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Road vehicles — Objective rating metrics for dynamic systems

Véhicules routiers — Mesures pour l'évaluation objective des systèmes dynamiques

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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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.

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The committee responsible for this document is ISO/TC 22, *Road vehicles*, Subcommittee SC 10, *Impact test procedures*, and SC 12, *Passive safety crash protection systems*.

Introduction

Computer-Aided Engineering (CAE) has become a vital tool for product development in the automobile industry. Various computer programs and models are developed to simulate dynamic systems. To maximize the use of these models, their validity and predictive capabilities need to be assessed quantitatively. Model validation is the process of comparing CAE model outputs with test measurements in order to assess the validity or predictive capabilities of the CAE model for its intended usage. The fundamental concepts and terminology of model validation have been established mainly by standard committees including the United States Department of Energy (DOE),[6] the American Institute of Aeronautics and Astronautics (AIAA),[1] the Defense Modeling and Simulation Office (DMSO) of the US Department of Defense (DOD),[5] the American Society of Mechanical Engineers Standards Committee (ASME) on verification and validation of Computational Solid Mechanics,[2] Computational Fluid Dynamics and Heat Transfer,[3] and various other professional societies.[4][22][23]

One of the critical tasks to achieve quantitative assessment of models is to develop a validation metric that has the desirable metric properties to quantify the discrepancy between functional or time history responses from both physical test and simulation result of a dynamic system.[7][19][20] Developing quantitative model validation methods has attracted considerable researchers' interest in recent years.[12][13][14][18][20][21][26][28][29][32] However, the primary consideration in the selection of an effective metric should be based on the application requirements. In general, the validation metric is a quantitative measurement of the degree of agreement between the physical test and simulation result.

In this Technical Report, four state-of-the-art objective rating metrics are investigated and they are: CORrelation and Analysis (CORA) metric,[10][30][31] Error Assessment of Response Time Histories (EARTH) metric,[28][34] model reliability metric,[18][27][35] and Bayesian confidence metric.[14][16][36] Multiple dynamic system examples for both tests and CAE models are used to show their advantages and limitations. Further enhancements of the CORA corridor rating and the development of an Enhanced Error Assessment of Response Time Histories (EEARTH) metric are proposed to improve the robustness of these metrics. A new combined objective rating metric is developed to standardize the calculation of the correlation between two time history signals of dynamic systems. Multiple vehicle safety case studies are used to demonstrate the effectiveness and usefulness of the proposed metric for an ISO Technical Report.

Road vehicles — Objective rating metrics for dynamic systems

1 Scope

This Technical Report specifies a method to calculate the level of correlation between two non-ambiguous signals. The focus of the methods described in this Technical Report is on the comparison of time-history signals or functional responses obtained in all kinds of tests of the passive safety of vehicles and the corresponding numerical simulations. It is validated with signals of various kinds of physical loads such as forces, moments, accelerations, velocities, and displacements. However, other applications might be possible too, but are not in the scope of this Technical Report.

2 Terms and definitions

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

2.1
filtering
smoothing of signals by using standardized algorithms

2.2
goodness or level of correlation
similarity of two signals

2.3
interval of evaluation
time domain that is used to calculate the correlation between two signals

2.4
rating
rating score
calculated value that represents a certain level of correlation (objective rating)

2.5
sampling rate
recording frequency of a signal

2.6
time sample
pair values (e.g. time and amplitude) of a recorded signal

2.7
time-history signal
physical value recorded in a time domain; those signals are non-ambiguous

3 Symbols and abbreviated terms

3.1 General abbreviated terms

CAE	Computer-Aided Engineering
CORA	CORrelation and Analysis
DTW	Dynamic Time Warping

EARTH	Error Assessment of Response Time Histories
EEARTH	Enhanced Error Assessment of Response Time Histories
SME	Subject Matter Expert

3.2 General symbols and subscripts

C, $C(t)$	analysed signal (CAE signal)
T, $T(t)$	reference signal (test signal)
t	time signal (axis of abscissa)
Δt	interval between two time samples
t_0	time zero of an event (e.g. test, crash, impact, etc.)
t_{start}	starting time of the interval of evaluation
t_{end}	ending time of the interval of evaluation
N	total number of sample points (e.g. time steps) between the starting time, t_{start}, and ending time, t_{end}
$N_{>0}$	all natural numbers without zero

3.3 CORA

Z_{CORA}	CORA rating
Z_1	corridor rating
$Z_1(t)$	corridor rating at time t (curve)
Z_2	cross-correlation rating
Z_{2a}	phase-shift rating
Z_{2b}	size rating
Z_{2c}	shape (progression) rating
w_{Z1}	weighting factor of the corridor rating, Z_1
w_{Z2}	weighting factor of the cross-correlation rating, Z_2
w_{Z2a}	weighting factor of the phase-shift rating, Z_{2a}
w_{Z2b}	weighting factor of the size rating, Z_{2b}
w_{Z2c}	weighting factor of the shape rating, Z_{2c}
k_{Z1}	exponent factor for calculating the corridor rating between the inner and outer corridors
k_{Z2a}	exponent factor for calculating phase-shift rating, Z_{2a}
k_{Z2b}	exponent factor for calculating size rating, Z_{2b}
k_{Z2c}	exponent factor for calculating shape rating, Z_{2c}
T_{norm}	absolute maximum amplitude of the reference signal, T
a_0	relative half width of the inner corridor

b_0	relative half width of the outer corridor
δ_i	half width of the inner corridor
δ_o	half width of the outer corridor
$\delta_i(t)$	lower/upper inner corridor at time t (curve)
$\delta_o(t)$	lower/upper outer corridor at time t (curve)
$D_{\min}$	coefficient of the allowable lower limit of the phase shift
$D_{\max}$	coefficient of the allowable upper limit of the phase shift
F_C	sum of the square of the area for the time-shifted evaluated curve, C
F_T	sum of the square of the area for the reference curve, T
$INT_{\min}$	percentage of the minimum remaining overlapping time of the reference and evaluation curves after time shift
m	shift of a signal along the axis of abscissa
$m_{\min}$	minimum m shift of a signal
$m_{\max}$	maximum m shift of a signal
n	number of samples
$n_{\min}$	time step shifted to get the maximum cross correlation
ρ	cross correlation
$\rho(m)$	cross correlation at shift, m
δ	phase-shift time at the maximum cross correlation, ρ
$\delta_{\min}$	lower limit of CORA phase shift
$\delta_{\max}$	upper limit of CORA phase shift

