRL Data Base

area	injury description	AIS	number
hip	dislocation	3	19
femoral artery	not specified	3	1
sciatic nerve	laceration	3	1
femur	fracture	3	159
knee	ligament laceration/dislocation	3	9
lower leg	fractures tibia/fibula, open/comminuted/displaced/nerve involvement	3	41

One of the recent activities of TRL is the development of a safer steering wheel. Test methods to assess the injury risk in steering wheel impacts were developed. In [12, 13, 14] accident data concerning head and facial injuries caused by head to steering wheel impact are presented and analyzed. The data show that restrained drivers frequently sustain brain injuries and facial bone fractures from striking the steering wheel. The facial fractures are usually not life-threatening but require considerable treatment. Considering all severity levels, the hub is responsible for 34% of the injuries and rim or spokes is responsible for the rest. It is concluded that the steering wheel is a major cause of facial bone fractures and AIS 2 brain injuries.

Reference [12] includes a comprehensive study on facial injuries of 940 accidents with 1603 occupants. Out of a total of 936 drivers, 91 suffered head and face injuries from steering wheel contact. In almost all cases (96%), the driver was wearing the seat belts. In 36 cases, head injuries are observed of which 28 had AIS 2 brain damage and 2 had AIS 3-6 brain damage. In 84 cases, the driver had facial injuries from steering wheel contact: 46 showed minor injuries (AIS 1-2), but 31 showed single bone fracture and 4 showed multiple fractures.

GESAC

To further support the development of a new frontal dummy within the AATD development programme, GESAC analyzed additional injury data [15], [16]. With respect to the head and face, an analysis of NASS air bag deployment cases is presented in [16]. In this analysis, weighting factors (average economic costs) for injuries at each severity level are introduced to form a quantity called Harm [17]. For head injuries, the Harm accounts for less than 10% of the Harm of the total body. The Harm for the head is caused by a variety of contacts. The pillars and upper structure are the largest contributors to head injuries. The NASS data further indicate that injury patterns appear to be changing due to the effectiveness of air bags and belts. For air bag equipped vehicles, the injuries from the steering assembly are greatly diminished. Injuries from the pillar, header and upper structure continue to be significant for both air bags and belts. The windscreen emerges as a significant source of injury for both air bag and belt restrained occupants.

With respect to the abdomen, the NASS data show that injury to this area account for about 10% of the Harm of all injuries. The injury statistics indicate that lap belt loading is a possible cause of these injuries, irrespective of whether the occupant was submarining or not. Injuries to the lower abdomen appear to be predominantly caused by lap belt contact and possibly by air bag contact. Injuries to the middle abdomen appear to be caused by lap belt contact, steering wheel contact and possibly air bag contact. Injuries to the upper abdomen appear to be caused predominantly by steering wheel contact and possibly by air bag contact.

Monash

Monash University has conducted an analysis of lower extremity injuries to car occupants [18], for the Federal Office of Road Safety (FORS, Australia). The following conclusions are derived from this study. Lower extremity injuries occur to front seat occupants in more than one third of all frontal crashes where someone is either hospitalized or fatally injured. Fractures occur in 88% of these cases and are the most common severe outcome. Oblique frontal impacts usually result in more lower extremity injuries than either full of offset frontal collisions. The most frequent combinations of fracture and contact are: ankle/foot with floor and toepan, lower leg with floor and toepan, thigh with instrument panel and knee with steering column. The combination of ankle/foot with floor and toepan is predominant. About 50% of all lower extremity fractures occurred at ΔV below 48 kph; about 80% occurred at ΔV below 70 kph. The number of fractures is directly proportional to ΔV. Lower limb fractures are more common among occupants of smaller cars. The most common mechanisms of lower limb fracture include compression (axial loading) of thigh and lower leg, perpendicular loading of the knee, and crushing or twisting of the foot. Foot and ankle movements of inversion and eversion and dorsi-flexion were most common among foot and ankle fractures.

TRC

The Transportation Research Centre, Inc. (TRC, USA) has conducted an in-depth study on lower extremity injury in the NASS data [19]. The TRC study concludes by summarizing the important common mechanisms of injury to the lower extremities, based on the analysis of NASS data and discussions with physicians:

Ankle and Foot:
- hyper-dorsiflexion, hyper-inversion or hyper-eversion, or combination,
- axial loading through the heel or forefoot,
- combined rotation and axial loading;

Tibia:
- shear or bending due to direct impact,
- axial loading due to floor shock or intrusion;

Knee:
- direct impact,
- underriding impacts to the proximal tibia,
- pocketing of knee combined with floor loading through foot;

Femur:
- impact loading along the femoral axis,
- antero-posterior or medio-lateral bending,
- combined bending and axial loading;

Hip:
- direct impact loading through femur,
- hyper-flexion or hyper-adduction of the hip,
- combinations of the above.

NHTSA: IPR

The AATD programme of NHTSA includes an injury priority analysis to establish the relative importance of various body parts to be protected as well as to define two important parameters in the loading conditions for the advanced dummy: the impact direction and the ΔV of the impact. The resulting injury priority rating (IPR) distributions are given in Tables 10, 11 and 12 [1]. It should be noted that the occupants under consideration in this analysis were nearly all unrestrained and sustained injuries ranging from AIS 2 to AIS 6 and that the IPR includes impacts in all directions.

Table 10: IPR Distribution by Body Region

Body Region	Distribution (%)	Body Region	Distribution (%)
Head	44.6	Ankle/Foot	0.6
Face	10.5	Lower Limb	0.0
Neck	5.1	Upper Arm	1.3
Shoulder	0.3	Elbow	0.5
Chest	18.9	Forearm	1.3
Back	1.6	Wrist/Hand	0.4
Abdomen	7.5	Upper Limb	0.3
Pelvis	1.1	Whole Body	0.9
Thigh	2.1	Unknown	0.2
Knee	1.6		
Lower Leg	1.0	TOTAL	100.0

Table 11: IPR Distribution by Direction of Force

Direction of Force	Distribution (%)	Direction of Force	Distribution (%)
1 o'clock	4.8	9 o'clock	3.3
2 o'clock	9.8	10 o'clock	7.9
3 o'clock	3.5	11 o'clock	5.0
4 o'clock	0.0	12 o'clock	6.9
5 o'clock	0.1	Non-Horizontal	16.1
6 o'clock	0.7	Unknown	10.4
7 o'clock	0.3		
8 o'clock	1.2	TOTAL	100.0

Table 12: IPR Distribution by ΔV

ΔV	Distribution (%)	ΔV	Distribution (%)
1-4 mph	0.1	41-45 mph	1.5
6-10 mph	0.6	46-50 mph	0.0
11-15 mph	2.0	51-55 mph	2.7
16-20 mph	4.3	> 55 mph	3.8
21-25 mph	7.0	Unknown	68.9
26-30 mph	4.9		
31-35 mph	2.6	TOTAL	100.0
36-40 mph	1.5		

Primary conclusions from the IPR analyses are:

