



BSI Standards Publication

Road vehicles — Injury risk curves for the THOR dummy

National foreword

This Published Document is the UK implementation of [ISO/TR 19222:2021](#).

The UK participation in its preparation was entrusted to Technical Committee AUE/7, Automobile occupant restraint systems.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

© The British Standards Institution 2022
Published by BSI Standards Limited 2022

ISBN 978 0 580 96415 2

ICS 43.180

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 March 2022.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

TECHNICAL REPORT

PD ISO/TR 19222:2021

**ISO/TR
19222**

First edition
2021-12-17

Road vehicles — Injury risk curves for the THOR dummy

*Véhicules routiers — Courbe de risques de blessures pour
mannequin THOR*



Reference number
ISO/TR 19222:2021(E)

AVA Documents
Document Sharing Hub
© ISO 2021



COPYRIGHT PROTECTED DOCUMENT

© ISO 2021, Published in Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Ch. de Blandonnet 8 • CP 401
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
copyright@iso.org
www.iso.org

Contents

Page

Foreword	iv
Introduction	v
1 Scope	1
2 Normative references	1
3 Terms and definitions and abbreviated terms	1
3.1 Terms and definitions	1
3.2 Abbreviated terms	1
4 Methodology	2
5 Injury risk curves	3
5.1 Head	3
5.1.1 HIC	3
5.1.2 Rotational criterion	6
5.2 Neck	14
5.2.1 N_{ij} – Eppinger	14
5.2.2 N_{te} – Mertz	16
5.3 Thorax	18
5.3.1 Maximum resultant deflexion	18
5.3.2 PC-Score	21
5.3.3 TIC	24
5.4 Abdomen	30
5.4.1 Penetration	30
5.5 Knee-thigh-hip	32
5.5.1 Femur z-force	32
5.5.2 Acetabulum force	34
5.5.3 Femur force versus acetabulum force	36
Annex A (informative) HIC data	37
Annex B (informative) Brain	40
Annex C (informative) Neck	74
Annex D (informative) Thorax	77
Annex E (informative) Abdomen	79
Annex F (informative) Knee-thigh-hip	80
Annex G (informative) HIII-THOR neck transfer function	98
Annex H (informative) Repeatability and reproducibility	100
Annex I (informative) Thorax repeatability and reproducibility	101
Bibliography	103

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 36, *Safety aspects and impact testing*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The THOR-M 50 dummy is in its final development phase and can be used to evaluate the occupant protection in frontal impact. US-NCAP and Euro-NCAP are currently developing test procedures using this dummy to evaluate car performances. However, injury risk curves (IRCs) are proposed by these organizations without a large consensus. Rules were established to develop IRCs ([ISO/TS 18506](#)). These rules were applied to the available data to evaluate IRCs for THOR-M 50. In addition to the quality evaluation as recommended in [ISO/TS 18506](#), considerations on the repeatability and reproducibility of the criteria, as well as their performance with regard to field investigations will be proposed.

This page deliberately left blank

Road vehicles — Injury risk curves for the THOR dummy

1 Scope

This document provides injury risk curves to assess occupant protection in frontal impact using the 50th percentile THOR metric dummy (THOR-M 50).

Injury risk curves developed specifically for the THOR dummy are chosen preferably, however, when not available, the applicability of the PMHS injury risk curve is evaluated with regard to the dummy biofidelity.

Finally, when possible, a field evaluation is provided.

2 Normative references

There are no normative references in this document.

3 Terms and definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 Terms and definitions

3.1.1

THOR-M 50

50th percentile metric dummy as defined in Reference [61]

3.1.2

injury criterion

physical parameter which correlates well with the severity of a specific injury or injuries of a body region under consideration

3.1.3

injury risk curve

IRC

curve giving the probability, for a defined population and for a given input, to sustain a specified severity of injury

3.1.4

injury risk function

IRF

mathematical function that relates a value of an *injury criterion* (3.1.2) and possible additional factors (variables) to a risk of sustaining an injury of a certain level

3.2 Abbreviated terms

AIS abbreviate injury score

BrIC	brain injury criterion
CI	confidence interval
CIBIC	convolution of impulse response for brain injury criterion
HIC	head injury criterion
KTH	knee-thigh-hip
MAIS	maximum abbreviate injury score
NFR	number of fractured ribs
NHP	non-human primate
NSFR	number of separated fractured ribs
PC-Score	principal component analysis score
PDB	partnership for dummy and biomechanics
PMHS	post mortem human subject
RVCI	rotational velocity change index
TBI	traumatic brain injury
THUMS	Toyota human body model
TIC	thoracic injury criterion
UBrIC	updated brain injury criterion

4 Methodology

The following steps were performed for each criterion:

- existing injury risk curves were collected;
- reference data were collected and verified;
- [ISO/TS 18506](#) was applied;
- criteria quotation was calculated:
 - [ISO/TS 18506](#) rules: from 1 for full application to 0 for a different method leading to different results, except if a rationale is provided;
 - [ISO/TS 18506](#) quality index: relative size of the confidence interval for 5 %, 25 % and 50 % risks of injury. The relative size of the confidence interval is defined as the width of the 95 % confidence interval at a given injury risk, relative to the value of the stimulus at this same injury risk;
 - evaluation of the repeatability and reproducibility (R&R) of the THOR-M 50 for the considered criterion, when R&R data are available, this criterion is equal to $1 - (\text{standard deviation} / \text{mean})$:
 - R&R data in certification tests are provided in [Annex H](#);

- R&R data in sled tests are provided in [Annex I](#) for the thorax;
- THOR applicability: this criterion has the following values:
 - THOR specific criterion: from 1 for full application to 0 for a different method leading to different results, except if a rationale is provided;
 - human IRC: biofidelity score;
 - transfer function between THOR and human: coefficient of correlation;
 - unknown: when the biofidelity score or the correlation coefficient are unknown;
- field data evaluation.

NHTSA is issuing a document on Injury Risk Curves for the THOR dummy (Reference [7]). This document was developed independently. Therefore, the readers can make their own comparisons and conclusions.

5 Injury risk curves

5.1 Head

5.1.1 HIC

5.1.1.1 HIC 15 ms / skull fracture – Mertz

- Injury target: skull fracture
- Source: ISO/TR 7861, Reference [51]
- Channels: linear accelerations (a_x, a_y, a_z) measured at the head centre of gravity
- Filtration: CFC1000

$$\text{— Formula: } H_{15} = \max_{15} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \cdot dt \right]^{2.5} \right\}$$

where

H_{15} is the variable for the head injury criterion (HIC);

t_1 is the beginning of the time window;

t_2 is the end of the time window;

a is the resultant acceleration expressed in g ;

t is the time expressed in milliseconds;

d is the derivative function;

$\max_{15}$ is the maximum of the function calculated between t_1 and t_2 , with $(t_2 - t_1)$ not exceeding 15 ms.

$$\text{— } P_{\text{skull_fracture}} = \Phi(H_{15}; \mu = 1\,500; \sigma = 488)$$

where

$P_{\text{skull_fracture}}$ is the injury probability for a skull fracture;

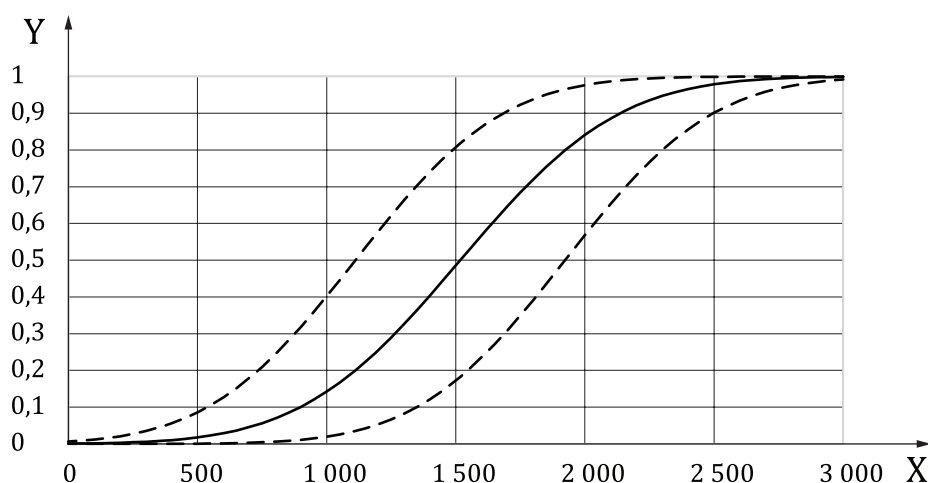
Φ is the cumulative distribution function of the normal distribution;

H_{15} Is the variable for the head injury criterion (HIC);

μ is the mean of the normal distribution;

σ is the standard deviation of the normal distribution.

- Data: 65 PMHS (References [20], [21], [82], [24], [25], [59]) provided in [Table A.1](#) of [Annex A](#)
- Statistics: modified median rank method (Reference [50])
- Version of dummy: injury risk curve developed directly from PMHS data and is applicable to dummies with a biofidelic response to head impact response.
- Comments:
 - This curve is a human injury risk curve.
 - THOR biofidelity: in the corridors of head drop tests (Table 14 and Figure 4 in Reference [61]).
 - Reasons for not following [ISO/TS 18506](#) rules: the modified median rank method has a better quality assessment than Eppinger's curve. Reference [51] points out that Hertz's log-normal curve predicts a 12 % risk of AIS ≥ 2 skull fracture at HIC=400, when no cases of skull fracture were observed at or below this value. This compares to 1 % risk predicted by Mertz's curve.
- Curves



Key

- X HIC
- Y risk of skull fracture
- IRF (skull fracture)
- - - - confidence interval

Figure 1 — Injury risk curves for Skull fracture as a function of HIC

- Quotation
 - [ISO/TS 18506](#) rules: 0,5

- Quality assessment
 - CI at 5 % = 1,12 (marginal)
 - CI at 25 % = 0,68 (fair)
 - CI at 50 % = 0,54 (fair)

NOTE The quality assessment at low levels of risk is relevant when assessing today's occupant restraint systems.