3.4 EARTH and EEARTH

E_E	overall EARTH score
E_M	EARTH magnitude score
E_P	EARTH phase score
E_S	EARTH slope (topology) score
w_M	weighting factor of the magnitude score, E_M
w_P	weighting factor of the phase score, E_P
w_S	weighting factor of the slope score, E_S
k_M	exponent factor for calculating the magnitude score, E_M
k_P	exponent factor for calculating the phase score, E_P
k_S	exponent factor for calculating the slope score, E_S
ε_{mag}	EARTH magnitude error

ε_{slope}	EARTH slope error
ε_M^*	maximum allowable magnitude error
ε_P^*	maximum allowable percentage of time shift
ε_S^*	maximum allowable slope error
$\bar{C}(t)$	mean value of CAE curve
C^{ts} , $C^{ts}(i)$	truncated and shifted CAE curve
C^{ts+d}	derivative CAE curve, C^{ts}
C^{ts+w}	warped CAE curve, C^{ts}
C^{ts+d+w}	derivative warped CAE curve, C^{ts}
$\bar{T}(t)$	mean value of test curve
T^{ts} , $T^{ts}(j)$	truncated and shifted test curve
T^{ts+d}	derivative test curve, T^{ts}
T^{ts+w}	warped test curve, T^{ts}
T^{ts+d+w}	derivative warped test curve, T^{ts}
ρ_E	maximum cross correlation of all $\rho_L(m)$ and $\rho_R(m)$
$\rho_L(m)$	cross correlation — signal is moved to the left
$\rho_R(m)$	cross correlation — signal is moved to the right
$d(i,j)$	local cost function to perform the dynamic time warping
m	time steps moved to evaluate the EARTH phase error
n_ε	number of time shifts to get, ρ_E

3.5 Model reliability metric

T_{norm}	absolute maximum amplitude of the reference signal, T
a	reliability target
b	threshold factor of the reliability assessment
ε_L	lower bound of the threshold interval
ε_U	upper bound of the threshold interval
ε_Φ^L	lower bound of the Bayesian interval hypothesis in probabilistic principal component analysis space (PPCA)
ε_Φ^U	lower bound of the Bayesian interval hypothesis in PPCA space
r	model reliability
P	cumulative probability

Φ , $\Phi(t)$	$p \times n$ reduced data matrix

3.6 Bayesian confidence metric

A	constant vector
B_{iM}	Bayes factor for multivariate case
δ	likelihood function
ε_{Φ}	predefined threshold vector
H_0	null hypothesis
H_1	alternative hypothesis
K	confidence of accepting the model
κ	measure of confidence within an interval
Λ	variance of error variable, ε_i^*
μ_{Φ}	p mean values obtained from Φ^*
N	normal distribution
$N(\rho, \Lambda)$	normal distribution of δ with mean vector, p , and variance matrix, Λ
π_0	prior probability of hypothesis
ρ	prior mean, δ
Σ_{Φ}	variance matrix of Φ^*
Φ , $\Phi(t)$	difference curve between test curve, T , and CAE curve, C
$f(\delta)$	prior density function of δ

3.7 Overall ISO rating

R	combined rating of EEARTH and the CORA corridor method
E	EEARTH rating score
Z	CORA corridor rating ($Z = Z_1$)
w_E	weighting factor of the EEARTH rating, E
w_Z	weighting factor of the CORA corridor rating, Z
r	rank of the sliding scale of the ISO metric
$SC_{lower}(r)$	lower threshold of rank, r
$SC_{upper}(r)$	upper threshold of rank, r

4 General requirements to the data

The metrics described in this Technical Report require non-ambiguous curves (e.g. time-history curves). Furthermore, it is required that the reference curve, $T(t)$, and the evaluated curve, $C(t)$, are both defined between starting time, t_{start} , and ending time, t_{end} . Both curves shall have the same number of sample points, N, with a constant time interval, Δt, within the evaluation interval.

5 CORA metric

The objective evaluation metric called CORA — correlation and analysis[10][30][31] — uses two independent sub-ratings, a corridor rating, and a cross-correlation rating to assess the correlation of two signals. The rating structure of CORA is shown in Figure 1.

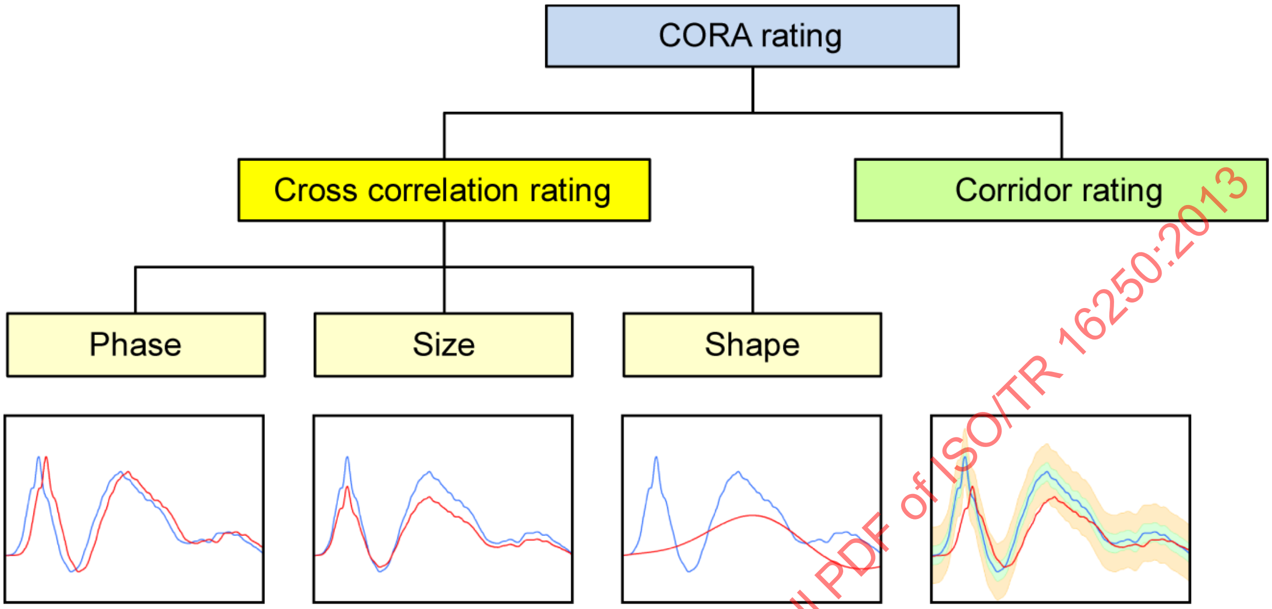


Figure 1 — CORA rating structure

The corridor and cross-correlation ratings are used to compensate each other's disadvantages, and the CORA rating tool is trying to separate an engineer's knowledge from the objective rating metric by using external parameters. However, it is possible to fine-tune the evaluation to the specific needs of the applications by adjusting those metric parameters to reflect the SME's knowledge of the applications.