- The combination of head, face and neck body regions accounts for 60% of the IPR to passenger car occupants.
- The combination of the chest, back and abdomen body regions accounts for 28% of the IPR to passenger car occupants.
- Over one-third of driver IPR occurs from collisions with a 12 o'clock direction of force. One-fifth results from collisions with non-horizontal directions of force.
- Oblique side collisions account for more IPR than direct side collisions. This applies both to drivers and to right-front passengers. Thus 9 o'clock collisions account for 4.3% of driver IPR, but 10 o'clock and 11 o'clock collisions account for 11.9%. Similarly, 3 o'clock collisions account for 9.4% of IPR to right-front passengers; 1 o'clock and 2 o'clock collisions account for 19.2%.
- Using only known values of ΔV, 84% of driver IPR with a 12 o'clock direction of force results from severe crashes, i.e. those with a ΔV > 20 mph. For right-front passengers, this figure is 97%. However, it should also be noted that for cases with known ΔV, 81% of driver IPR and 77% of right-front passenger IPR was attributable to crashes with a ΔV of 45 mph or less.
- Again, using only cases with known ΔV, 66% of driver IPR for injuries to the head, face and neck result from severe crashes. For injuries to the chest, beck and abdomen, the comparable figure is 81%; for injuries to the upper extremities 45%, and for injuries to the lower extremities 93%. Thus one might conclude that, for drivers, serious injuries to the upper extremities are the most easy to prevent because a higher proportion of them occur in less severe crashes. Next would come the combination of the head, face and neck, followed by the combination of the chest, back and abdomen, and last the lower extremities.
- Comparison of IPR with an earlier Harm-model indicated that the two models were in complete agreement in assigning relative priority to the direction of force in the 1980 and 1981 NASS data. When ranking body regions, however, the IPR model gives higher priority to the head, face and neck, and correspondingly less prominence to the chest, abdomen and extremities. This is because of the relatively severe long-term consequences of injury to the head, face or neck.

2.4 Discussion

Details of accident and injury data are important to establish the priority of body parts to be protected, to understand the nature of the injuries occurring and to understand the circumstances under which they occur. All these factors play an important role in the development and design of a crash dummy. As an addition to the AATD development programme, in which US accident and injury data have been analyzed in detail, data from Europe (and other parts of the world) are analyzed in this chapter. The European data analyzed in this report is consistent with those used by EEVC-WG11, addressing the frontal impact test procedure, since the same sources have been used.

Comparison between the different samples presented in this report is somewhat limited because the databases apply different selection criteria. Whereas the European data included in this chapter only address front impact (11 to 1 o'clock), the US data include all directions of impact. Furthermore, some differences exist between the various European data sources, however, the analyses of European data all concern front impact and focus on more severe injuries/accidents.

Despite the differences in selection criteria, the priority rankings of body parts to be protected are in reasonable agreement between the US and European data. The IPR applied by the NHTSA shows that the head/face is by far the most important part of the body to be protected. The other body parts are ranked as follows -in decreasing order of importance-: thorax, abdomen, lower extremities, neck, upper extremities, pelvis. The European data also show that the head/face is the most important part, however, an important difference exists between the US data base and the European data bases. Whereas in the US the use of air bags is well established, this is not (yet) the case in Europe. On the other hand, seat belts are mandatory in Europe but are not mandatory in all parts of the US. The fact that this results in different injury patterns, particularly to the head/face, is obvious (e.g. contact with the steering wheel is of lesser concern when an air bag is present). Furthermore, the importance of head/face injury is less prominent for belt restrained front seat passengers (see Table 5).

The European data result in a high ranking (second or third) of lower extremity injuries, especially if also AIS 2 injuries to the legs are considered because of the risk of permanent impairment and costs resulting from these injuries. The importance of preventing lower extremity injuries is also indicated by Australian and US data and should be further considered in the development and design of an advanced frontal dummy. The type of lower extremity injuries that occur and circumstances under which these occur show large variations and appropriate assessment certainly requires enhanced dummy parts.

In general, the thorax and abdomen are both recognized in the IPR and the European data bases as important body parts requiring protection. Though the injury data analyzed does not suggest completely different injury patterns between the US and Europe, different restraints are known to cause different risks. Belt loading, as commonly seen in Europe, affects different parts of the thorax and abdomen compared to air bag loading, as commonly seen in the US. Obviously, belts also load the body differently than air bags. An advanced frontal dummy should hence be capable of assessing the different risks, according to the different loading conditions.

Both the US data and European data suggest that the test conditions currently applied in the US may not appropriately or sufficiently cover the risks of injuries in frontal crashes worldwide. The test conditions themselves are not subject of extended research here, however, will affect the design of an advanced frontal dummy. Within the EEVC (particularly WG11 and WG12) sufficient communication takes place to take the appropriate test conditions into account.

In conclusion:

- The head/face area is the most important part to be protected.
- Injury assessment of the head, particularly for the face, may require different criteria or assessment methods for different types of contact (e.g. air bag contact v. steering wheel contact). The currently applied HIC seems insufficient to cover the complete risk of head and face injury.
- Injuries to the lower extremities need more attention than given so far. Assessment of intrusion as well as dummy responses need further study.
- The advanced frontal dummy needs to include assessment of thorax and abdomen injury to various loading conditions and should also be able to distinguish different risks resulting from different restraints.
- An advanced frontal dummy should be developed and designed to suit different test conditions as have been applied so far, particularly off-axis (non-longitudinal) loading, higher test velocities and various contacts will affect the design of the dummy.

3 Development of and Experience with Adult Frontal Impact Dummies

3.1 Introduction

Dummies vary in their degree of sophistication, depending on the application for which they will be used. First, distinction is made between devices representing a part of the human body and full body dummies. In this report, only full body dummies are considered.

Second, distinction is made between "loading devices" and "injury assessment devices". Relatively simple dummies with appropriate joint positions and mass distribution are used, for instance, in routine dynamic checking of the strength and stretching of seat belts (e.g. TNO-10 [20]). These type of dummies are considered loading devices and their main use is to load vehicles and/or their components in a repeatable manner. More complex dummies are required for the evaluation of injury risk to car occupants in vehicle impacts. These dummies are considered anthropomorphic injury assessment test devices and have to comply with various design and performance specifications.

In this chapter a short historical review is given of the development of adult frontal impact dummies for automotive crash protection (section 3.2). Subsequently, several limitations of the design of current frontal dummies are discussed (section 3.3), specifically with regard to the injury assessment capabilities/biomechanical background, the design concept and the appropriateness for use in future vehicle crash testing/restraint evaluation.

3.2 Short Historical Review

A summary of the historical development of crash dummies is contained in [21]. The first dummy to be specified for automotive testing was the VIP-50A, developed by Alderson Research Laboratories (ARL), Ford and General Motors (GM) in 1966. The first dummy used for automotive compliance testing was the Hybrid-II, developed by GM in 1972. This dummy is based on a limited set of biomechanical data and allows to measure head, chest and pelvis accelerations and femur loads only. Since 1973, the Hybrid-II is specified as the standard tool for approval testing of passenger cars in the USA. While still in use, the Hybrid-II is now considered less appropriate for compliance testing for several reasons. The most important limitation of Hybrid-II is its inappropriateness for use with adult belt restraints - still the predominant restraint type in Europe. The unrealistically high stiffness of its rib cage and non-humanlike articulation of its clavicle, provide unrealistic interactions of the Hybrid-II with three-point belt systems. As a result, the dummy tends to roll out of the diagonal belt, resulting in more forward movement of the head and much lower head accelerations. In addition, the interaction of the lap belt with the anterior superior iliac spine of the human pelvis is poorly represented in the Hybrid-II.