- R&R: 95 %
- THOR applicability: 1

5.1.1.2 HIC 15ms/skull fracture – Eppinger

- Injury target: skull fracture
- Source: Reference [12], Reference [23]
- Channels: linear accelerations (a_x, a_y, a_z) measured at the head centre of gravity
- Filtration: CFC1000

— Formula:
$$H_{15} = \max_{15} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \cdot dt \right]^{2,5} \right\}$$

where

H_{15} is the variable for the head injury criterion (HIC);

t_1 is the beginning of the time window;

t_2 is the end of the time window;

a is the resultant acceleration expressed in g ;

d is the derivative function;

t is the time expressed in milliseconds;

$\max_{15}$ is the maximum of the function calculated between t_1 and t_2 , with $(t_2 - t_1)$ not exceeding 15 ms.

— $P_{\text{skull_fracture}} = \Phi(\ln(H_{15}); \mu = 6,96; \sigma = 0,847)$

where

$P_{\text{skull_fracture}}$ is the injury probability for a skull fracture;

Φ is the cumulative distribution function of the normal distribution;

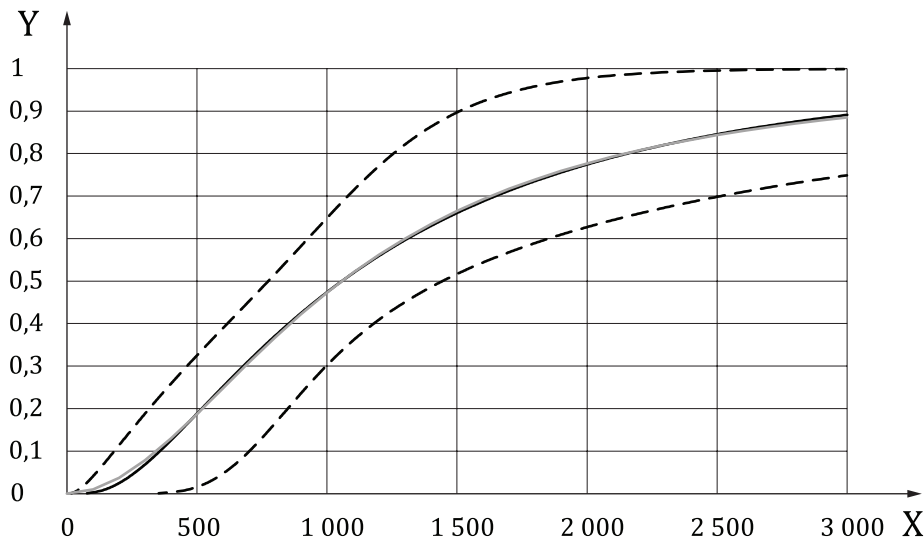
H_{15} is the variable for the head injury criterion (HIC);

μ is the mean of the normal distribution;

σ is the standard deviation of the normal distribution.

- Data: 54 PMHS (References [20], [21], [82], [24] and [25]) provided in Table A.2 of Annex A
- Statistics: maximum likelihood of log-normal

- Version of dummy: injury risk curve developed directly from PMHS data and is applicable to dummies with a biofidelic response to head impact response.
- Comments:
 - Human injury risk curve
 - THOR biofidelity: in the corridors of head drop tests (Table 14 and Figure 4 in Reference [61])
 - Risk curve close to the survival (log-normal) curve used in [ISO/TS 18506](#)
- Curves



- Key**
- X HIC
 - Y risk of skull fracture
 - IRF (skull fracture)
 - - - CI (skull fracture)
 - IRF (maximum likelihood of log-normal)

Figure 2 — Injury risk curves for Skull fracture as a function of HIC

- Quotation
 - [ISO/TS 18506](#) rules: 1
- Quality assessment
 - CI at 5 % = 1,88 (unacceptable)
 - CI at 25 % = 0,89 (fair)
 - CI at 50 % = 0,63 (fair)
- R&R: 95 %
- THOR applicability: 1

5.1.2 Rotational criterion

Numerous brain injury metrics have been proposed to predict diffuse-type traumatic brain injuries (TBIs) with the use of rotational response of head kinematics. Diffuse-type TBIs are hypothesized

to be caused by shear deformation of the brain tissue due to a rapid rotational motion of the head (Reference [26]). According to the hypothesis, the following five kinematics-based brain injury metrics derived from rotational head kinematic variables, BrIC (Reference [81]), CIBIC (Reference [80]), DAMAGE (Reference [18]), RVCi (Reference [91]), UBrIC (Reference [16]), were selected based on correlations with brain tissue strain response, as detailed in B.1.5.

As measurement channels for calculation of the kinematic-based brain injury metrics, angular velocities are obtained with gyro sensors fixed at the head centre of gravity of THOR. Angular velocities are filtered to channel frequency class (CFC) 60, and angular accelerations are obtained by differentiating the filtered angular velocity data.

Using survival analysis with Weibull distribution, injury risk curves (IRCs) for AIS 2 and AIS 4 traumatic brain injuries (TBIs), as given in Figure 3 to Figure 7, are formulated as the following function of the five kinematics-based brain injury metrics, DAMAGE, UBrIC, CIBIC, BrIC and RVCi, respectively.

$$P = 1 - e^{\left(-e^{\left(\frac{1}{b} \times \ln(dy+c) - \frac{a}{b} \right)} \right)}$$

Where a and b are coefficients corresponding to the shape ($1/b$) and scale (e^a) parameters in the Weibull distribution and y is the kinematics-based brain injury metric. The coefficients and quality indexes are provided in Table 1. P is the injury probability.

All IRCs given in this document for the THOR 50th percentile male were newly developed and are detailed in Annex B. Using survival analysis with Weibull distribution, original IRCs for AIS 2+ and AIS 4+ TBIs were developed based on the 95th percentile peak maximum principle strain of brain deformation (MPS95) in the finite element (FE) reconstruction simulations of human and Non-Human Primate (NHP) experiment data. The IRCs based on MPS95 were transferred to IRCs based on the kinematics-based brain injury metrics according to linear correlations between MPS95 and the kinematics-based brain injury metrics.

Table 1 — Coefficients and quality of the injury risk curves

Injury	Metrics	Scale (e^a)	Shape ($1/b$)	Intercept (c)	Slope (d)	5 % Risk (QI)	25 % Risk (QI)	50 % Risk (QI)
AIS2	DAMAGE	0,459	3,875	0,017	0,957	0,205 (0,41)	0,330 (0,25)	0,418 (0,25)
	UBrIC			-0,014	1,054	0,215 (0,36)	0,329 (0,22)	0,409 (0,23)
	CIBIC			0,016	0,505	0,390 (0,41)	0,627 (0,25)	0,794 (0,25)
	BrIC ^a			-0,103	0,600	0,527 (0,26)	0,726 (0,18)	0,867 (0,19)
	RVCi			0,012	0,012	16,75 (0,40)	26,70 (0,24)	33,76 (0,24)
AIS4	DAMAGE	0,646	6,051	0,017	0,957	0,395 (0,45)	0,531 (0,27)	0,617 (0,23)
	UBrIC			-0,014	1,054	0,388 (0,42)	0,512 (0,25)	0,590 (0,22)
	CIBIC			0,016	0,505	0,751 (0,45)	1,009 (0,27)	1,172 (0,23)
	BrIC ^a			-0,103	0,600	0,830 (0,35)	1,048 (0,22)	1,185 (0,19)

QI: Quality index and its categories based on (Reference [64]), the quality of injury risk functions can be categorized into 'good' (0,0 – 0,5); 'fair' (0,5 – 1,0); 'marginal' (1,0 – 1,5); and 'unacceptable' (> 1,5).

^a BrIC: caution should be used with the IRCs for BrIC presented here from the original injury risk curves provided in Reference [81].

Injury	Metrics	Scale (e^a)	Shape (1/b)	Intercept (c)	Slope (d)	5 % Risk (QI)	25 % Risk (QI)	50 % Risk (QI)
	RVCI			0,012	0,012	31,93 (0,45)	42,79 (0,27)	49,64 (0,23)

QI: Quality index and its categories based on (Reference [64]), the quality of injury risk functions can be categorized into 'good' (0,0 – 0,5); 'fair' (0,5 – 1,0); 'marginal' (1,0 – 1,5); and 'unacceptable' (> 1,5).

^a BrIC: caution should be used with the IRCs for BrIC presented here from the original injury risk curves provided in Reference [81].

5.1.2.1 DAMAGE

$$\begin{aligned} & \begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{bmatrix} \begin{Bmatrix} \ddot{\delta}_x \\ \ddot{\delta}_y \\ \ddot{\delta}_z \end{Bmatrix} + \begin{bmatrix} c_{xx} + c_{xy} + c_{xz} & -c_{xy} & -c_{xz} \\ -c_{xy} & c_{xy} + c_{yy} + c_{yz} & -c_{yz} \\ -c_{xz} & -c_{yz} & c_{xz} + c_{yz} + c_{zz} \end{bmatrix} \begin{Bmatrix} \dot{\delta}_x \\ \dot{\delta}_y \\ \dot{\delta}_z \end{Bmatrix} \\ & + \begin{bmatrix} k_{xx} + k_{xy} + k_{xz} & -k_{xy} & -k_{xz} \\ -k_{xy} & k_{xy} + k_{yy} + k_{yz} & -k_{yz} \\ -k_{xz} & -k_{yz} & k_{xz} + k_{yz} + k_{zz} \end{bmatrix} \begin{Bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{Bmatrix} = \begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{bmatrix} \begin{Bmatrix} \ddot{u}_x \\ \ddot{u}_y \\ \ddot{u}_z \end{Bmatrix} \end{aligned}$$

— Formula: $B_{\text{DAMAGE}} = \beta \times t_{\text{max}} \{ |\bar{\delta}(t)| \}$

where

$$\bar{\delta}(t) = [\delta_x(t) \quad \delta_y(t) \quad \delta_z(t)]^T$$

β is the scale factor;

m is the mass expressed in kg;

c_{ij} is the damping expressed in Ns/m;

k_{ij} is the stiffness expressed in N/m;