The corridor rating, Z_1, calculates the deviation between both curves with the help of user-defined or automatically generated corridors. The cross-correlation rating, Z_2, analyses specific curve characteristics, such as phase shift, Z_{2a}, size, Z_{2b}, and shape of the signals, Z_{2c}. The rating results range from "0" (no correlation) to "1" (perfect match). The influence of the sub-ratings on the global rating is adjusted by user-defined weighting factors. Formulae (1) and (3) show how to calculate the CORA rating by using weighting factors [see Formulae (2) and (4)]. Details of each sub-rating are introduced in the following subsections.

$$Z_{CORA} = w_{Z1} \cdot Z_1 + w_{Z2} \cdot Z_2 \quad (1)$$

$$w_{Z1} + w_{Z2} = 1 \quad (2)$$

$$Z_2 = w_{Z2a} \cdot Z_{2a} + w_{Z2b} \cdot Z_{2b} + w_{Z2c} \cdot Z_{2c} \quad (3)$$

$$w_{Z2a} + w_{Z2b} + w_{Z2c} = 1 \quad (4)$$

5.1 Corridor rating

The corridor rating calculates the deviation between two signals by means of corridor fitting. The two sets of corridors, the inner and the outer corridors, are defined along the mean curve. If the evaluated curve (e.g. CAE curve) is within the inner corridor bounds, a score of "1" is given, and if it is outside the outer corridors, the rating is set to "0". The assessment declines from "1" to "0" between the bounds of inner and outer corridors resulting in three different rating zones as shown in Figure 2. This transition is user-defined. The compliance with the corridors is calculated at each specific time, t, and the final corridor rating, Z_1, of a signal is the average of all ratings, $Z_1(t)$, at specific times, t.

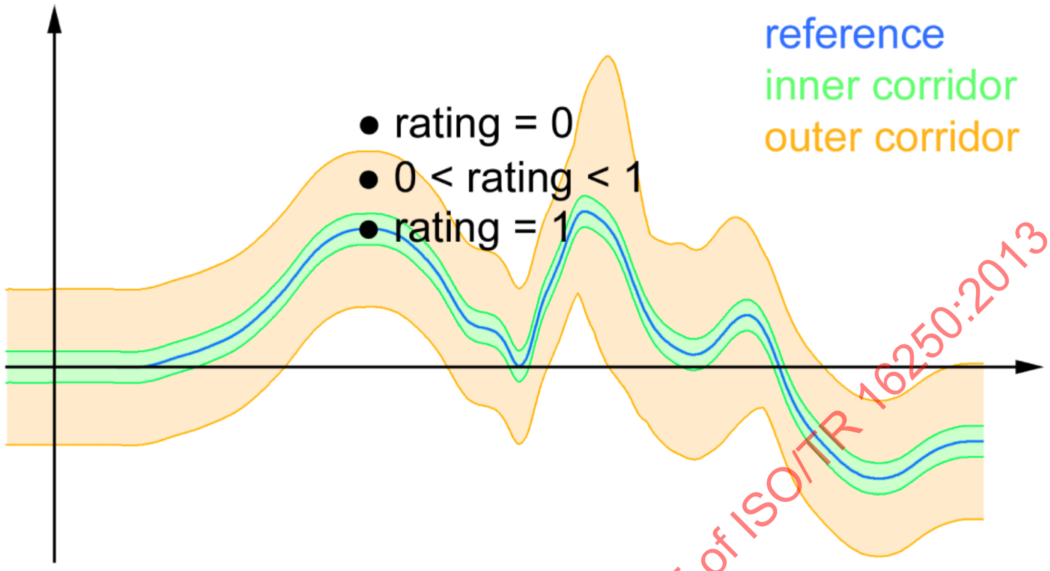


Figure 2 — Rating zones of the corridor method (corridors of constant width)[10]

The philosophy is to use a narrow inner corridor and a wide outer corridor.[17] It limits the number of "1" ratings to only good correlations and gives the opportunity to distinguish between poor and fair correlations. If the outer corridor is too narrow, too many curves of a fair or moderate correlation would get the same poor rating of "0", like signals of almost no correlation with the reference. The width of the corridors can be adjusted in order to reflect the specific signal characteristic, and it can be constant for the whole duration of the dynamic responses or vary at the different time steps.

This Technical Report applies the most common approach of using the constant corridor widths for the whole duration of the dynamic response. The parameters a_0 and b_0 define the relative half width of the inner and the outer corridors. Both shall be between "0" and "1", and a_0 must be less than b_0. The absolute half widths of both corridors are defined as the product of relative half width and the absolute maximum amplitude, T_{norm}, of the reference signal, T. Formula (5) shows the calculation of T_{norm}.

$$T_{norm} = \max\{|\min(T)|, |\max(T)|\} \quad (5)$$

The absolute half width of the inner corridors (absolute distance from reference signal to outer bounds of the inner corridors) is defined by Formula (6). The calculation of the absolute half width of the outer corridors [see Formula (7)] is similar to that of the inner corridors.

$$\delta_i = a_0 \cdot T_{norm} \qquad 0 \le a_0 \le 1 \quad (6)$$

$$\delta_o = b_0 \cdot T_{norm} \qquad 0 \le b_0 \le 1 \quad \text{and} \quad a_0 < b_0 \quad (7)$$

Based on these definitions, the upper and lower bounds of the inner corridors are defined by Formula (8) and the upper and lower bounds of the outer corridors are defined by Formula (9).

$$\delta_i(t) = T(t) \pm \delta_i \quad (8)$$

$$\delta_o(t) = T(t) \pm \delta_o \tag{9}$$

Formula (10) shows the calculation of the corridor rating for the correlation between the reference signal, T, and the analysed signal, C, at each evaluation time, t. If the absolute difference between the signals T and C is less than the half width of the inner corridors, δ_i, then the rating is set to "1". The rating is calculated by Formula (10) when the absolute difference between both signals is in between $\delta_i \le |T(t) - C(t)| \le \delta_o$. If the absolute difference between both signals is greater than the half width of the outer corridors, δ_o, then the rating is set to "0". The parameter k_{Z1} assesses the location of the analysed signal within the outer corridor and it applies the appropriate penalty on the rating score. A linear ($k_{Z1} = 1$), quadratic ($k_{Z1} = 2$), cubical ($k_{Z1} = 3$), or any other regression relationship can be defined accordingly.

$$Z_1(t) = \begin{cases} 1 & \text{if} \quad |T(t) - C(t)| < \delta_i \\ \left(\dfrac{\delta_o - |T(t) - C(t)|}{\delta_o - \delta_i} \right)^{k_{Z1}} & \\ 0 & \text{if} \quad |T(t) - C(t)| > \delta_o \end{cases} \qquad k_{Z1} \in N_{>0} \tag{10}$$

The final corridor rating, Z_1, is calculated by averaging all single time step ratings, $Z_1(t)$, as shown in Formula (11). The parameter N represents the total number of sample points (e.g. time steps) between the starting and ending times of the interval of evaluation.

$$Z_1 = \frac{\sum_{t=t_{start}}^{t_{end}} Z_1(t)}{N} \tag{11}$$

One of the advantages of the corridor rating is the simplicity and the clearness of the algorithm. It reflects criteria which are used intuitively in engineering judgment. Sometimes, this simplicity may be the disadvantage of the method. For example, a small distortion of the phase can lead to a undesirable rating.