Its more advanced successor, the Hybrid-III, was developed in 1976 also by GM. The Hybrid-III is specified for the US.FMVSS 208 and is the most widely used adult crash dummy in the world. More recently, besides the 50th percentile male version, 5th female and 95th male Hybrid-III dummies have been developed. The Hybrid-III still represents the current state of the art of adult frontal dummies.

From the late sixties to mid seventies, only loading devices were used in Europe. The TNO-10 resulting hereof is still in use for strength testing of adult belt systems [22]. By the time the Hybrid-II was released in the USA and used worldwide, two alternatives were developed in Europe. In the UK, the OPAT was developed by Ogle Design, Ltd., TRL and MIRA. In France the ONSER 50 was developed by ONSER. The use of these dummies, however, remained restricted to the countries in which they were developed.

Until now, no full body crash dummy is specified for automotive compliance testing in Europe, except for the TNO-10 (testing of adult belt systems). European car manufacturers and research organisations have, nevertheless, extensively used the Hybrid-II and Hybrid-III dummies. The Hybrid-III has recently been proposed by the EEVC Working Group 11 as the dummy to be used in the first phase introduction of a new European full scale frontal impact regulation.

The most recent development in terms of full body adult frontal dummies, concerns the National Highway Traffic Safety Administration's (NHTSA) Advanced Anthropomorphic Test Device (AATD) development programme [1]. Started in the mid-eighties, this programme will result in a new frontal dummy design expected to be advanced in terms of biomechanical background and injury assessment capabilities compared to the Hybrid-III. A first prototype of the complete dummy was presented at the ESV conference in Melbourne, Australia in May 1996.

3.3 Limitations of the Hybrid-III

A comprehensive description of all features of current adult frontal dummies is beyond the scope of this report. Below, only the most important limitations of the Hybrid-III - the most widely used dummy- are discussed, particularly to provide further guidance for development of advanced frontal dummies.

Currently, the Hybrid-III allows assessment of over 40 measurements of acceleration, deflection and load in various body areas.

Head injury assessment using the Hybrid-III relies on the Head Injury Criterion (HIC), based on time histories of the linear accelerations of the head centre of gravity. Limitations of HIC as criterion for head injuries have often been expressed, and amongst these is the lack of evaluating the effect of rotational accelerations.

In its standard form, the Hybrid-III does not allow to assess the risk of facial injuries nor does its represent the human face deformation characteristics in direct contact.

Some alternative designs for the Hybrid-III facial structure have been proposed [23] but none has gained worldwide acceptance yet.

The biofidelity of the neck of the Hybrid-III is based on limited biomechanical data. Neck biofidelity is questioned especially for frontal flexion [39].

Compared to the Hybrid-II, the Hybrid-III has a slightly more profiled rib cage, a more compliant chest and more distinct clavicles. While an improvement of the Hybrid-II, the clavicles do not articulate correctly and the chest is still not compliant in the same way as a human chest. The primary thoracic performance objective for the Hybrid-III was to assess the efficiency of energy absorbing steering columns [24]. So the thorax was developed to have appropriate responses to these type of blunt sternal impacts. The cadaver chest response corridors used in this development were adjusted by 667 N to account for the lack of muscle tone. The Hybrid-III thorax was not designed to reproduce human thoracic response to the type of asymmetric strip loading applied by the shoulder belt. The force/deflection response of the Hybrid-III chest to a three point belt loading has been shown to be almost twice as stiff as that of cadavers [25].

Both the biofidelity and injury assessment capabilities of the Hybrid-III abdomen are limited. Attempts have been made to enhance both [26] using a deformable abdominal insert and a load sensing plate attached to the pelvis. This alternative design, however, has never been considered for compliance testing and proved to be rather unpractical.

The biomechanical basis of the lumbar spine of the Hybrid-III is unknown and its performance is specified in quasi-static conditions only. Though not directly at severe risk of the injury itself, the lumbar spine significantly determines the behaviour of the dummy in belt restrained conditions. Submarining is an important example of a phenomenon highly affected by the lumbar spine's response.

The pelvis of the Hybrid-III is the same as the Hybrid-II, but is rotated rearwards. In Japan, the US and Europe it was observed that the shape of the pelvis as well as the femur of the Hybrid-III differs from that of the human body in such a manner that hard contact can occur, e.g. in airbag tests, between the iliacs and the femur, causing high vertical chest accelerations which are believed to be unrealistic.

Over the last years, the ankle of the Hybrid-III is subject of re-design since the range of motion in the mid-sagittal plane (dorsi-flexion/extension) proved to be unrealistically low and the stiff contact at the end of ankle range of motion provided unrealistic spikes in the tibial load responses. The increasing interest in assessing the injury risk of the lower legs, resulted in recently proposed design improvements of the Hybrid-III ankle.

3.4 Discussion

In the past, the Hybrid-III and its predecessors have successfully been applied to increase car occupant protection. Today, the Hybrid-III is the most widely used injury assessment anthropomorphic test device. Accepted for the US regulation FMVSS 208 and (in improved state) accepted for the proposed European frontal impact procedure, it is the most advanced production dummy now available. Nevertheless, both US and European regulatory bodies have recognized the need for further enhancements. With respect to the current regulatory Hybrid-III, the EEVC-WG12 recommends enhancements for the following: head and face biofidelity and measurement capabilities, neck biofidelity, thorax biofidelity, abdomen biofidelity and measurement capability, pelvis anthropometry and sensitivity and leg biofidelity and measurement capabilities. The following chapters discuss further enhancements of frontal impact dummies by specifying response and design recommendations. These recommendations are to be regarded as enhancements of existing dummies, such as Hybrid-III, and additions or comments to the specifications set up in the NHTSA AATD development programme.

4 Overall Dummy Requirements

4.1 Introduction

Once the application of a crash dummy has been defined, specifications are set up addressing several so called "dummy requirements". In this chapter, requirements are discussed addressing the complete dummy, i.e. anthropometry (section 4.2), overall biofidelity and injury assessment (section 4.3), repeatability and reproducibility (section 4.4), durability (section 4.5), sensitivity (section 4.6) and handling (section 4.7). A short summarizing discussion is enclosed at the end of this chapter (section 4.8). Requirements per body part are discussed in chapter 5.

It should be pointed out that the advanced frontal dummy under consideration is primarily intended to assess the protection in front impact, offered by cars and their restraint systems to (adult) occupants in restrained condition. The unrestrained condition, i.e. without any protective device, is considered of secondary priority for the development of an advanced frontal dummy.