$\ddot{\delta}$, $\dot{\delta}$, δ are the acceleration, velocity and displacement respectively;

$\ddot{u}$ is the applied angular acceleration;

and the following variables have the following values:

$$m_x = 1; \quad m_y = 1; \quad m_z = 1;$$

$$k_{xx} = 32\,142; \quad k_{yy} = 23\,493; \quad k_{zz} = 16\,935;$$

$$k_{xy} = 0; \quad k_{yz} = 0; \quad k_{xz} = 1\,636,3;$$

$$\lambda = 5,914\,8; \quad \beta = 2,990\,31;$$

$$[c] = \lambda \times [k]$$

— Curves

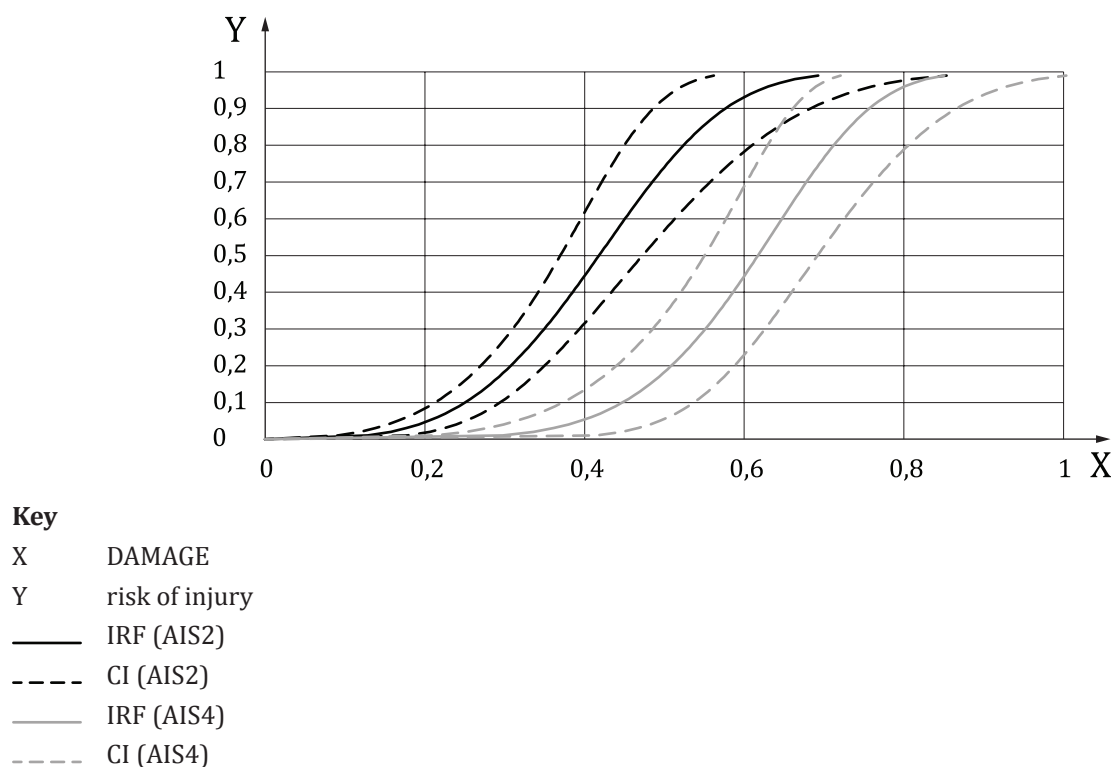


Figure 3 — Injury risk curves for AIS 2 and AIS 4 as a function of DAMAGE

— Quotation

- [ISO/TS 18506](#) rules: 1
- R&R: 97 % (mean of head angular rates in flexion, extension, lateral flexion and torsion neck tests)
- THOR applicability: unknown

5.1.2.2 UBrIC

— Formula:
$$B_{\text{UBrIC}} = \left\{ \sum_i \left[\omega_i^* + \left(\alpha_i^* - \omega_i^* \right) e^{-\frac{\alpha_i^*}{\omega_i^*}} \right]^2 \right\}^{\frac{1}{2}}$$

where

B_{UBrIC} is the variable for the brain injury criterion UBrIC;

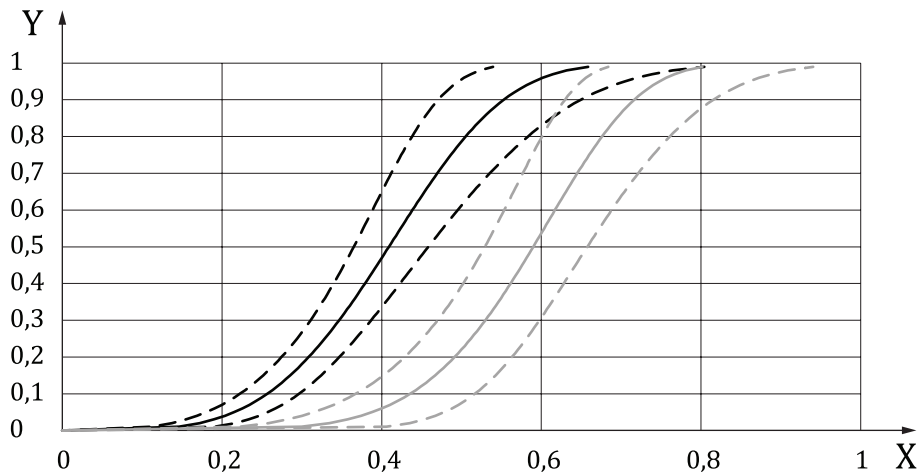
ω_i^* and α_i^* ($i = x, y, z$) are directionally dependent maximum magnitudes of the head angular velocity and angular acceleration which are each normalized by a critical value (cr);
 $\omega_i^* = \omega_i / \omega_{i\text{cr}}$ and $\alpha_i^* = \alpha_i / \alpha_{i\text{cr}}$. ω_i^* are expressed in rad/s and α_i^* are expressed in rad/s²:

$$\omega_{\text{xcr}} = 211; \alpha_{\text{xcr}} = 20,0 \times 10^3 ;$$

$$\omega_{\text{ycr}} = 171; \alpha_{\text{ycr}} = 10,3 \times 10^3 ;$$

$$\omega_{zcr} = 115; \alpha_{zcr} = 7,76 \times 10^3 .$$

— Curves



Key

X	UBrIC
Y	risk of injury
—	IRF (AIS2)
- - - -	CI (AIS2)
—	IRF (AIS4)
- - - -	CI (AIS4)

Figure 4 — Injury risk curves for AIS 2 and AIS 4 as a function of UBrIC

— Quotation

- [ISO/TS 18506](#) rules: 1
- R&R: 97 % (mean of head angular rates in flexion, extension, lateral flexion and torsion neck tests)
- THOR applicability: unknown

5.1.2.3 CIBIC

— Formula:
$$B_{CIBIC} = \max \left\{ \sqrt{\sum_{i=1}^3 \left\{ \beta_i \int_0^t x_i(t-\tau) \alpha_i(\tau) d\tau \right\}^2} \right\}$$

where

B_{CIBIC} is the variable for the brain injury criterion CIBIC;

$i=1, 2, 3$ are x, y and z axes;

α_i is an angular acceleration;

d is the derivative function;

$$x_i(t) = E_{1i} e^{-A_{1i}t} - e^{-A_{2i}t} \{E_{1i} \cos(B_i t) + E_{2i} \sin(B_i t)\}$$

$$A_{1i} = -s_i, s_i: \text{real root of } s_i^3 + \frac{k_{2i}}{c_i}s_i^2 + \frac{k_{1i} + k_{2i}}{m}s_i + \frac{k_{1i}k_{2i}}{c_im} = 0;$$

$$A_{2i} = \frac{\frac{k_{2i}}{c_i} - A_{1i}}{2};$$

$$B_i = \frac{1}{2} \sqrt{\frac{4(k_{1i} + k_{2i})}{m} - 2A_{1i} \frac{k_{2i}}{c_i} + 3A_{1i}^2 - \frac{k_{2i}^2}{c_i^2}};$$

$$E_{1i} = \frac{A_{1i} - \frac{k_{2i}}{c_i}}{\left(2A_{1i} \frac{k_{2i}}{c_i} - 3A_{1i}^2 - \frac{(k_{1i} + k_{2i})}{m} \right)};$$

$$E_{2i} = \frac{\frac{2A_{1i}^2 - \frac{k_{2i}}{c_i} + A_{1i}A_{2i} - A_{2i} \frac{k_{2i}}{c_i} + \frac{(k_{1i} + k_{2i})}{m}}{B_i}}{\left(2A_{1i} \frac{k_{2i}}{c_i} - 3A_{1i}^2 - \frac{(k_{1i} + k_{2i})}{m} \right)};$$

m is the mass, expressed in kg;

c_i is the damping expressed in Ns/m;

k_i is the stiffness expressed in N/m;

β_i is the scaling factor expressed in 1/m;

$$k_{1x} = 12760; \quad k_{1y} = 16390; \quad k_{1z} = 17040;$$

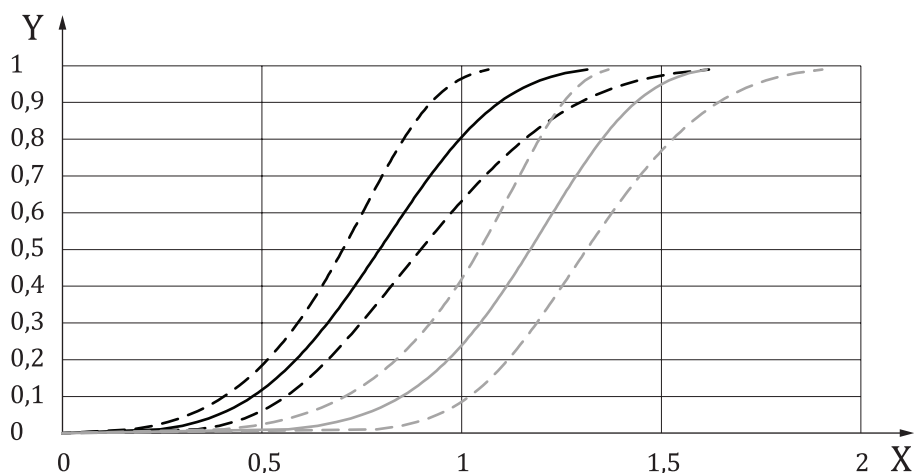
$$k_{2x} = 22670; \quad k_{2y} = 3163170; \quad k_{2z} = 4751890;$$

$$c_x = 129,1; \quad c_y = 120,4; \quad c_z = 74,4;$$

$$m = 1;$$

$$\beta_x = 0,00313, \quad \beta_y = 0,00395, \quad \beta_z = 0,00494.$$

— Curves



Key

X	CIBIC
Y	risk of injury
—	IRF (AIS2)
- - -	CI (AIS2)
—	IRF (AIS4)
- - -	CI (AIS4)