5.2 Cross-correlation rating

The cross-correlation rating may compensate for the disadvantages resulting from the corridor rating by analysing the characteristics of signals. Three sub-ratings (phase, size, and shape) with individual weighting factors are implemented.

The calculated maximum cross correlation is the base of the analysis of phase shift, size, and shape of the signals.

5.2.1 Maximum cross correlation

In general, the cross-correlation metric moves the test signal, T, by multiples of Δt in relation to the CAE signal, C. The cross-correlation value, $\rho(m)$, is calculated at each shifted state. The time shift with the maximum ρ is the base of the calculation of the cross-correlation rating.

Formula (12) shows the calculation of the cross correlation at each time shift, m. Curve C is moved by multiples $m \in (m_{\min}, m_{\max})$ of Δt between the minimum and the maximum shift [see Formulae (13) and (14)]. The range of the time shift is limited by the parameter $INT_{\min}$. Therefore, the signals T and C are at least overlapping within the interval $INT_{\min} \cdot (t_{end} - t_{start})$. The parameter n in Formula (12) is not constant but is reduced to $n_{\min}$ [see Formula (15)].

$$\rho(m) = \frac{\sum_{i=0}^{n-1} C(t_{start} + (m+i)\cdot \Delta t)\cdot T(t_{start} + i\cdot \Delta t)}{\sqrt{\sum_{i=0}^{n-1} C^2(t_{start} + (m+i)\cdot \Delta t)\cdot \sum_{i=0}^{n-1} T^2(t_{start} + i\cdot \Delta t)}} \qquad -1 \le \rho \le 1 \tag{12}$$

$$m_{\min} = \frac{(INT_{\min} - 1)\cdot (t_{end} - t_{start})}{\Delta t} \qquad 0 < INT_{\min} < 1 \tag{13}$$

$$m_{\max} = \frac{(1 - INT_{\min})\cdot (t_{end} - t_{start})}{\Delta t} \qquad 0 < INT_{\min} < 1 \tag{14}$$

$$n_{\min} = INT_{\min} \cdot n \tag{15}$$

As described above, the cross correlation ρ is the maximum of all $\rho(m)$ [see Formula (16)].

$$\rho = \max\{\rho(m)\} \tag{16}$$

5.2.2 Phase-shift rating

The phase-shift rating requires the parameters $D_{\min}$ and $D_{\max}$ to limit the phase shift. Both are defined within $(0,1)$. The thresholds of the phase shift are calculated by Formulae (17) and (18).

$$\delta_{\min} = D_{\min} \cdot (t_{end} - t_{start}) \qquad 0 < D_{\min} \le 1 \tag{17}$$

$$\delta_{\max} = D_{\max} \cdot (t_{end} - t_{start}) \qquad 0 < D_{\max} \le 1 \tag{18}$$

The phase-shift rating is calculated by Formula (19) at the maximum cross correlation, ρ, and the corresponding time shift, δ. The parameter k_{Z2a} describes the decline of the rating between "1" and "0". A linear ($k_{Z2a} = 1$), quadratic ($k_{Z2a} = 2$), cubical ($k_{Z2a} = 3$), or any other regression relationship can be defined accordingly.

$$Z_{2b} = \begin{cases} 1 & \text{if} \quad |\delta| < \delta_{\min} \\ \left(\dfrac{|\delta_{\max} - |\delta||}{\delta_{\max} - \delta_{\min}} \right)^{k_{Z2a}} & \\ 0 & \text{if} \quad |\delta| > \delta_{\max} \end{cases} \qquad k_{Z2a} \in N_{>0} \tag{19}$$

5.2.3 Size rating

The size of the signals is analysed by comparing the area below the two curves after the phase shift. It is a necessary evaluation but it may not be sufficient to evaluate the overall level of correlation. For instance, the area below a signal with high and narrow peak could be identical to the area of a curve with low but wide peak. The size method would evaluate this example with “1” although the shape of the signals is completely different.

$$\frac{F_C}{F_T} = \frac{\sum_{i=1}^{n} C^2(t_{start} + \delta + i \cdot \Delta t)}{\sum_{i=1}^{n} T^2(t_{start} + i \cdot \Delta t)} \qquad (20)$$

$$Z_{2b} = \begin{cases} \left(\frac{F_C}{F_T}\right)^{k_{Z2b}} & \text{if} \quad F_T > F_C \\ \left(\frac{F_T}{F_C}\right)^{k_{Z2b}} & \end{cases} \qquad k_{Z2b} \in N_{>0} \qquad (21)$$

The analysis of size is done by comparing the square of the areas between the curves and the time axis. Due to equidistant supporting points of both signals, the area can be represented by Formula (20). Finally, the size rating is calculated by Formula (21). The meaning of k_{Z2b} is similar to k_{Z2a} (see 5.2.2).

5.2.4 Shape rating

As shown in Formula (22), the shape rating, Z_{2c}, is derived from the maximum cross correlation, ρ, described in 5.2.1. The meaning of k_{Z2c} is similar to k_{Z2a} (see 5.2.2).

$$Z_{2c} = \frac{1}{2}(\rho + 1)^{k_{Z2c}} \qquad k_{Z2c} \in N_{>0} \qquad (22)$$

5.3 Step-by-step procedure

The signals shall be pre-processed as described in Clause 10. After preparing the signals for the analysis and defining the interval of evaluation, the maximum absolute amplitude, T_{norm}, of the reference signal, *T*, shall be determined within this interval. It is used to calculate the inner and outer corridors. The actual corridor and cross-correlation assessment can be executed within the defined interval. The overall rating ranges between “0” and “1”. A score of “1” does not mean that both signals are identical. Solely, their correlation is mathematically perfect within the defined tolerances.

To summarize, the following step-by-step procedures shall be followed to calculate CORA rating:

1) Pre-process both signals according to Clause 10.