4.2 Anthropometry

The AATD programme uses anthropometry data representative of the US population, established in the late seventies [27], [28]. The database resulting from these studies is probably the most comprehensive study of adults in the automotive position up to now, and includes dimensional and inertial properties of a 5th female, 50th male and 95th male. The advanced dummy developed in the AATD programme is based on the 50th percentile male data.

Comparative anthropometry data between US population and European population is scarce. To illustrate the differences: the average stature of 20-year-old Dutch adult males is 1831 mm (standard deviation 67 mm) [29]; the average stature of 20-year-old US males is 1759 mm (standard deviation 67 mm) [30]. Comparable figures for females are 1705 mm (Dutch, standard deviation 62) and 1629 mm (US, standard deviation 64 mm). Probably also differences exist between inertial characteristics of both populations, however, these data were not readily available.

No additional requirements are proposed with respect to the anthropometry specifications already used in the AATD programme, partly for practical reasons but also because of lack of extensive and comparable anthropometry studies of different populations. One exception to this, however, is the distribution of mass between soft tissues and skeletal structures. In current adult dummies, skeletal structures are predominantly represented by metal parts, known to have much higher density than its human counterparts. Especially in contact conditions, the effective mass of the dummy could therefore differ considerably to that of a human. This would result in differences between the dynamic and kinematic response of the dummy compared to that of the human. It is therefore recommended to include a more realistic mass distribution in the advanced dummy compared to that of existing frontal dummies. The use of 50th percentile male data seems appropriate at this time but in future, the use of differently sized dummies could become important (e.g. using the 5th female and 95th male data).

4.3 Overall Biofidelity and Injury Assessment

Specific data on biofidelity of parts of the dummy are discussed in chapter 5. Below only general statements are given with respect to biofidelity of the dummy and its injury assessment capabilities.

An advanced frontal dummy should be positioned in the automotive seating posture and should interact correctly with the vehicle interior and the restraint system. This implies that parts of the dummy contacting the vehicle interior and/or the restraint system should deform in a representative manner as can be expected from real human beings, even if that body part is not directly at risk of injury. Deformation on the vehicle interior inflicted by the dummy, should be similar to that found in tests using PMHSs/volunteers in vehicle impacts and to that observed in real accidents.

The overall level of biofidelity of a crash dummy can be divided into kinematic biofidelity, which is required up to impact, and dynamic biofidelity, which is required at impact. Generally speaking, dynamic biofidelity is required for all parts for which injury assessment is foreseen and/or for those parts liable to contact the vehicle interior or restraint, i.e. the head, face, neck, thorax (rib cage), shoulders, abdomen, femurs and lower legs. For most other parts kinematic biofidelity is considered sufficient.

It is strongly recommended that an advanced frontal dummy is biofidelic not only at standard impact velocities (currently in the order of 50 kph) but also at intermediate and low velocities (e.g. 30 kph or less). Injury prevention at high velocities does not necessarily imply that the injuries occurring at low velocity are prevented. This is illustrated in Figure 1. In this Figure, a typical distribution of injuries with impact velocity is shown. Optimizing vehicles at 50 kph for injuries of AIS3+ implies that the injuries in the hatched area are effectively prevented. The largest number of injuries per accident, however, occur at lower velocities but are usually less severe. Optimizing vehicles also at lower velocities could hence be very effective in the overall prevention of injuries. In fact, some car manufacturers already assess the performance of their cars at several impact velocities [31].

The EEVC therefore recommends the use of biofidelity requirements established at -so called- standard impact velocities but also at intermediate velocities.

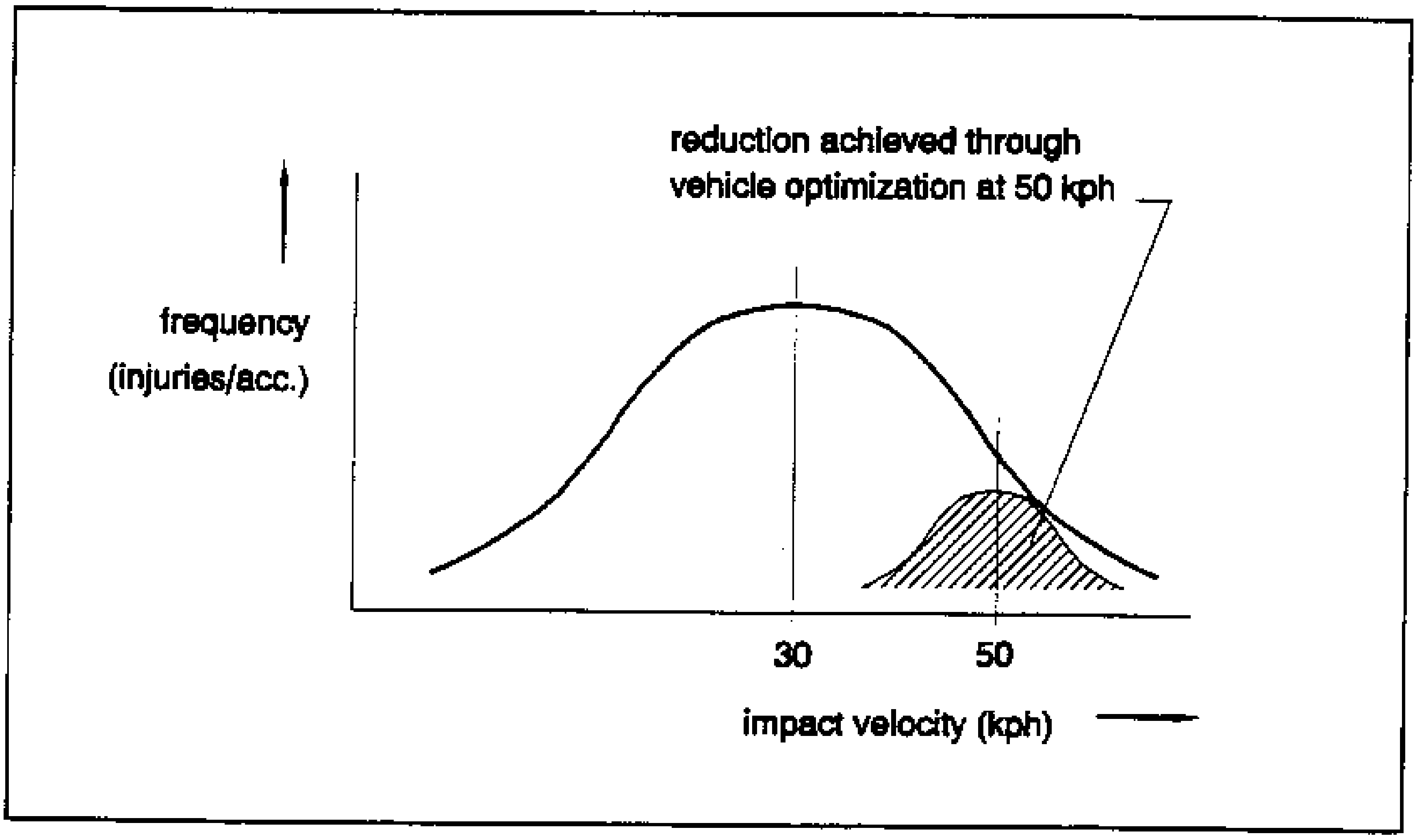

Figure 1: Distribution of injuries with impact velocity (for explanation, see text)

4.4 Repeatability and Reproducibility

When a dummy is use, it is important to have comparable responses from this dummy subjected to comparable impact conditions (repeatability) and to have comparable responses between dummies of the same design in comparable impact conditions (reproducibility). Without the actual design known, it is difficult to specify quantitative guidelines for repeatability and reproducibility. The repeatability of a dummy is generally considered good if its responses show a CV[ftn 4] of 5% or less and acceptable if the responses show a CV of 10% or less [32], [33].