Figure 5 — Injury risk curves for AIS 2 and AIS 4 as a function of CIBIC

- Quotation
 - [ISO/TS 18506](#) rules: 1
 - R&R: 97 % (mean of head angular rates in flexion, extension, lateral flexion and torsion neck tests)
 - THOR applicability: unknown

5.1.2.4 BrIC

— Formula:
$$B_{BrIC} = \sqrt{\left(\frac{\omega_x}{\omega_{xcr}}\right)^2 + \left(\frac{\omega_y}{\omega_{ycr}}\right)^2 + \left(\frac{\omega_z}{\omega_{zcr}}\right)^2}$$

where

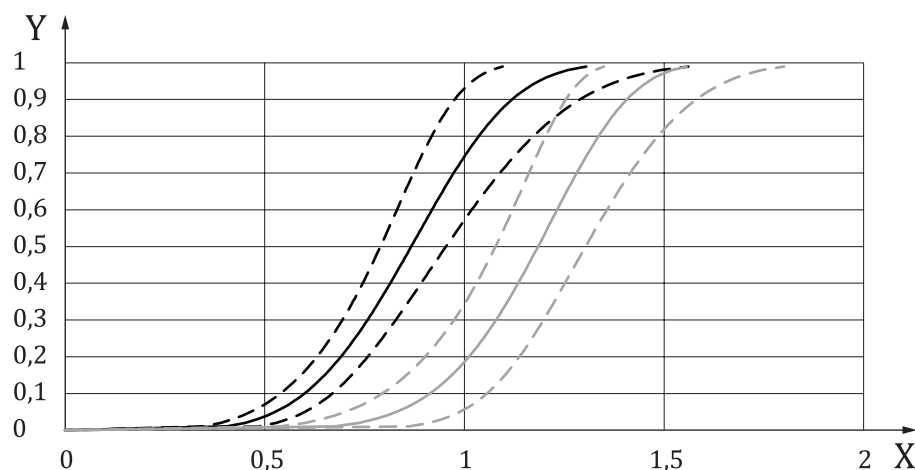
B_{BrIC} is the variable for the brain injury criterion BrIC;

ω_i ($i = x, y, z$) are directionally dependent maximum magnitudes of the head angular expressed in rad/s;

ω_{icr} ($i = x, y, z$) are critical values expressed in rad/s;

$\omega_{xcr} = 66,25$, $\omega_{ycr} = 56,45$, $\omega_{zcr} = 42,87$.

- Curves



Key

X	BrIC
Y	risk of injury
—	IRF (AIS2)
- - - -	CI (AIS2)
—	IRF (AIS4)
- - - -	CI (AIS4)

Figure 6 — Injury risk curves for AIS 2 and AIS 4 as a function of BrIC

— Quotation

- [ISO/TS 18506](#) rules: 1
- R&R: 97 % (mean of head angular rates in flexion, extension, lateral flexion and torsion neck tests)
- THOR applicability: unknown

5.1.2.5 RVCi

— Formula:
$$B_{RVCi} = \max(t_1, t_2) \sqrt{W_x \left(\int_{t_1}^{t_2} \alpha_x \cdot dt \right)^2 + W_y \left(\int_{t_1}^{t_2} \alpha_y \cdot dt \right)^2 + W_z \left(\int_{t_1}^{t_2} \alpha_z \cdot dt \right)^2}$$

where

B_{RVCi} is the variable for the brain injury criterion RVCi;

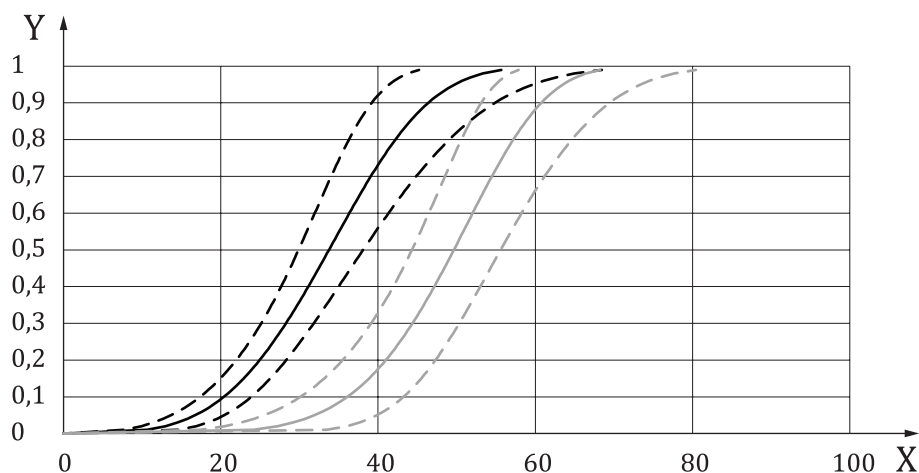
W_i are weighting factors about each orthogonal axis;

α_i ($i = x, y, z$) are directionally dependent maximum magnitudes of the head angular acceleration expressed in rad/s^2 ;

d is the derivative function;

$$W_x = 1,00, W_y = 1,00, W_z = 1,17 .$$

— Curves



Key

X	RVCi
Y	risk of injury
—	IRF (AIS2)
- - - -	CI (AIS2)
—	IRF (AIS4)
- - - -	CI (AIS4)

Figure 7 — Injury risk curves for AIS 2 and AIS 4 as a function of RVCi

- Quotation
 - [ISO/TS 18506](#) rules: 1
 - R&R: 97 % (mean of head angular rates in flexion, extension, lateral flexion and torsion neck tests)
 - THOR applicability: unknown

5.2 Neck

5.2.1 N_{ij} – Eppinger

- Injury target: AIS3+ neck injury
- Source: Reference [12]
- Channels: upper neck force F_z and moment M_y
- Filtration: forces CFC600 ; moments CFC600

— Formula:
$$N_{ij} = \frac{F_z}{F_{zc}} + \frac{M_y}{M_{yc}}$$

where

F_z is the upper neck force in the z direction expressed in N;

M_y is the upper neck moment in the y direction expressed in Nm;

F_{zc} (tension/compression) = 2 520/-3 640 N;

M_{yc} (flexion/extension) = 48/-72 Nm.

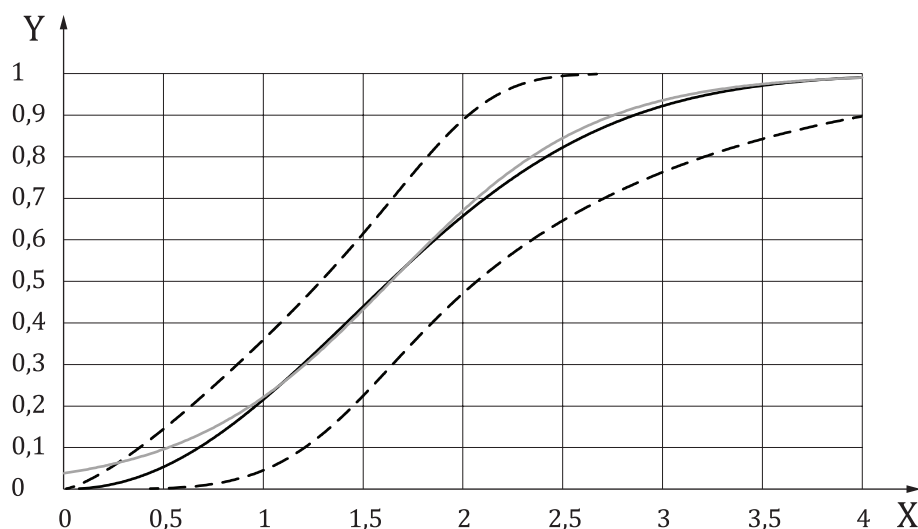
- NHTSA Eppinger curve: $P_{AIS \geq 3} = \frac{1}{1 + e^{3,227 - 1,969 N_{ij}}}$
- Survival with Weibull: $P_{AIS \geq 3} = 1 - \exp\left(-\left[\frac{N_{ij}}{1,936}\right]^{2,142}\right)$

where

$P_{AIS \geq 3}$ is the injury probability for an AIS3+ neck injury;

N_{ij} is the neck injury criterion.