2) Calculate T_{norm} within this interval by using the reference signal.

3) Calculate the inner and the outer corridors.

4) Calculate the corridor rating, $Z_1(t)$, at every specific time, *t*, within the interval of evaluation.

5) Calculate the corridor rating, Z_1, based on $Z_1(t)$ and the number, *N*, of time samples.

6) Calculate the maximum cross correlation, ρ, between *T* and *C*.

7) Calculate phase rating, Z_{2a}.

8) Calculate size rating, Z_{2b}.

9) Calculate shape rating, Z_{2c}.

10) Calculate the cross-correlation rating, Z_2.

11) Calculate the overall CORA rating, Z_{CORA}.

6 EARTH metric

Another objective rating metric called Error Assessment of Response Time Histories (EARTH) was developed for dynamic system applications.[28][34] Figure 3 shows the structure of the EARTH error measures.

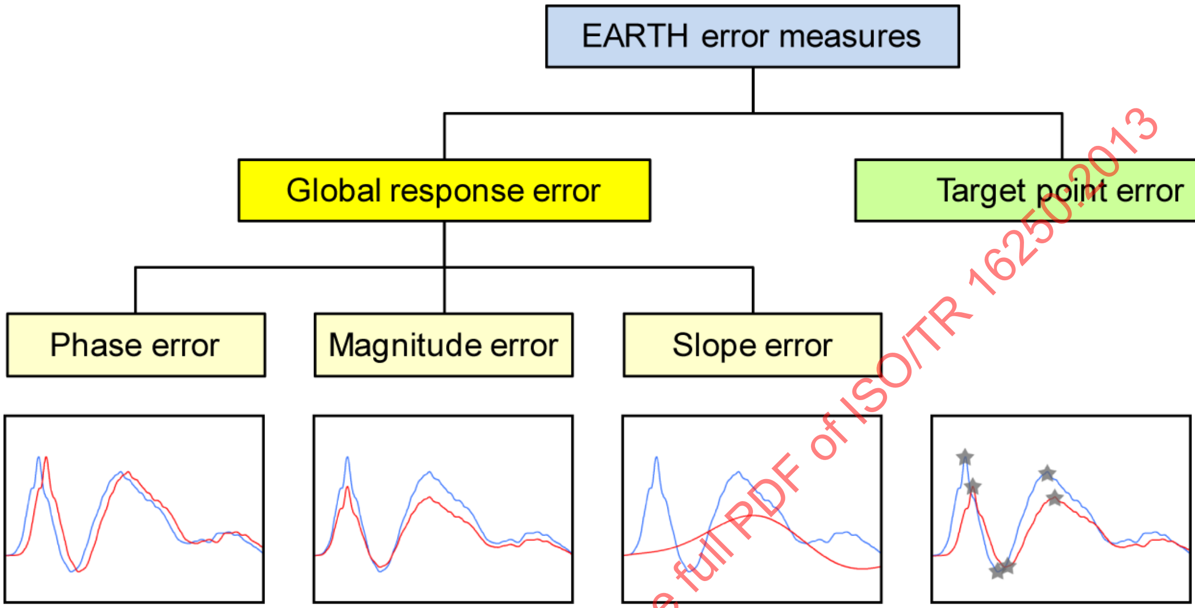


Figure 3 — EARTH error measures structure[28]

The EARTH metric is divided into two categories: global response error and target point response error. The global response error is defined as the error associated with the complete time history with equal weight on each point. The three main components of the global response error are phase error, magnitude error, and topology (or so-called slope) error. The target point error is defined as the error associated with a certain localized phenomenon of interest, such as peak error and time-to-peak error. The target point error represents the characteristic of a part of the time history, but does not indicate an overall performance of the entire time history. In addition, the target point error is generally application-dependent; hence, it is not the focus of this Technical Report.

Quantifying the errors associated with these features of phase, magnitude, and topology (slope) separately is challenging because there are strong interactions among them. For example, to quantify the error associated with magnitude, the presence of a phase difference between the time histories may result in a misleading measurement. A unique feature dynamic time warping (DTW)[25] of the EARTH metric is used to separate the interaction of phase, magnitude, and topology (slope) errors. DTW is an algorithm for measuring discrepancy between time histories. It aligns peaks and valleys as much as possible by expanding and compressing the time axis according to a given cost (distance) function.[9]