To better control repeatability and reproducibility of a dummy, the EEVC recommends that the dummy allows to be tuned, that the dummy can be calibrated and that positioning of the dummy in the test environment is controlled. These aspects are discussed below.

[ftn 4] CV = coefficient of variation = standard deviation of a response divided by the mean value of that response. The CV meant here is associated with the dummy only; the total CV of a response also depends on variations of the test set-up and variations in the data acquisition; in formula: $(CV_{tot})^2 = (CV_{dummy})^2 + (CV_{set\text{-}up})^2 + (CV_{data\ acq.})^2$.

4.4.1 Tunability

Since a crash dummy can and will be subjected to extreme loading conditions, its response could alter with its use. The option to re-set the response of (a part of) the dummy to a standard response without the part being damaged previously, is called tunability. An example is the rib module of EUROSID-1, which stiffness can be set prior to the actual crash by means of choosing the correct spring [34]. Depending on the design, tunability is recommended for those parts liable to change their performance during the sequence of testing over its life time. Tuning therefore extends a dummy's life time.

4.4.2 Certification

The term certification[ftn 5] refers to a regular check of a (part of a) crash dummy to a specified set of performance requirements. Recommendations for certification of an advanced frontal dummy are given below.

- A visual check on damage should be part of the certification procedure.
- Dynamic certification tests are preferred over (quasi-)static tests.
- Certification tests are preferred that correspond to the velocities the body parts or the complete dummy is subjected to during a full-scale crash (note: this does not imply that the energy level corresponds to the full-scale crash condition).
- Certification should only be performed using calibrated instrumentation.
- All parts of the dummy expected to be of importance for injury assessment should be subjected to certification, even if that part is not associated with protection criteria.
- A standard seating procedure for full dummy certification tests is required.
- Standard climate conditions apply, however, the EEVC recommends that the temperature specifications for certification are widened to 18 - 26°C in stead of 20 - 26 °C as specified in "Part 572" [35].
- The transducer readings may be used directly (after the associated data reduction/-filtering) to evaluate a dummy's response in certification tests, provided these readings correspond unambiguously with the performance criteria in the full scale condition.
- Loading conditions and test response in certification tests should be relevant to the loading conditions and test response in the full scale environment.
- Certification tests should preferably check the response of a dummy part and its instrumentation over the full range of sensitivity needed in the full scale condition.
- The dummy should show full recovery within 10 to 15 minutes after a certification test.

4.4.3 Positioning

The positioning of the dummy is a subject for test procedures rather than an aspect for the dummy's design, apart from the ability to assume the required initial positions. The ability of a dummy to maintain these initial positions -the stability- is, however, a design aspect strongly influencing repeatability and reproducibility. The advanced frontal dummy should be capable of maintaining its initial position during the pre-impact vehicle motion.

[ftn 5] In some references, the term "calibration" is used; in this report the term certification is used.

Repeatable positioning of the dummy is important, especially if the dummy becomes a regulatory tool. An advanced frontal dummy should preferably be designed such that it is easy to position and that it is possible to check its initial position, e.g. by using built-in levelling instrumentation.

4.5 Durability

The recommended level of durability is expressed here as overload with respect to performance or tolerance levels. An advanced frontal dummy should be capable of withstanding loads causing the responses to exceed the anticipated performance or tolerance levels by at least 50 percent. Under these conditions, the dummy should not show damage or permanent deformation, except when frangible elements are applied. Note that it is not required to have a biofidelic response up to this level (see also section 4.3).

Storage of the dummy is expected for at least 3 to 5 years and should not influence the dummy responses. During its life time, the dummy should withstand at least 150 tests of equivalent severity as a standard full scale test. Full recovery of the dummy should occur within 2 hours after a standard full scale test.

4.6 Sensitivity

The direction of impact, for which the advanced dummy is specified, can be described as 0 ± 30 degrees (11 o'clock to 1 o'clock); see Figure 2. This implies that the main response of the dummy will be parallel to its mid-sagittal plane but deviations of ± 30 degrees are anticipated. In fact, for some body parts it is essential to have a correct response also outside the mid-sagittal plane. Multi-directional response of certain body areas is further discussed in chapter 5.

The primary use of the advanced dummy will be in full scale tests, e.g. frontal barrier tests, angled barrier tests, offset barrier tests and car to car crashes. Barriers can either be rigid or deformable. In the future, a more extensive use of the dummy is expected, e.g. in roll-over and rear-end collisions.

The impact velocity change (ΔV) may differ per type of impact and may reach up to 70 kph. The main ΔV range expected for the types of impact mentioned above is 48 to 60 kph but also impacts at intermediate velocities (around 30 kph) are expected.

In general, the advanced dummy should detect differences in restraint and vehicle design that pose a different risk of injury to the occupant. The dummy should, however, not be sensitive to small differences in restraint/vehicle design or small test set-up variations. In terms of test set-up, the (initial) seating posture and climate conditions are liable to show variations. Controlling variation of the seating posture concerns a test procedure rather than the dummy itself and a procedure for positioning the dummy in the vehicle should account for small variations. The climate conditions most liable to affect dummy responses, are temperature and air humidity. A normal temperature range in which the dummy will be used is 18 - 26 °C (in certification tests as