- Data: 43 piglet tests and associated 3 years old airbag dummy (Reference [52]) provided in [Table C.1](#) of [Annex C](#)
- Statistics: logistic for Eppinger curve; survival with Weibull for ISO curve
- Comments:
 - Original curve for 3 years old airbag dummy transferred to HIII M50
 - The THOR intercepts were proposed in Reference [10] and the SAE THOR evaluation task group based on the human tolerance and the THOR biofidelity.
 - PMHS critical values from literature (References [4], [56], [57] and [65]): F_{zc} (tension/compression) = (2 100/-3 030) N; M_{yc} (flexion/extension) = (40/-60) Nm
 - Scale for age (References [31], [44], [56]): factor of 1,2
 - The biofidelity of the THOR was not accounted for and it is assumed that PMHS values are conservative when used for the THOR.
 - Paired sled tests were performed with HIII and THOR head neck complex. The sled acceleration was the same for the two dummies. The results are provided in [Annex G](#). Both in flexion and extension, the N_{ij} were much higher for the THOR compared to the HIII (0,68 versus 0,29 in flexion; 0,55 versus 0,27 in extension). A factor of about 2,2 on the THOR intercepts is needed to get the same risk with the THOR and the HIII in these simple and controlled configurations. However, this comment just intends to demonstrate that the proposed intercepts are not consistent with intercepts on HIII, not to propose alternative intercepts. In addition, for extension tests, THOR exhibited neck compression, while Hybrid III exhibited neck tension, therefore a simple scaling of the intercepts is not adequate.
 - Further investigations are needed, and it is not recommended to use these curves as provided.
- Curves



Key

X	N_{ij}
Y	risk of neck AIS3+
—	IRF (survival Weibull)
- - -	CI (survival Weibull)
—	IRF (Eppinger logistic)

Figure 8 — Injury risk curves for AIS 3+ as a function of N_{ij}

- Quotation
 - [ISO/TS 18506](#) rules: 0,7
- Quality assessment
 - CI at 5 % = 1,64 (unacceptable)
 - CI at 25 % = 0,73 (fair)
 - CI at 50 % = 0,48 (good)
- R&R: 96 % (mean of upper neck forces and moments in flexion, extension, lateral flexion and torsion neck calibration tests)
- THOR applicability: 0

5.2.2 N_{te} - Mertz

- Injury target: AIS3+ neck injury
- Source: Reference [53]
- Channels: Upper neck force F_z and moment M_y
- Filtration: Forces CFC600 ; Moments CFC600

— Formula:
$$N_{te} = \frac{F_t}{F_{tc}} + \frac{M_e}{M_{ec}}$$

where

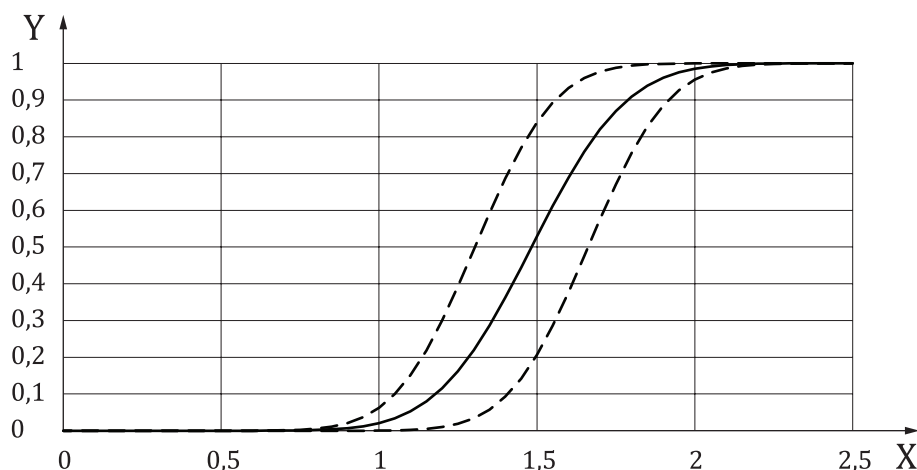
- F_z is the upper neck force in the z direction expressed in N;
- M_y is the upper neck moment in the y direction expressed in Nm;
- F_t is the portion of F_z when the neck is in tension (positive values);
- M_e is the portion of M_y when the neck is in extension (negative values);
- F_{tc} (tension) = 6 200 N;
- M_{ec} (extension) = -122 Nm.

— $P_{AIS \geq 3} = \varphi(N_{te}; \mu = 1,480; \sigma = 0,235)$

where

- $P_{AIS \geq 3}$ is the injury probability for an AIS3+ neck injury;
- Φ is the cumulative distribution function of the normal distribution;
- N_{te} is the neck injury criterion;
- μ is the mean of the normal distribution;
- σ is the standard deviation of the normal distribution.

- Data: 43 piglet tests and associated 3 years old airbag dummy (Reference [53]) provided in [Table C.2](#) of [Annex C](#)
- Statistics: Modified median rank method (Reference [50])
- Comments:
 - Original curve for 3 years old airbag dummy transferred to HIII M50
 - The THOR intercepts were proposed by Reference [10] and the SAE THOR evaluation task group based on the human tolerance and the THOR biofidelity.
 - PMHS Critical values from literature (References [4], [56], [57] and [65]): F_{zc} (tension/compression) = (2100/-3030) N; M_{yc} (flexion/extension) = (40/-60) Nm
 - Scale for age (References [31], [44], [56]): factor of 1,2
 - The biofidelity of the THOR was not accounted for and it is assumed that PMHS values are conservative when used for the THOR
 - Paired sled tests were performed with HIII and THOR head neck complex. The sled acceleration was the same for the two dummies. The results are provided in [Annex G](#). Both in flexion and extension, the N_{ij} were much higher for the THOR compared to the HIII (0,68 versus 0,29 in flexion; 0,55 versus 0,27 in extension). A factor of about 2,2 on the THOR intercepts is needed to get the same risk with the THOR and the HIII in these simple and controlled configurations.
 - Further investigations are needed, and it is not recommended to use these curves as provided.
- Curves



Key

X	N_{te}
Y	risk of neck AIS3+
—	IRF (Mertz-Weber)
- - - -	CI (Mertz-Weber)

Figure 9 — Injury risk curves for AIS 3+ as a function of N_{te}

- Quotation
 - [ISO/TS 18506](#) rules: 0
 - Quality assessment
 - CI at 5 % = 0,33 (good)
 - CI at 25 % = 0,27 (good)
 - CI at 50 % = 0,24 (good)
 - R&R: 95 % (mean of upper neck forces and moments in extension neck calibration tests)
 - THOR applicability: 0

5.3 Thorax

According to the AIS definition, several rib fractures NFS (Non-Further Specified) correspond to AIS2. The definition of an AIS3 in the thorax corresponds to 3 fractured ribs. Nevertheless, several studies have shown that this definition cannot be applied directly to the PMHS. On the one hand they are more fragile than living subjects of the same age, and on the other hand there is a detection bias. On living subjects, the detection is performed by X-ray, which only detects displaced fractures with a gap between the fractured edges. Non-displaced fractures cannot be detected and are therefore not counted. If a practitioner detects several rib fractures without being able to identify them with X-rays, he will therefore indicate NFS and rate AIS2. On a PMHS, the detection is usually performed by autopsy and all fractures can be detected, whether displaced or not. To take this bias into account, Reference [87] defined AIS3 as 6 fractured ribs, Reference [40] as 7 fractured ribs. More recently, Reference [85] recommended to count only displaced fractured ribs to assess the clinical risk. The following curves are defined for 3 and 7 fractured ribs for deflection, PC-score and TIC_NFR and for 3 separate fractured ribs for TIC_NSFR.

5.3.1 Maximum resultant deflexion

- Injury target: AIS3+ chest injury (3 fractured ribs)

- Source: Reference [66]
- Channels: 4 3D rib deflections ($D_{ulx}, D_{uly}, D_{ulz}, D_{urx}, D_{ury}, D_{urz}, D_{llx}, D_{lly}, D_{llz}, D_{lrx}, D_{lry}, D_{lrz}$)
- Filtration: CFC180
- Formula:

$$R_{\max} = \max(D_{ul\max}, D_{ur\max}, D_{ll\max}, D_{lr\max})$$

where

$$D_{ul\max} = \max\left(\sqrt{D_{ulx}^2 + D_{uly}^2 + D_{ulz}^2}\right);$$

$$D_{ur\max} = \max\left(\sqrt{D_{urx}^2 + D_{ury}^2 + D_{urz}^2}\right);$$

$$D_{ll\max} = \max\left(\sqrt{D_{llx}^2 + D_{lly}^2 + D_{llz}^2}\right);$$

$$D_{lr\max} = \max\left(\sqrt{D_{lrx}^2 + D_{lry}^2 + D_{lrz}^2}\right);$$

D_{ijk} is the deflection measured at the ij position in the k direction and expressed in mm:

$i = (u, l)$ for upper and lower positions;

$j = (l, r)$ for left and right positions;

$k = (x, y, z)$ for the direction.

$$P_{NFR \geq 3|\dot{A}, R_{\max}} = 1 - \exp\left(-\left[\frac{R_{\max}}{\exp(4,477\,75 - 0,017\,1\dot{A})}\right]^{3,356}\right)$$

$$P_{NFR \geq 7|\dot{A}, R_{\max}} = 1 - \exp\left(-\left[\frac{R_{\max}}{\exp(4,470\,1 - 0,007\,6\dot{A})}\right]^{2,547\,6}\right)$$

where

P is the injury probability;

$\dot{A}$ is the age;

$R_{\max}$ is the chest injury criterion.

- Data: 40 PMHS sled tests (28 belt only; 7 3-point belt+AB; 2 lap belt+AB; 3 inflatable belt) provided in [Table D.1](#) of [Annex D](#)
- Statistics: Survival (Weibull)
- Dummy version: THOR mod-kit 2013
- Comments:
 - No impactor tests
- Curves