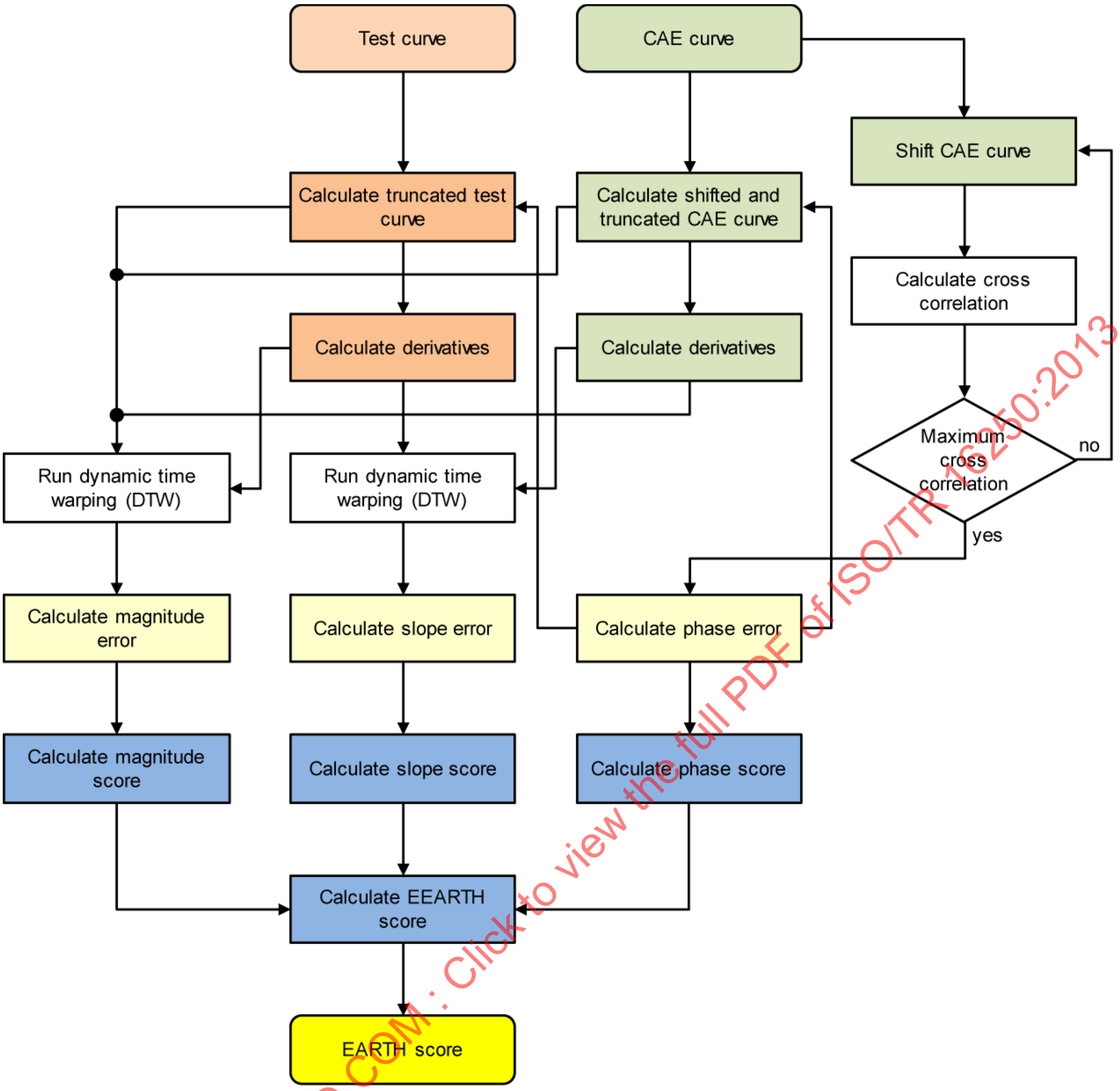


Figure 4 — Workflow of the revised EARTH metric

Since the ranges of the three errors are quite different and there is no single rating that can provide a quantitative assessment alone, the initial EARTH metric study employs a linear regression method to combine the three errors into one score. Numerical optimization method is employed to identify the linear coefficients so that the resulting EARTH rating can match the SME's ratings closely for a specific application.[8][24] However, the resulting linear combination of the EARTH metric is mainly numerical-based and application-dependent; hence, it may not be scalable to other applications. In order to provide more intuitive ratings while maintaining the advantages of the original EARTH metric, a revised EARTH metric is proposed.[28] Figure 4 shows the flowchart of the revised EARTH metric, and the details of the algorithms are described in the following subclauses.

6.1 EARTH phase score

The EARTH phase score, E_P, is used to measure the phase lag between the two time histories. The maximum allowable percentage of time shift is ε_P^*, and it is predefined. In this step, the initial curve, C, is shifted left then right one step at a time to the original test data, and the cross correlation between the truncated test curve and shifted and truncated C are calculated until reaching the maximum allowable time-shift limits $\varepsilon_P^* \cdot (t_{end} - t_{start})$.

When the initial curve, C, is moved to the left by m time steps, the number of overlap points of the two time histories after time shift $m \cdot \Delta t$ is reduced to $N - m$ and the corresponding cross-correlation value, $\rho_L(m)$, is calculated by Formula (23).

$$\rho_L(m) = \frac{\sum_{i=0}^{n-1} [(C(t_{start} + (m+i)\cdot \Delta t) - \bar{C}(t)) \cdot (T(t_{start} + i \cdot \Delta t) - \bar{T}(t))]}{\sqrt{\sum_{i=0}^{n-1} [C(t_{start} + (m+i)\cdot \Delta t) - \bar{C}(t)]^2} \cdot \sqrt{\sum_{i=0}^{n-1} [T(t_{start} + i \cdot \Delta t) - \bar{T}(t)]^2}} \quad (23)$$

When the initial curve, C, is moved to the right by m time steps, the number of overlap points after time shift $m \cdot \Delta t$ is reduced to $N - m$ and the corresponding cross-correlation value, $\rho_R(m)$, is calculated by Formula (24).

$$\rho_R(m) = \frac{\sum_{i=0}^{n-1} [(C(t_{start} + i \cdot \Delta t) - \bar{C}(t)) \cdot (T(t_{start} + (m+i)\cdot \Delta t) - \bar{T}(t))]}{\sqrt{\sum_{i=0}^{n-1} [C(t_{start} + i \cdot \Delta t) - \bar{C}(t)]^2} \cdot \sqrt{\sum_{i=0}^{n-1} [T(t_{start} + (m+i)\cdot \Delta t) - \bar{T}(t)]^2}} \quad (24)$$

The maximum cross correlation, ρ_E, is the maximum of all $\rho_L(m)$ and $\rho_R(m)$. The number of the time-shifting steps that yields the maximum cross correlation, ρ_E, is defined as the EARTH phase error, n_ε. The corresponding shifted and truncated CAE curve C is recorded as C^{ts} and the corresponding truncated test curve is recorded as T^{ts}.

The EARTH phase score, E_P, is calculated by Formula (25). The best EARTH phase score is “1”, which means there is no need to shift CAE curve to reach the maximum cross correlation between the initial test and CAE curves. If the time shift, n_ε, is equal to or greater than the maximum allowable time-shift threshold $\varepsilon_P^* \cdot N$, then the EARTH phase score is “0”. In between, the EARTH phase score is calculated by a regression method; it is either linear ($k_P = 1$), quadratic ($k_P = 2$), or cubical ($k_P = 2$).

$$E_P = \begin{cases} 1 & \text{if} \quad n_\varepsilon = 0 \\ \left(\dfrac{\varepsilon_P^* \cdot N - n_\varepsilon}{\varepsilon_P^* \cdot N} \right)^{k_P} & \\ 0 & \text{if} \quad n_\varepsilon \geq \varepsilon_P^* \cdot N \end{cases} \qquad k_P \in \{1, 2, 3\} \quad (25)$$

6.2 EARTH magnitude score

The magnitude error is a measure of discrepancy in the amplitude of the two time histories. The magnitude error is defined as the difference in amplitude of the two time histories when there is no time lag between them. Before calculating the magnitude error, the difference between the time histories caused by error in phase and topology (slope) are minimized by using dynamic time warping. The local cost function, $d(i, j)$, for DTW used considers both the distance and the slope as shown in Formula (26). Once the local cost matrix is built, the algorithm finds the alignment path which runs through the low-cost areas on the cost matrix. This alignment path defines the corresponding elements of both $C^{ts}(i)$ and $T^{ts}(j)$ that will lead to the minimum accumulated cost function.

$$d(i,j)=(C^{ts}(i)-T^{ts}(j))^2+(t_i-t_j)^2\cdot\left|\left(\frac{dC^{ts}(i)}{dt}\right)_{t=t_i}-\left(\frac{dT^{ts}(j)}{dt}\right)_{t=t_j}\right| \tag{26}$$