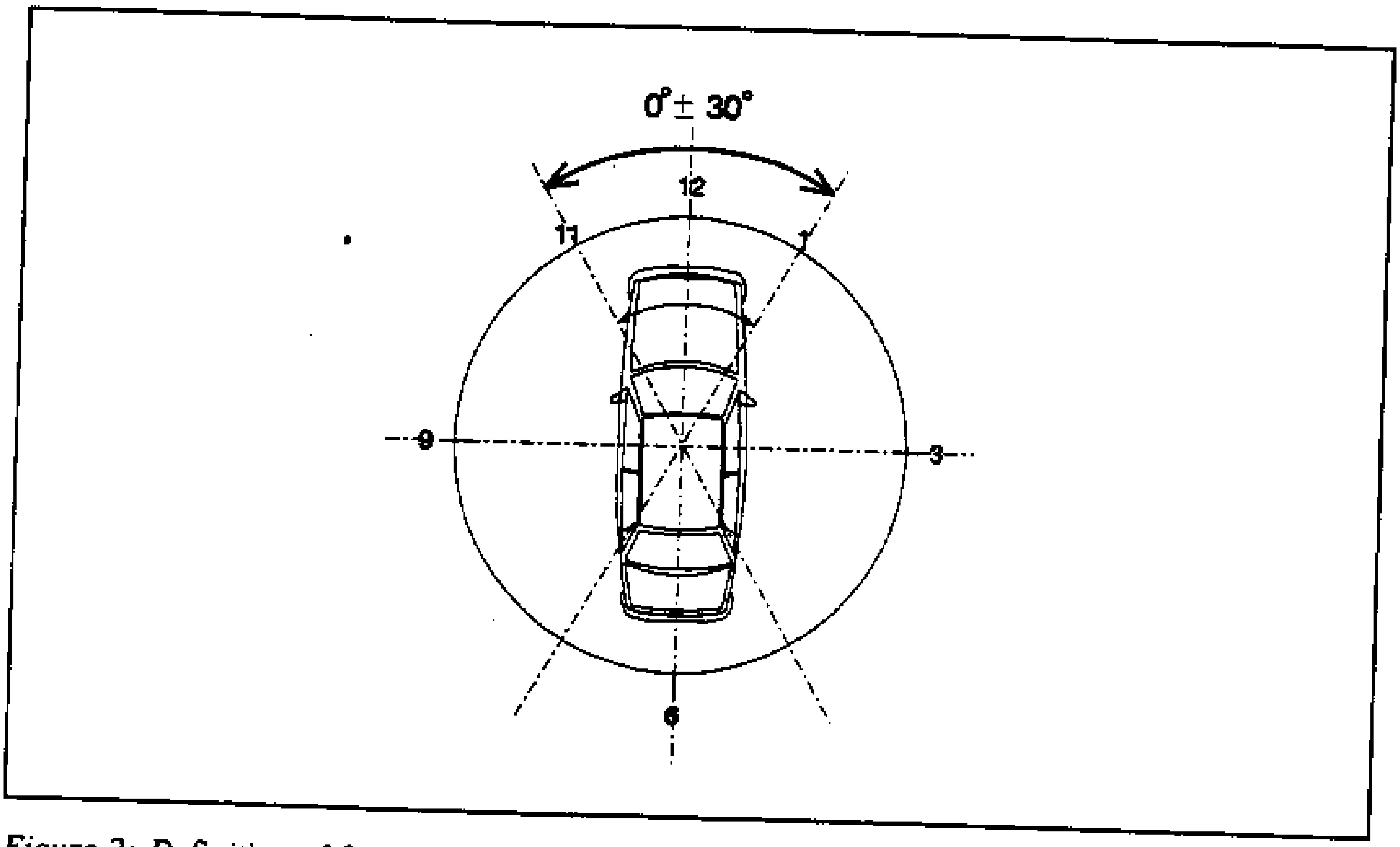

Figure 2: Definition of frontal impact direction

well as full scale tests). Air humidity may vary between 10 - 70 %, but is considered of lesser importance. Variations within these ranges should not affect dummy responses.

The assessment of injury risk may differ in terms of injury severity per body part, e.g. protection of the face may concern a lower injury risk (expressed in AIS) than protection of the head. The assessment of injury risk should be sensitive at the protection level of that particular body part thus responses of the dummy should clearly distinguish between acceptable and non-acceptable levels of loading. For most body parts, protection should be offered against severe and fatal injuries thus the responses of the dummy should clearly distinguish risks of AIS2/AIS3/AIS4 injuries. Some body parts may, however, require a different level of protection according to the AIS classification (e.g. face and leg require sensitivity of the dummy around AIS2 level).

4.7 Handling

The engineering phase of the development of a dummy highly determines its ease of use or handling. Assembly and disassembly of the dummy should be easy, especially for those parts needing certification and for those parts that can be instrumented. The use of special tools should be kept to a minimum, it is recommended to use metric tools and the specifications should be expressed in SI units.

The use of an in-dummy data acquisition system would greatly improve a dummy's handling, especially when preparing a test. Furthermore, such a system would allow to use the dummy partly independent of the data acquisition systems currently available at laboratories worldwide. Some in-dummy data acquisition systems already exist, however, their appropriateness for compliance testing has not yet been assessed. In the design of an advanced dummy, already provisions could be made to include an in-dummy data acquisition system in the future.

4.8 Discussion

The first set of recommendations for the design of an advanced frontal dummy concern overall dummy characteristics, i.e. characteristics addressing all body parts and/or the overall behaviour or use of the dummy. In summary, the most important recommendations are given below.

- The dummy should have a more realistic/humanlike mass distribution between soft tissues and skeletal parts.
- The dummy should exhibit a biofidelity at the required impact velocity as well as at a lower -intermediate- velocity.
- The dummy should have a tunable design, i.e. allow some adjustment of its response in certification to standard (prescribed) response.
- The dummy should be easy to calibrate, preferably in dynamic tests at velocities representative of the full scale test condition.
- The dummy has to be sufficiently durable to withstand at least 150 tests of equivalent severity to a standard full scale test.
- The dummy should be sufficiently sensitive to car design changes liable to affect the risk of injury (e.g. changes in restraint conditions), but at the same time should not be sensitive to small variations in test conditions between various laboratories.
- The dummy should be easy to assemble, disassemble and instrument.
- All specifications of the dummy should be given in SI units.

5 Characteristics per Body Part

5.1 Introduction

Per body part, recommendations are given in this chapter concerning biomechanical response, instrumentation/injury assessment and design of an advanced frontal dummy. The body parts are discussed from top to bottom (sections 5.1 through 5.11). A short summarizing discussion is enclosed at the end of this chapter (section 5.12).

5.2 Head

Two different types of loading condition give cause for head injuries: contact and non-contact impacts. In restrained conditions, the occupant is less likely to contact the A-pillar, instrument panel or (front/side) windscreen but still may contact the steering wheel or the restraint (e.g. airbag) in forward motion. Most contacts occur at the facial area but the frontal, parietal and temporal region of the neuro-cranium may be impacted in forward motion, the occipital area in rearward motion (contacting the headrest/backrest) and the vertex of the head may be at risk in roll-over conditions.

Most biomechanical studies address the overall head response by assessing 3D linear and rotational accelerations but their direct relationship to the risk of brain and skull injuries is still controversial. Measuring the 3D linear and rotational accelerations at the centre of gravity of the head seems to reflect the current state of knowledge in head impact biomechanics and dummy development and is therefore recommended for the advanced frontal impact dummy.

Head injury mechanisms, in spite of the vast amount of research carried out, are still not well understood. The current injury criterion HIC has strong limitations and only has certain validity for translational types of head motions. No well based alternatives however are available yet. One promising possibility seems to be the application of finite element models to simulate brain and skull response under impact conditions. A well validated model would allow the prediction of injuries using the measured 3D dummy head motions/accelerations as input. EEVC-WG12 recommends to develop this method further and to evaluate its potential as an alternative for the HIC in conjunction with a new frontal impact dummy.

5.3 Face

In 1992, an additional task was included for EEVC-WG12 by the EEVC Steering Committee. This additional task concerns the study, assessment and evaluation of facial injuries in frontal impact condition, especially related to airbag contact but also in other contacts [36]. So far, the EEVC-WG12 has reviewed injury data and the developments of devices used for this purpose and a discussion document was set up [37]. Main conclusions from the discussions on facial injury assessment are listed below.