Figure 10 — Injury risk curves for NFR3+ as a function of $R_{\max}$

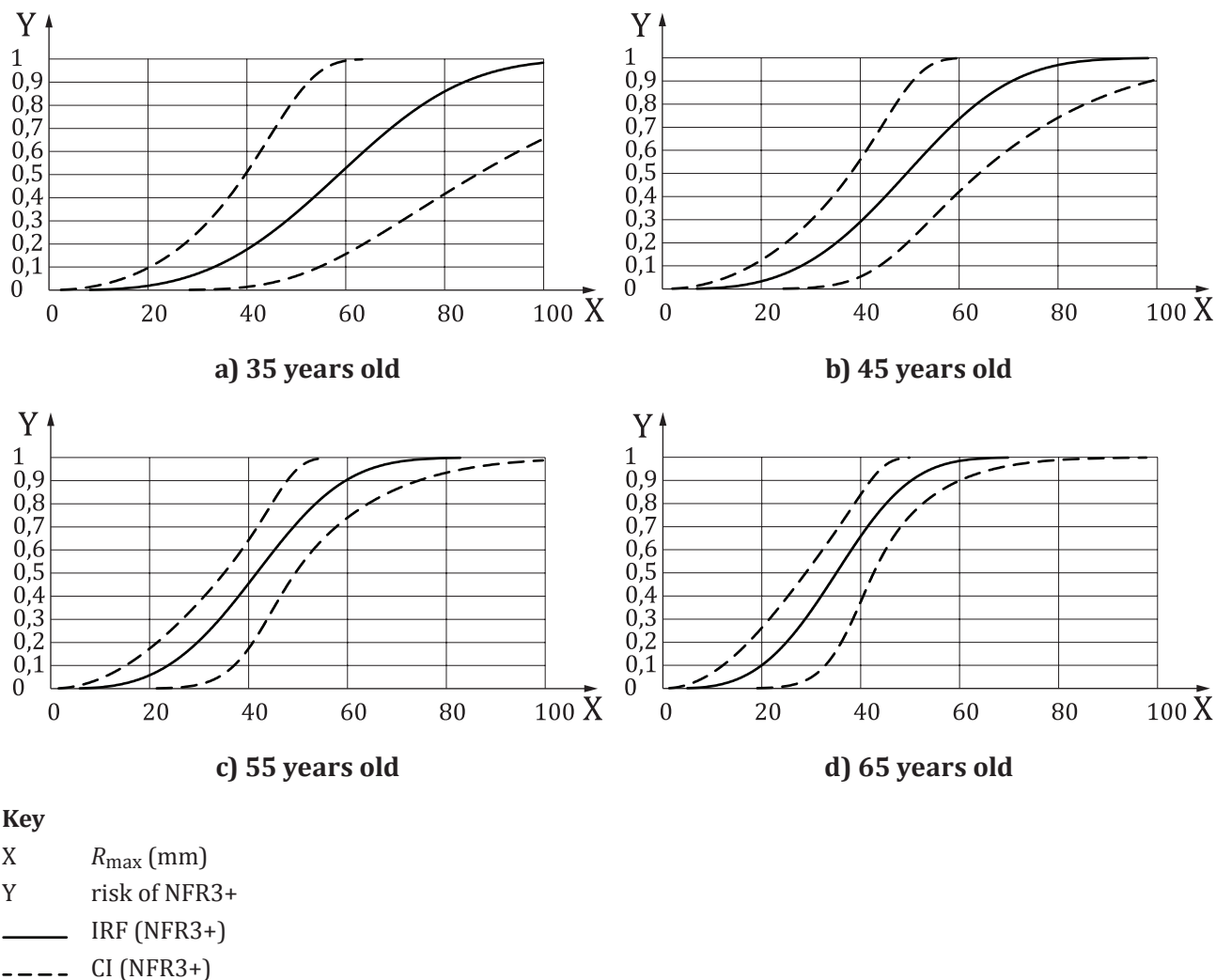
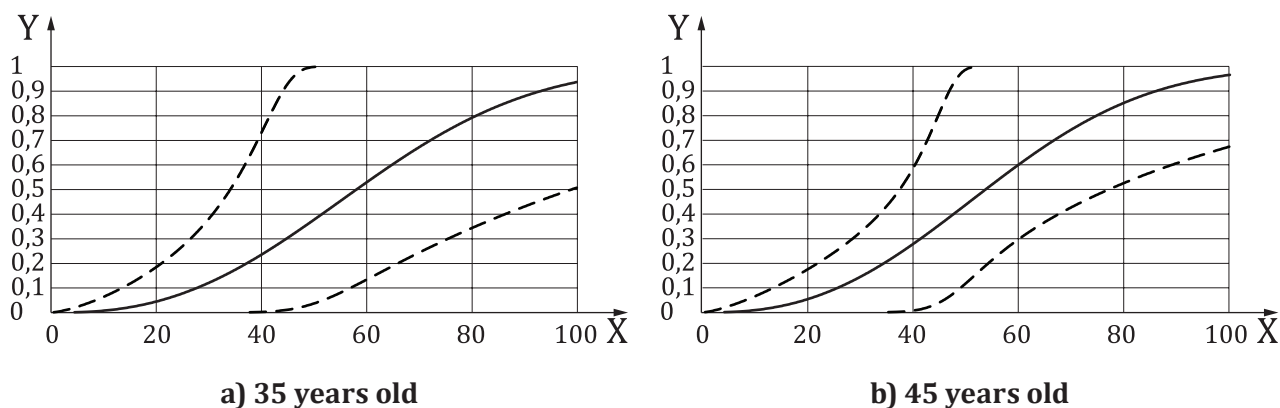
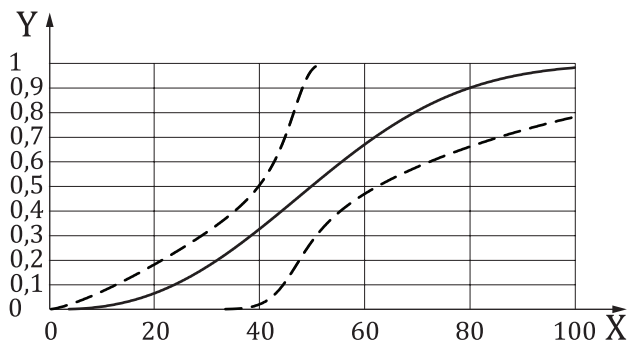
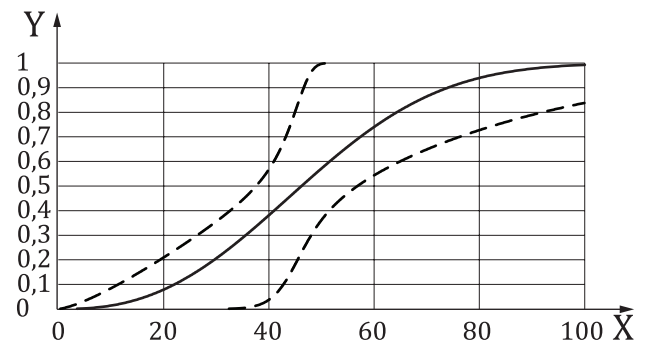


Figure 11 — Injury risk curves for NFR7+ as a function of $R_{\max}$





c) 55 years old



d) 65 years old

Key

- X $R_{\max}$ (mm)
- Y risk of NFR7+
- IRF (NFR7+)
- CI (NFR7+)

— Quotation

- [ISO/TS 18506](#) rules: 1
- Quality assessment ([Table 2](#))

Table 2 — Quality assessment of $R_{\max}$

Age	35 years old	45 years old	55 years old	years old
NFR3+				
5 % CI	1,24	1,18	1,21	1,34
25 % CI	0,83	0,64	0,57	0,66
50 % CI	0,80	0,53	0,35	0,39
NFR7+				
5 % CI	2,07	1,94	1,94	2,04
25 % CI	1,13	0,83	0,67	0,73
50 % CI	1,12	0,74	0,45	0,42
NFR3+ calculated with enlarged database of TIC				
5 % CI	1,75	1,85	2,02	2,24
25 % CI	0,90	0,83	0,87	1,01
50 % CI	0,80	0,59	0,48	0,53
Quotation: $0 \leq \text{good} \leq 0,5 < \text{fair} \leq 1,0 < \text{marginal} \leq 1,5 < \text{unacceptable}$.				

- R&R: 94 %
- THOR applicability: 1

5.3.2 PC-Score

- Injury target: AIS3+ chest injury (3 fractured ribs)
- Source: Reference [[66](#)]

- Channels: 4 3D rib deflections ($D_{ulx}, D_{uly}, D_{ulz}, D_{urx}, D_{ury}, D_{urz}, D_{llx}, D_{lly}, D_{llz}, D_{lrx}, D_{lry}, D_{lrz}$)
- Filtration: CFC180
- Formula: $S_{pca} = 0,486 \left(\frac{D_{uptot}}{17,439} \right) + 0,492 \left(\frac{D_{lowtot}}{14,735} \right) + 0,496 \left(\frac{D_{updif}}{9,672} \right) + 0,526 \left(\frac{D_{lowdif}}{12,384} \right)$

where

$$D_{uptot} = \max \left(\sqrt{D_{ulx}^2 + D_{uly}^2 + D_{ulz}^2} \right) + \max \left(\sqrt{D_{urx}^2 + D_{ury}^2 + D_{urz}^2} \right) ;$$

$$D_{updif} = \max \left(\left| \sqrt{D_{ulx}^2 + D_{uly}^2 + D_{ulz}^2} - \sqrt{D_{urx}^2 + D_{ury}^2 + D_{urz}^2} \right| \right) ;$$

$$D_{lowtot} = \max \left(\sqrt{D_{llx}^2 + D_{lly}^2 + D_{llz}^2} \right) + \max \left(\sqrt{D_{lrx}^2 + D_{lry}^2 + D_{lrz}^2} \right) ;$$

$$D_{lowdif} = \max \left(\left| \sqrt{D_{llx}^2 + D_{lly}^2 + D_{llz}^2} - \sqrt{D_{lrx}^2 + D_{lry}^2 + D_{lrz}^2} \right| \right) ;$$

D_{ijk} is the deflection measured at the ij position in the k direction and expressed in mm:

$i = (u, l)$ for upper and lower positions;

$j = (l, r)$ for left and right positions;

$k = (x, y, z)$ for the direction;

S_{pca} is the variable for chest injury criterion PC-Score.

$$\begin{aligned} \text{— } P_{NFR \geq 3|\dot{A}, S_{pca}} &= 1 - \exp \left(- \left[\frac{S_{pca}}{\exp(2,8677 - 0,0181\dot{A})} \right]^{3,3118} \right) \\ \text{— } P_{NFR \geq 7|\dot{A}, S_{pca}} &= 1 - \exp \left(- \left[\frac{S_{pca}}{\exp(2,5337 - 0,0079\dot{A})} \right]^{2,4708} \right) \end{aligned}$$

where

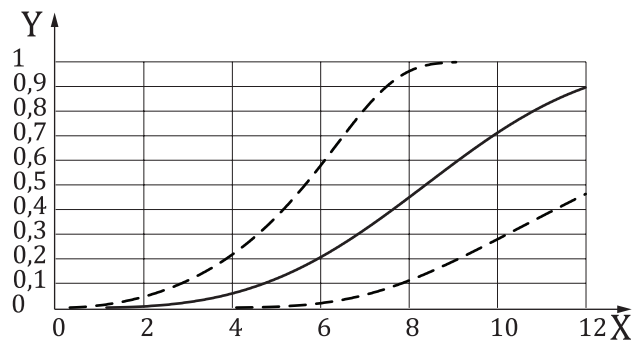
P is the injury probability;

$\dot{A}$ is the age;

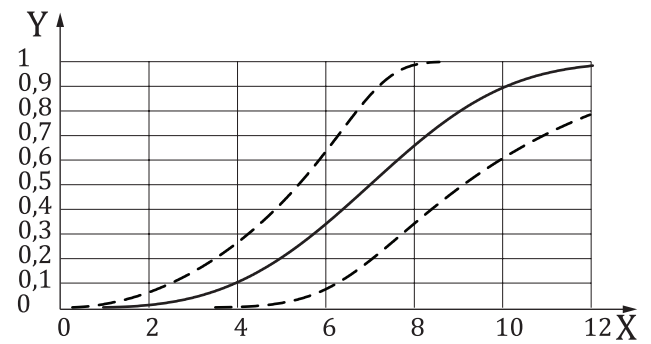
S_{pca} is the variable for the chest injury criterion PC-Score.