The derivatives at each data points of the truncated test curve, T^{ts}, and the shifted and truncated CAE curve, C^{ts}, are first calculated, which yields the truncated test slope curve, T^{ts+d}, and the shifted and truncated CAE slope curve, C^{ts+d}. Next, DTW is performed to the truncated test curve, T^{ts}, and the shifted and truncated CAE curve, C^{ts}, which results in the truncated and warped test slope curve, T^{ts+w}, and the shifted, truncated, and warped CAE slope curve, C^{ts+w}. The EARTH magnitude error, ε_{mag}, is calculated by Formula (27).

$$\varepsilon_{mag}=\frac{\left\|C^{ts+w}-T^{ts+w}\right\|_1}{\left\|T^{ts+w}\right\|_1} \tag{27}$$

Formula (28) is used to calculate the EARTH magnitude score, E_M, where ε_M^* is the maximum allowable magnitude error, and k_M defines the order of the regression. The best EARTH magnitude score is “1”, which means there is no difference in the amplitudes after phase shift and dynamic time warping. If the EARTH magnitude error, ε_{mag}, is equal to or greater than the maximum allowable magnitude error threshold, ε_M^*, then the EARTH magnitude score is “0”. In between, the EEARTH magnitude score is calculated by regression method.

$$E_M=\begin{cases}1 & \text{if} \quad \varepsilon_{mag}=0\\ \left(\dfrac{\varepsilon_M^*-\varepsilon_{mag}}{\varepsilon_M^*}\right)^{k_M} & k_M\in\{1,2,3\}\\ 0 & \text{if} \quad \varepsilon_{mag}\geq\varepsilon_M^*\end{cases} \tag{28}$$

6.3 EARTH slope score

The topological error is a measure of discrepancy in topology (slope) of the two time histories. The topology of a time history is defined by the slope at each point. In order to ensure that the effect of global time shift is minimized, the slope is calculated from the time-shifted histories T^{ts} and C^{ts}. Thus, by taking the derivative at each point, the derivative time-shifted histories, represented by T^{ts+d} and C^{ts+d}, are obtained. Dynamic time warping is performed on T^{ts+d} and C^{ts+d}, which results in the truncated and warped test slope curve, T^{ts+d+w}, and the shifted, truncated, and warped CAE slope curve, C^{ts+d+w}. These two curves are then used to calculate the EARTH slope error, ε_{slope}, by Formula (29).

$$\varepsilon_{slope}=\frac{\left\|C^{ts+d+w}-T^{ts+d+w}\right\|_1}{\left\|T^{ts+d+w}\right\|_1} \tag{29}$$

Formula (30) is used to calculate the EARTH slope score, E_S, where ε_S^* is the maximum allowable slope error, and k_S defines the order of the regression. The best EARTH slope score is “1”, which means there is no difference between the two slope curves. If the slope error, ε_{slope}, is equal to or greater than the maximum allowable slope error, ε_S^*, then the EARTH slope score is "0". In between, the EARTH slope score is calculated by regression method.

$$E_S = \begin{cases} 1 & \text{if} \quad \varepsilon_{slope} = 0 \\ \left(\dfrac{\varepsilon_S^* - \varepsilon_{slope}}{\varepsilon_S^*} \right)^{k_S} & \\ 0 & \text{if} \quad \varepsilon_{slope} \geq \varepsilon_S^* \end{cases} \qquad k_S \in \{1,2,3\} \tag{30}$$

6.4 Overall EARTH score

The above three EARTH scores are combined into one EARTH score by using weighting factors shown in Formulae (31) and (32).

$$E_E = w_P \cdot E_P + w_M \cdot E_M + w_S \cdot E_S \tag{31}$$

$$w_P + w_M + w_S = 1 \tag{32}$$

The goal is to translate the initial three EARTH errors into a standardized score between "0" and "1". Due to the similarity with the cross-correlation rating in the CORA metric, the consistent weighting factors with the CORA cross-correlation rating are used. In addition, the parameters of the EARTH metric, such as thresholds for phase, magnitude, and topological errors, are defined by matching the EARTH rating with the SME's knowledge using a validation database and optimization technique.[28]

6.5 Step-by-step procedure

The following step-by-step process shall be followed to calculate the EARTH rating:

1) Pre-process both signals according to Clause 10 (T and C).

2) Calculate the phase error in terms of time steps, n_ε, by maximizing cross correlation.

3) Calculate the phase score, E_P.

4) Calculate the shifted and truncated time history curves, T^{ts} and C^{ts}.

5) Calculate the slope curves of the shifted and truncated time history curves, T^{ts+d} and C^{ts+d}.

6) Perform dynamic time warping to the shifted and truncated time history curves to generate the shifted, truncated, warped time history curves, T^{ts+w} and C^{ts+w}.

7) Calculate the magnitude error, ε_{mag}, between T^{ts+w} and C^{ts+w}.

8) Calculate the magnitude score, E_M.

9) Perform dynamic time warping to the slope curves to generate the shifted, truncated, warped slope time history curves, T^{ts+d+w} and C^{ts+d+w}.

10) Calculate the slope error, ε_{slope}, between T^{ts+d+w} and C^{ts+d+w}.

11) Calculate the slope score, E_S.

12) Calculate the overall EARTH rating, E_E.

7 Model reliability metric

A model reliability-based validation metric was developed for dynamic system applications.[14] Figure 5 shows the illustration of this metric. The difference between CAE and test curves is taken as the validation feature [see Formula (33)]. The threshold factor, *b*, is defined by the SME's experience; the lower and upper bounds of the threshold interval, $\left[\varepsilon_L, \varepsilon_U\right]$, are defined as the product of the threshold factor, *b*, and the absolute maximum amplitude, T_{norm}, of the reference signal, *T* [see Formulae (34), (35), and (36)]. A simple validation metric $r = P(\varepsilon_{\Phi}^{L} < \Phi < \varepsilon_{\Phi}^{U})$ is defined to indicate the model reliability, which represents the probability that the observed difference, $\Phi(t)$, is within a small interval of $[\varepsilon_{\Phi}^{L}, \varepsilon_{\Phi}^{U}]$. If the adequacy or confidence requirement, $r > a$, is met, where a is a predefined reliability target, the model prediction is accepted. Since this difference time-history curve has much better normality than those of the test and CAE curves, a normal distribution of Φ can then be assumed and the model reliability metric can be simply calculated by Formula (37).