- The EEVC recommends that the dummy face has a smooth surface. Representation of the nose and other 'protrusions' are not desirable for repeatability and reproducibility reasons.
- The dummy face should be deformable and its force-deflection characteristics should be uniform over the whole facial area. The force-deflection biofidelity should be based on non-fracture biomechanical tests and is required up to fracture level. Biofidelity beyond fracture is of lesser importance, however, deformation beyond fracture is desirable and the EEVC proposes to base the response of the face beyond fracture on linear extrapolation of the facial response up to fracture. The biofidelity requirements for the face should not be based on tests using rigid impactors only; this could lead to an incorrect facial response in non-rigid contacts [38].
- The EEVC recommends to use peak force and force distribution as parameters to establish a facial fracture injury criterion. The number of data channels for the face should be restricted to a maximum of 10. The recommended number of data channels is 5 to 6.
- The tolerance for facial fracture should be based on the characteristics of the weakest important bones of the face, the zygoma.
- The EEVC recommends that it is desirable that the dummy face is designed such that it can also be used in subsystem tests. If this proves to be impractical, consistency between the dummy head and face and a separate test tool for subsystem testing has to be established.
- On the basis of current data, the EEVC cannot recommend whether or not assessment of non-fracture facial injuries is desirable. This subject needs further research.

5.4 Neck

While the neck transfers load from the upper part of the body to the head (and vice versa), it also strongly controls the motion of the head. In frontal impact conditions the head-neck motions are often 3-dimensional because of asymmetry of restraint systems and possible contact of the head with the vehicle interior. For the neck this implies that a correct 3-dimensional behaviour is required.

First priority is a correct response in frontal impact direction. The NHTSA AATD neck biofidelity requirements are primarily based on volunteer tests conducted by the Naval Biodynamics Laboratory (NBDL) in New Orleans and additional cadaver tests conducted by the University of Heidelberg. This indeed reflects the most reliable, extensive and complete data available to-day. Recently a new analysis of the NBDL data has been carried out [39], resulting in an update and improvement of the performance requirements. EEVC-WG12 recommends to use the results of this new analysis for the evaluation of neck biofidelity of an advanced frontal dummy.

For lateral and oblique (i.e. 45 degrees forward) impact direction the most reliable and complete neck biofidelity data have been derived from NBDL data as well. These requirements have been included in the NHTSA AATD program and consequently should be applied to the neck design. For torsion (or twist) motion of the head it is important to note that different definitions have been used in literature for the head torsion (twist) angle and due to this incorrect interpretation of the NBDL data might be the result. So the definition of head rotation angle should be consistent with the definition used in the original analysis of the NBDL data [40].

Furthermore it is also desirable to have correct rearward neck biofidelity in order to have a proper neck behaviour in the rebound phase and consequently a proper interaction of the head with a head-restraint system, provided repeatability and reproducibility of the dummy are at an acceptable level. Suitable data to derive biofidelity requirements for this impact direction, however, are still very scarce and moreover only based on low severity impacts.

Neck injury mechanisms are still not well understood particularly since a number of different injury mechanisms can be observed and since small changes in initial conditions might result in quite different mechanisms. Moreover a high proportion of the injuries are low severity injuries (AIS-1) with usually no visible anatomical damage but with often long lasting effects. Resulting loads (forces and torques in 3 directions) in the neck at the head-neck junction (occipital condyles, OC) and the neck-thorax junction (C7-T1) currently constitute the only parameters which can provide some indication of neck injury risk.

5.5 Shoulders

The human shoulder interacts directly with the shoulder belt, hence its design is important in frontal impact assessment of seat belt restrained occupants. Injury/accident data do not give cause for injury assessment at this body part but correct shoulder-belt interaction (including clothes) is considered important for thorax injury assessment. The complex, 3-dimensional, mechanical behaviour of the shoulder should sufficiently be represented by the dummy's shoulder to load the dummy's thorax in a similar way the occupant's thorax would be loaded. This requires a generally correct stiffness and kinematics of the belt-shoulder interaction (particularly in the anterior-posterior and superior-inferior directions). Furthermore, friction between the belt, shoulder and the dummy's clothes is important in order to have a correct positioning of the belt.

5.6 Upper Extremities

The upper extremities are not of particular concern in terms of injuries and interaction with belt restraints is limited. Interaction with the steering wheel is, however, obvious. The advanced dummy should preferably have hands that are able to "grab" the steering wheel, articulating wrists and elbows and a lower and upper arms having a generally correct shape and anthropometric geometry and inertia. The EEVC is aware of risk of arm injuries induced by airbags, such as seen in the US, but has no further recommendations at this stage. Compromises to the design of the arms could be made if the repeatability of the dummy requires so: in general, the arms of crash dummies are known to behave rather unrepeatable in impact conditions.

5.7 Thorax

The thorax is one of the body parts to be protected in frontal impact conditions, both in interactions with belt and bag restraints and with the vehicle interior. These interactions cause local as well as distributed loading of the thorax. A biofidelic shape and response is therefore required for the thorax, being able to assess the injury risk of local and distributed loadings on this body part. Elements that need to be represented for injury assessment are: the ribcage (including its contents), the flesh system and the thoracic spine. Especially in interaction with the (shoulder) belt, enhancements of the designs of existing frontal dummies are required for the thorax.

With respect to the review of biomechanical data in the AATD development programme [1], additional data on the thorax are obtained form a study performed by INRETS [41]. Biofidelity response requirements proposed in this study are recommended as additions to the ones established in the AATD development programme.

5.8 Lumbar Spine

The characteristics of the lumbar spine directly influence the thoracic, abdominal and pelvic response during impact. Lumbar spine injuries are, however, not frequently observed in frontal impact accidents and a biofidelic kinematic response is therefore considered sufficient for the lumbar spine. Different behaviour may be expected of volunteers and cadavers because of muscle activity, however, no data are available on this subject.

Another important aspect of the lumbar spine is its ability to "stabilize" the dummy in the seating posture during pre-impact motion. Again, no data are readily available to quantify the lumbar spine's or dummy's stability.

5.9 Abdomen

The abdomen is the only body part containing organs that are at high risk of injury in crash conditions, without the natural protection of the skeleton. Particularly, liver and spleen injuries tend to be severe in an impact, predominantly caused by belt loading due to submarining. Other phenomena may, however, also cause abdominal compression/intrusion (e.g. steering wheel interaction) but some are related to the unrestrained condition. Nevertheless, detection of submarining is considered insufficient to assess abdominal injury risk. The advanced frontal dummy should therefore incorporate means of assessing abdominal injury risk, which is supposed to be predominantly related to compression and viscous response [42], rather than just assessing the risk of submarining. A biofidelic shape and response of the abdomen of the advanced frontal dummy is therefore required. A biofidelic response in terms of the load acting on the abdomen is considered insufficient since this would not require biofidelic compression of the abdomen and could thus lead to an incorrect kinematics of the dummy.

Compared to the review of biomechanical data performed within the AATD development programme, one additional source for biomechanical data is found [43]. Without further analysis, the data presented in this reference is, however, considered not suitable to define response requirements for the abdomen.

