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Road vehicles — Injury risk curves for the THOR dummy

Véhicules routiers — Courbe de risques de blessures pour mannequin THOR

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Foreword

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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.

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 if 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-(standard deviation/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
- Formula: $H_{15} = \max_{15}\left\{(t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t).\mathrm{d}t\right]^{2,5}\right\}$

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.

- $P_{\text{skull\_fracture}} = \Phi(H_{15}; \mu = 1\ 500; \sigma = 488)$

where

$P_{skull\_fracture}$ 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.

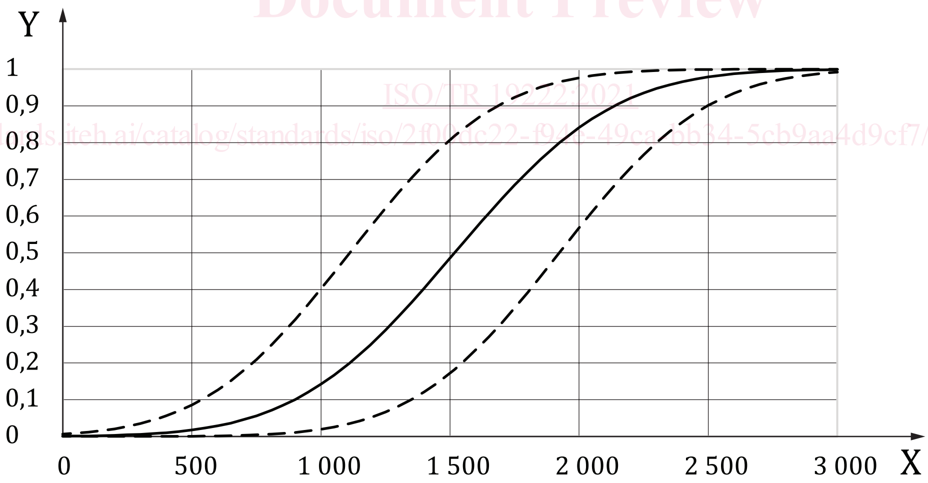
— Comments:

  — 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: $H_{15} = \max_{15}\left\{(t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t1}^{t2} a(t).\mathrm{d}t\right]^{2,5}\right\}$

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.

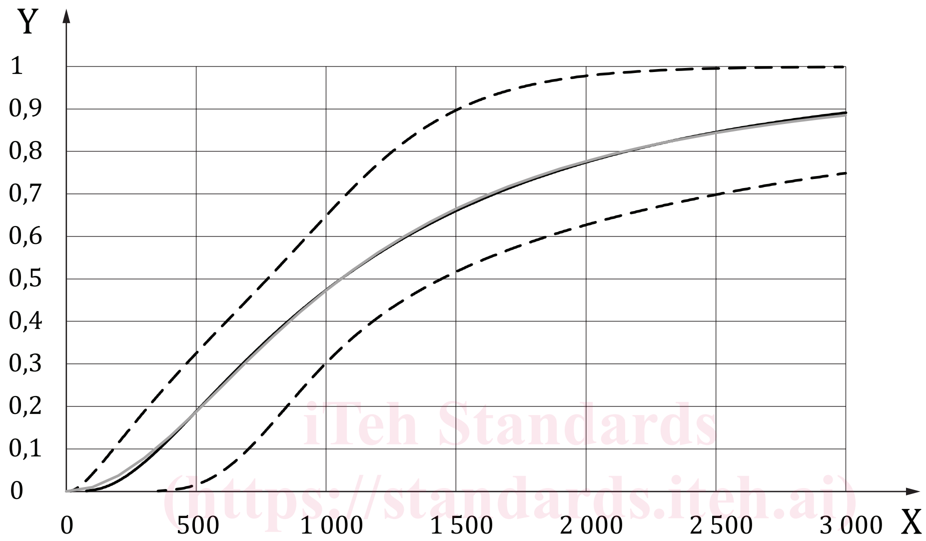
— Comments:

  — 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].

Table 1 *(continued)*

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

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

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

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

where

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

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:

$m_x = 1$; $m_y = 1$; $m_z = 1$;

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

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

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

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

— Curves