- Data: 40 PMHS sled tests (28 belt only; 7 3-point belt+AB; 2 lap belt+AB; 3 inflatable belt) provided in [Table D.1](#) of [Annex D](#)
- Statistics: PCA then survival (Weibull)
- Dummy version: THOR mod-kit 2013
- Comments:
 - No impactor tests
- Curves

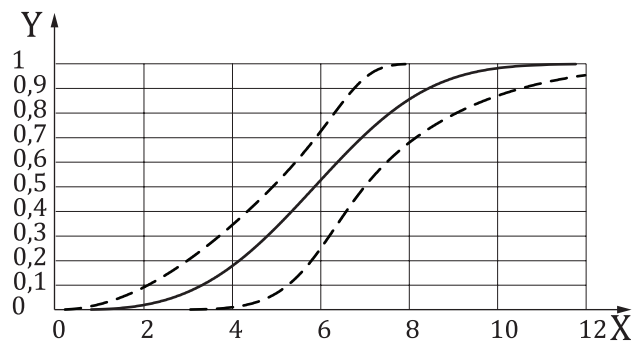
Figure 12 — Injury risk curves for NFR3+ as a function of PC-Score



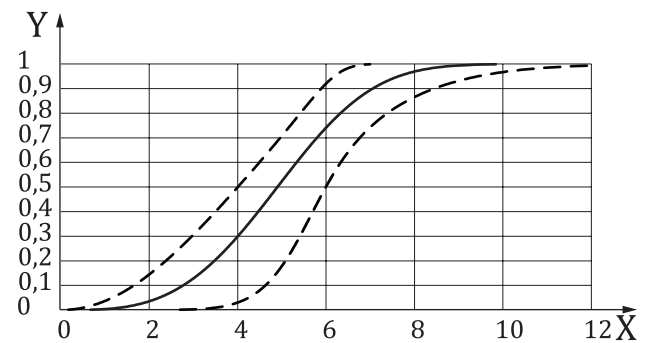
a) 35 years old



b) 45 years old



c) 55 years old

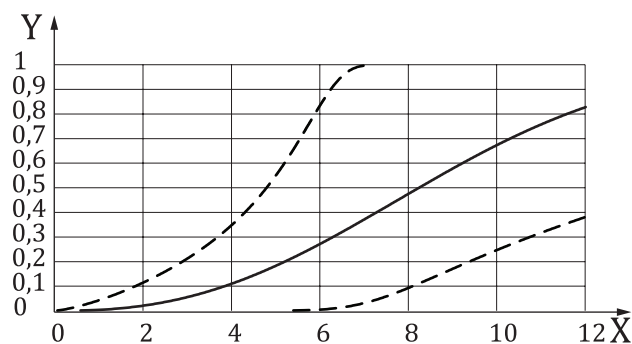


d) 65 years old

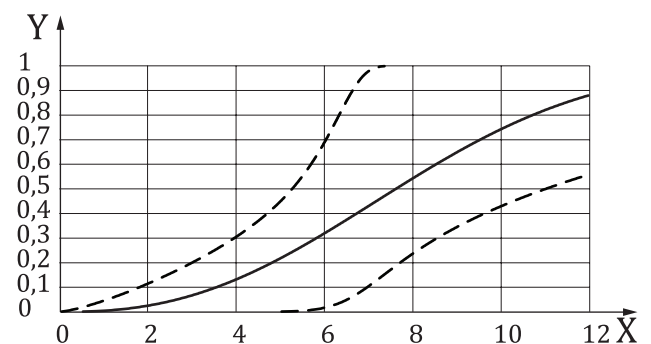
Key

- X PC-Score
- Y risk of NFR3+
- IRF (NFR3+)
- - - CI (NFR3+)

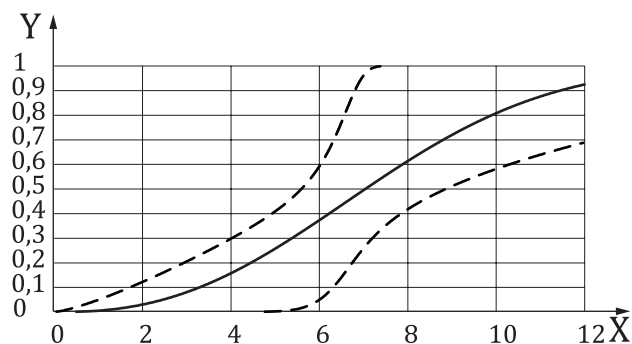
Figure 13 — Injury risk curves for NFR7+ as a function of PC-Score



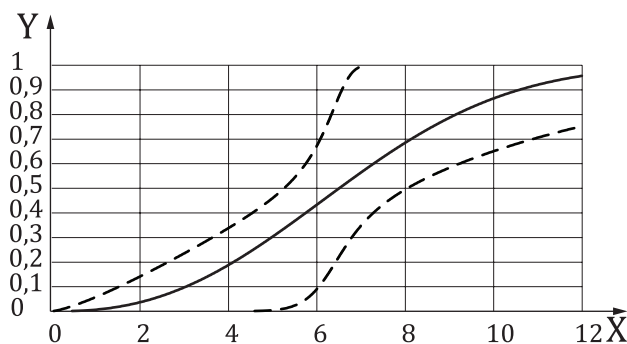
a) 35 years old



b) 45 years old



c) 55 years old



d) 65 years old

Key

- X PC-Score
- Y risk of NFR7+
- IRF (NFR7+)
- - - CI (NFR7+)

— Quotation

- [ISO/TS 18506](#) rules: 1
- Quality assessment ([Table 3](#))

Table 3 — Quality assessment of PC-Score

Age	35 years old	45 years old	55 years old	65 years old
NFR3+				
5 % CI	1,28	1,22	1,26	1,39
25 % CI	0,85	0,65	0,59	0,69
50 % CI	0,81	0,53	0,35	0,41
NFR7+				
5 % CI	2,17	2,05	2,04	2,15
25 % CI	1,17	0,86	0,70	0,76
50 % CI	1,14	0,75	0,46	0,43
NFR3+ calculated with enlarged database of TIC				
5 % CI	1,26	1,30	1,37	1,48
25 % CI	0,70	0,64	0,64	0,71
50 % CI	0,61	0,46	0,38	0,40
Quotation: $0 \leq \text{good} \leq 0,5 < \text{fair} \leq 1,0 < \text{marginal} \leq 1,5 < \text{unacceptable}$.				

- R&R: 94 %
- THOR applicability: 1

5.3.3 TIC

- Injury target: AIS3+ chest injury (3 fractured ribs or 3 displaced fractured ribs)
- Source: Reference [\[85\]](#)

- Channels: 4 3D rib deflections ($D_{ulx}, D_{uly}, D_{ulz}, D_{urx}, D_{ury}, D_{urz}, D_{llx}, D_{lly}, D_{llz}, D_{lrx}, D_{lry}, D_{lrz}$)
- Filtration: CFC180
- Formula:

$$T_{\text{NRF}} = R_{\text{max}} + 1,66 D_{\text{updif}}$$

$$T_{\text{NSRF}} = R_{\text{max}} + 3 D_{\text{updif}}$$

where

$$R_{\text{max}} = \max(D_{\text{ulmax}}, D_{\text{urmax}}, D_{\text{llmax}}, D_{\text{lrmax}});$$

$$D_{\text{ulmax}} = \max\left(\sqrt{D_{\text{ulx}}^2 + D_{\text{uly}}^2 + D_{\text{ulz}}^2}\right);$$

$$D_{\text{urmax}} = \max\left(\sqrt{D_{\text{urx}}^2 + D_{\text{ury}}^2 + D_{\text{urz}}^2}\right);$$

$$D_{\text{llmax}} = \max\left(\sqrt{D_{\text{llx}}^2 + D_{\text{lly}}^2 + D_{\text{llz}}^2}\right);$$

$$D_{\text{lrmax}} = \max\left(\sqrt{D_{\text{lrx}}^2 + D_{\text{lry}}^2 + D_{\text{lrz}}^2}\right);$$

$$D_{\text{updif}} = \max\left(\left|\sqrt{D_{\text{ulx}}^2 + D_{\text{uly}}^2 + D_{\text{ulz}}^2} - \sqrt{D_{\text{urx}}^2 + D_{\text{ury}}^2 + D_{\text{urz}}^2}\right|\right);$$

D_{ijk} is the deflection measured at the ij position in the k direction and expressed in mm:

$i = (u, l)$ for upper and lower positions;

$j = (l, r)$ for left and right positions;

$k = (x, y, z)$ for the direction;

T_{NRF} is the variable for the chest injury criterion TIC_{NRF} ;

T_{NSFR} is the variable for the chest injury criterion TIC_{NSFR} .

$$— \quad P_{\text{NFR} \geq 3|\dot{A}, T_{\text{NFR}}} = 1 - \exp\left(-\left[\frac{T_{\text{NFR}}}{\exp(5,2675 - 0,0135\dot{A})}\right]^\gamma\right)$$