5.10 Pelvis

The pelvis of belt restrained occupants is not at high risk of severe injuries in frontal impacts. For unrestrained and bag only restrained occupants, acetabulum injuries are, however, frequently observed in the US [44]. Assessment of pelvic injuries for belt restrained occupants is hence not considered important. The pelvis should, however, provide a biofidelic kinematic response of the dummy, particularly in two loading conditions: 1) (lap) belt loading and 2) loading transferred from the legs to the pelvis (and vice-versa).

The first loading condition (belt) relates to the risk of submarining and requires a biofidelic shape of the pelvis bones (especially in the area of the anterior superior iliac spines (ASIS), the orientation of the pelvic bones and stiffness and friction characteristics of the flesh system surrounding the pelvic bones at the ASIS.

The second loading condition (load transferred from/to the legs through the pelvis to/from the lumbar spine) relates to the overall kinematics of the dummy and possibility of leg injuries. This loading requires a correct representation of the articulations at the pelvis, shape and orientation of the pelvic bones and probably the stiffness and friction characteristics of the flesh system of the buttocks. A detailed representation of the complex articulations, stabilized by muscles and ligaments, is probably not necessary, provided the degrees of freedom, ranges of motion and transfer of load are sufficiently represented. Furthermore, the orientation of the pelvis of the advanced dummy should be similarly sensitive to the profile and stiffness of the vehicle seat as that of the human being and not be fixed by dummy design or installation procedure.

An analysis of the pelvis anthropometry data used in the AATD development programme [1] has confirmed that the dimensions are appropriate also for European data [45].

5.11 Lower Extremities

Injuries to the lower extremities are usually not life-threatening but they are very frequent and they often give rise to long-term disability and high costs. Legs (femur and tibia) should allow to look at different mechanisms: compression and bending. Several interactions with the vehicle interior may be expected of which loading to the foot (pedal/firewall) and knee (bolster/instrument panel) are the most important ones. More generally, possible intrusion of the passenger compartment requires both sufficient anthropometric representation of the body parts and articulations, to have a biofidelic kinematic response of the dummy, as well as assessment of loads/displacements on these parts. The prevention of severe injuries (fractures) to the long bones of the legs requires assessment of loads (forces and moments) to the tibia and femur. The prevention of severe injuries to the articulations (ankles, knees) may further require assessment of displacements or loads at these parts.

5.12 Discussion

In summary, main recommendations per body part are given below.

- In addition to 3D linear acceleration transducers, transducers to measure the 3D rotational acceleration of the head.
- Further development of injury criteria for the head.
- Improved biofidelity and injury assessment capability for the face.
- Improved kinematic and dynamic response (biofidelity) of the neck.
- Improved interaction of the shoulders with belt restraint systems.
- Improved biofidelity of the thorax and enhanced sensitivity of the thorax with respect to different loading conditions caused by different restraint systems.
- Improved biomechanical basis for the lumbar spine.
- Improved biofidelity and injury assessment capability of the abdomen, in particular a compressible abdomen.
- Improved interaction of the pelvis with belt restraints and car seats.
- Improved biofidelity and injury assessment capability of the lower extremities.

6 General Discussion and Conclusions

6.1 Discussion

Injury biomechanics still seems to be at its childhood compared to many other technologies, nevertheless, much more is known now that it was some 20 years ago when the most widely used frontal crash dummy -Hybrid-III- was developed. The limitations of the Hybrid-III, discussed in this report, are brought forward by increased knowledge of human behaviour under impact conditions and by experience using crash dummies over the last two decades.

Already in the mid eighties, the NHTSA launched the Advanced Anthropomorphic Test Device (AATD) development programme. This programme has now resulted in the first prototype of a complete advanced frontal dummy that will be evaluated in the near future. Having learned from the experience in side impact, worldwide appreciation for the AATD development is sought, which in Europe resulted in a close cooperation between the NHTSA and the European Experimental Vehicles Committee (EEVC). The EEVC urges other organisations worldwide to do the same, as far as possible, but also to include the review of all advanced frontal dummies or parts hereof.

On the other hand, the EEVC urges the NHTSA to consider a wider application of the AATD, i.e. also taking into account more than just the US impact conditions. In this respect, the EEVC recommends to take notice of the following:

- Belt systems currently are, and for the next decades also tend to be, the predominant type of adult restraint in Europe. More and more cars are being equipped with airbags, but only in combination with belt systems. The question of how future "smart" restraints could affect injury assessment cannot be addressed yet.
- The optimization of (passenger) vehicles should not only focus on the standard impact velocities. Also assessment of vehicle/restraint performance at intermediate and even low velocities should be considered.
- Once its design concept has been established, stringent repeatability and reproducibility requirements are predominant factors in the acceptance of a crash dummy, not only as a regulatory tool but also as a research tool.

The EEVC recognizes that any crash dummy design is a compromise between numerous design and performance requirements. Implicitly, therefore, any design will be subject to critique. It is not the intent of the EEVC to express their critique as such, but to assist in the development and evaluation of any advanced frontal dummy design. This report includes additional recommendations to that already expressed by the NHTSA. Below, the most important recommendations are presented as conclusions.

6.2 Conclusions

The data used for the IPR analysis and the European data analyzed here are not directly comparable because of differences in the selection criteria applied to set up the databases. Nevertheless, quite a few similarities are observed between the different data sets but also some differences are apparent. Most important differences seem to be caused by different restraint systems applied in de US and Europe. A worldwide acceptable advanced frontal dummy will have to be able to assess differences in injury risk as a result of different restraint systems. Injury assessment is certainly required for the following body parts: head/face, thorax, abdomen and lower extremities, but also measurements at other body parts are recommended to fully understand the responses in frontal impact, such as measurement of neck, lumbar spine and pelvis responses. For all measurements taken, but particularly for the high priority body parts, a review of injury criteria is recommended once the level of biofidelity of these body parts is sufficient.

The circumstances under which the injuries occur in real accidents differ from the "usual" full scale test conditions in which the Hybrid-III has been used so far. In themselves, the test conditions are not subject of extensive study for EEVC-WG12 but certainly affect the development and design of an advanced frontal dummy. Most notable results from the accident analysis in the current study are that the impact velocity will likely be higher than 50 kph but also tests at intermediate velocities should be taken into account and that loads outside the sagittal plane are very likely to occur. The durability and sensitivity of an advanced frontal dummy hence need specific attention.

Many of the recommendations expressed in this report address the biofidelity and injury assessment capabilities of an advanced frontal dummy. Appropriate biofidelity and injury assessment by themselves are, however, insufficient to ensure that an advanced frontal dummy can successfully be applied to improve car occupant protection using regulatory test procedures. Repeatability and reproducibility are two essential dummy characteristics to ensure consistency of data generated using the dummy worldwide, not only in regulatory tests but also in research tests. Repeatability and reproducibility of a dummy can only be assessed once a dummy has been designed and manufactured and hence will certainly be subject for evaluation programmes of (prototype) dummy parts. A similar comment applies to the characteristics durability, sensitivity and handling.

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