— With

$$— \quad \gamma = \frac{1}{(0,09325 + 0,00475\dot{A})}$$

$$— \quad P_{\text{NSFR} \geq 3|\dot{A}, T_{\text{NSFR}}} = 1 - \exp\left(-\left[\frac{T_{\text{NSFR}}}{\exp(6,125 - 0,015\dot{A})}\right]^\gamma\right)$$

— With

$$— \quad \gamma = \frac{1}{(0,02525 + 0,00415\dot{A})}$$

- Data: 71PMHS sled tests (58 belt only; 7 3-point belt+AB; 3 lap belt+AB; 3 inflatable belt and 9 PMHS static AB tests) provided in [Table D.2](#) of [Annex D](#)

- Statistics: survival (Weibull)

- Dummy version: THOR mod-kit 2013
- Comments:
 - No impactor tests
 - Enlarged test sample including airbag only loading and a larger range of deflections. Tests consisting of the deployment of unfolded airbags were included because they were carried out in such a way as to generate only a membrane effect close to the loading of a subject in a crash test
 - Meaningful gauss like distribution of age (median 68,5 years), mass (median 70,5 kg) and height (median 175 cm)
 - A principal component analysis of this sample indicated that a good criterion describing the chest deflection needs two components: one describing the extent of the deflection; one describing the left-right asymmetry of the deflection
 - For the development of TIC, different THORs have been used and it is unclear if some effects (e.g. belted vs. only airbag) seen in the development of TIC are real effects or just dummy artefacts
- Curves

Figure 14 — Injury risk curves for NFR3+ as a function of TIC_NFR

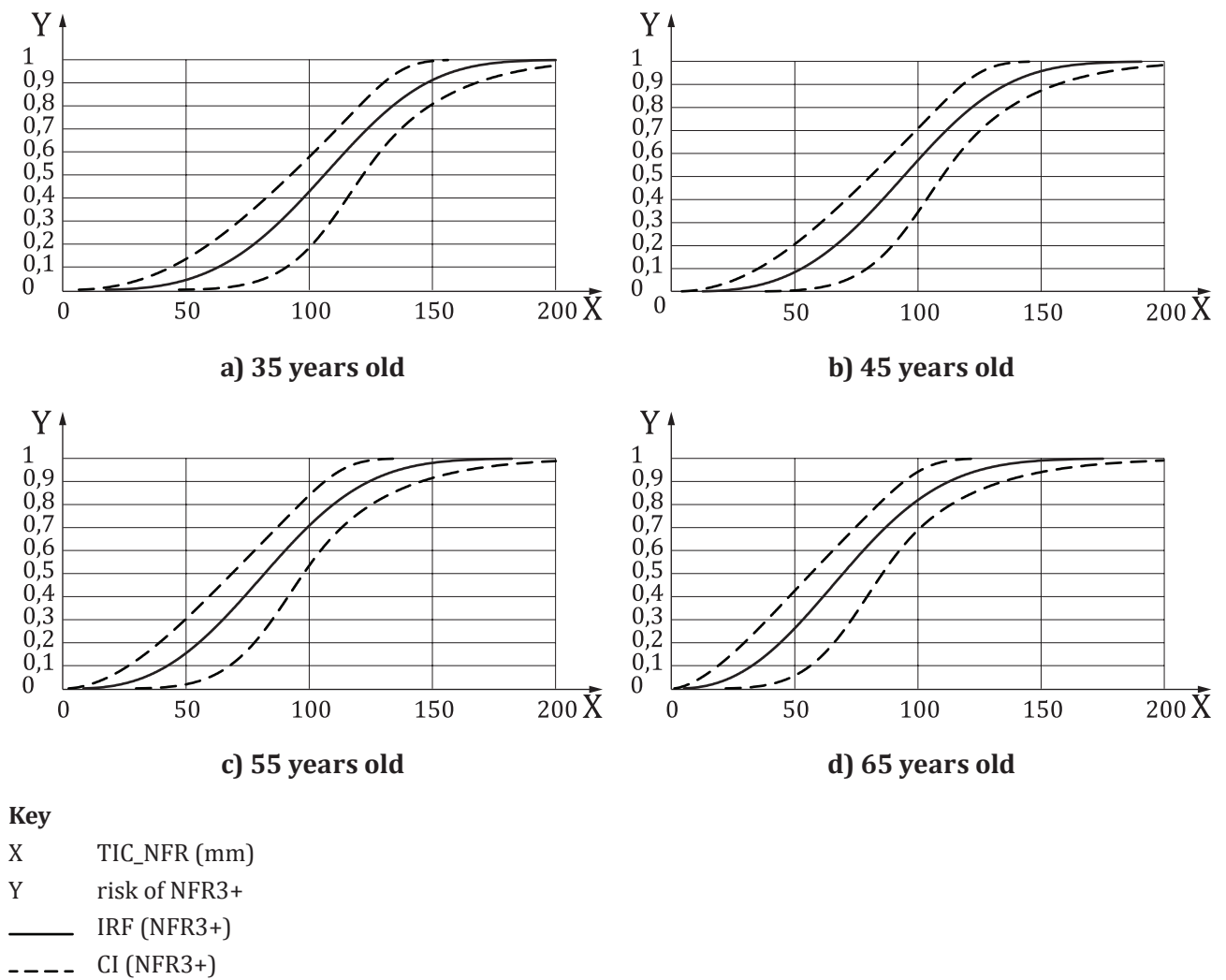
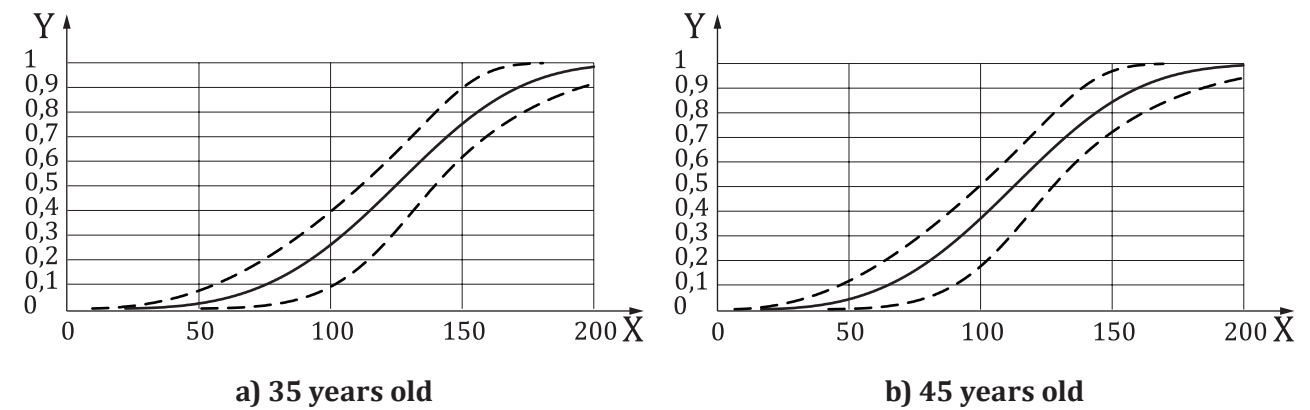


Figure 15 — Injury risk curves for NFR7+ as a function of TIC_NFR



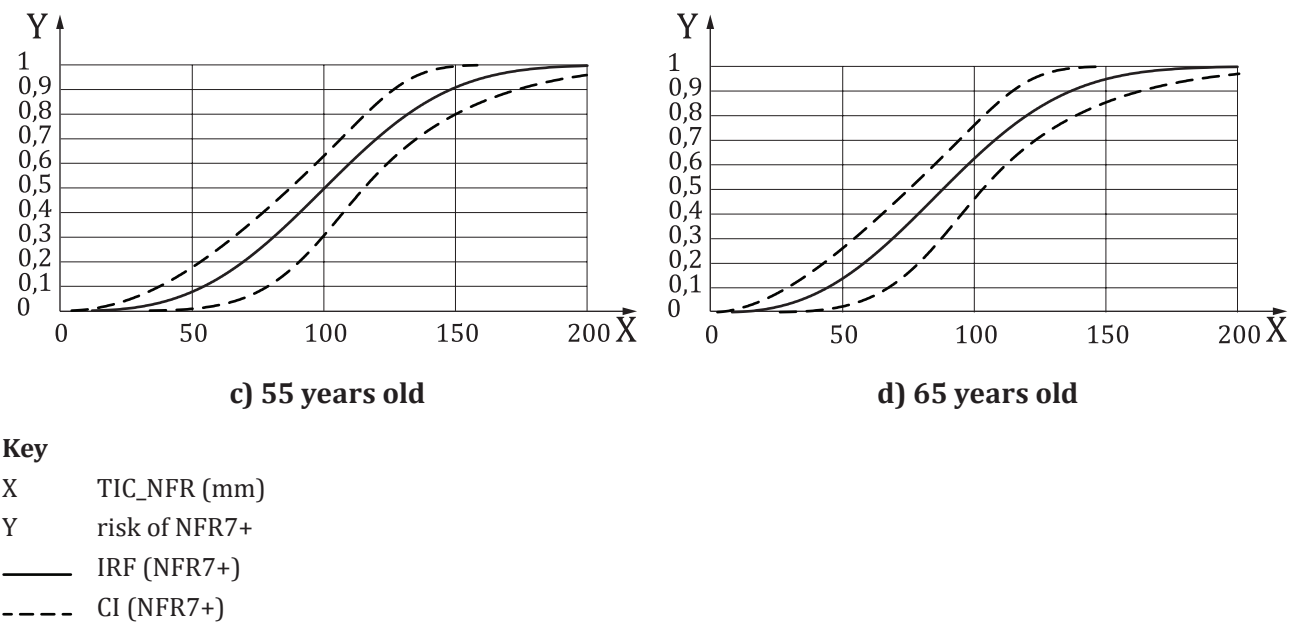


Figure 16 — Injury risk curves for NSFR3+ as a function of TIC_NSFR