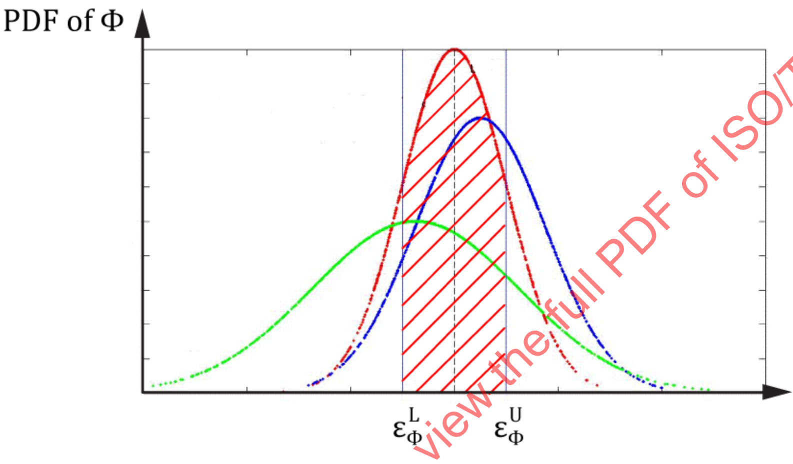


Figure 5 — Illustration of model reliability metric

$$\Phi(t) = C(t) - T(t) \tag{33}$$

$$T_{norm} = \max\left\{\left|\min(T)\right|, \left|\max(T)\right|\right\} \tag{34}$$

$$\varepsilon_{\Phi}^{L} = -b \cdot T_{norm} \tag{35}$$

$$\varepsilon_{\Phi}^{U} = b \cdot T_{norm} \tag{36}$$

$$r = P(\Phi < \varepsilon_{\Phi}^{U}) - P(\Phi < \varepsilon_{\Phi}^{L}) \tag{37}$$

There are only two adjusting parameters: threshold factor, b, and reliability target, a, and both have clear physical meanings. The model reliability metric is one of the simplest metrics for dynamic system applications, and it is easy to understand and interpret.

8 Bayesian confidence metric

A Bayesian confidence-based validation metric was developed for dynamic system applications.[13] Similar to the model reliability metric, the difference curve, $\Phi(t)$, between the test and CAE curves are selected as the validation feature. Assume $\Phi \sim N(\mu_\Phi, \Sigma_\Phi)$ and prior density function $f(\delta) \sim N(\rho, \Lambda)$, where $\Phi(t) = C(t) - T(t)$, $\rho = 0$ and $\Lambda = \Sigma_\Phi$, if there is no prior information available. The interval-based Bayesian hypotheses are represented as: $H_0 : |\Phi| \le \varepsilon_\Phi$ versus $H_1 : \Phi > |\varepsilon_\Phi|$, where ε_Φ is a predefined threshold vector. Using Bayes' theorem and assumptions given in [11] and [15], the Bayes factor, B_{iM}, for the multivariate case is equivalent to the volume ratio of the posterior density of testing data under null and alternative hypotheses [see Formula (38)].

$$B_{iM} = \frac{P(\Phi \mid H_0)}{P(\Phi \mid H_1)} = \frac{\int_{-\varepsilon_\Phi}^{\varepsilon_\Phi} f(\delta \mid \Phi) d\delta}{\int_{-\infty}^{-\varepsilon_\Phi} f(\delta \mid \Phi) d\delta + \int_{\varepsilon_\Phi}^{\infty} f(\delta \mid \Phi) d\delta} = \frac{A \cdot K}{A \cdot (1 - K)} \tag{38}$$

where A is a constant vector, and the multivariable integral of K can be expressed in normal distribution. The Bayesian measure of evidence that the computer model is valid may be quantified by the posterior probability of the null hypothesis $P(H_0 \mid \Phi)$. Using the Bayes' theorem, the confidence in the model based on the validation data can be obtained as Formula (39).

$$\kappa = P(H_0 \mid \Phi) = \frac{B_{iM} \cdot \pi_0}{1 + (B_{iM} - 1) \cdot \pi_0} \tag{39}$$

where κ is a measure of confidence in the range of $[0\%, 100\%]$. Obviously, $B_{iM} \to 0$ indicates 0 % confidence in accepting the model, and $B_{iM} \to \infty$ indicates 100 % confidence.

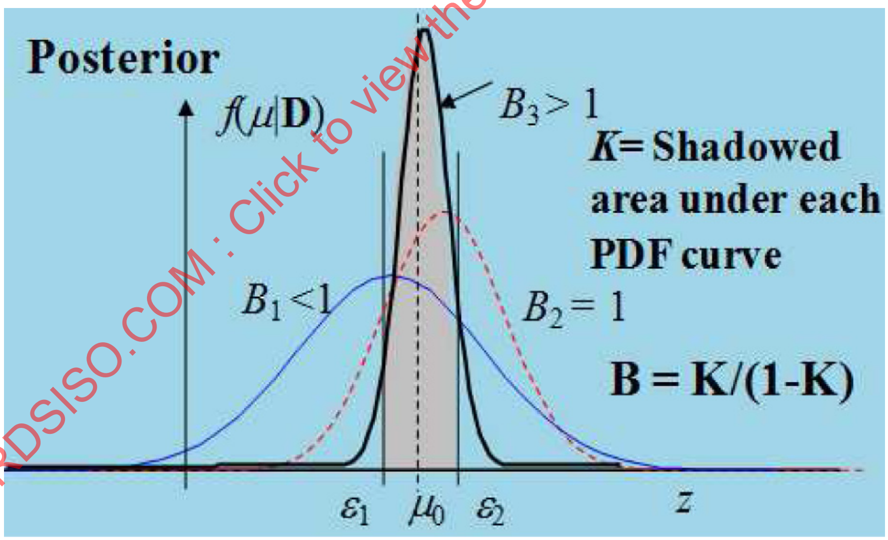


Figure 6 — Illustration of Bayesian confidence metric

Note that expert's opinion of the model accuracy may be incorporated in the confidence quantification in Formula (40) in terms of prior π_0. If prior knowledge of each hypothesis (model accuracy) before testing is unavailable, $\pi_0 = 0.5$ is assumed. Thus, Formula (40) becomes:

$$\kappa = \frac{B_{iM}}{B_{iM} + 1} = K \tag{40}$$

Formula (40) is used in this Technical Report to quantify the model confidence in the absence of expert's opinion.

9 ISO metric

The objective of this Technical Report is to combine different types of algorithms to obtain reliable and robust assessments of the correlation of two signals. The calculated scores must provide an assessment for the degree of correlation of two signals. Two most promising metrics are identified by this working group, and they are CORA corridor and EARTH. Further sensitivity and robustness studies are conducted (e.g. see Annex A, Annex B, and Annex C) to identify potential issues and limitations, which lead to the improvement of CORA corridor metric and the development of the enhanced EARTH (EEARTH) metric. A combined metric based on the improved CORA corridor method and EEARTH is then proposed for an ISO standard which has been fully validated using responses from multiple vehicle passive safety applications. All details are described in the following subsections.

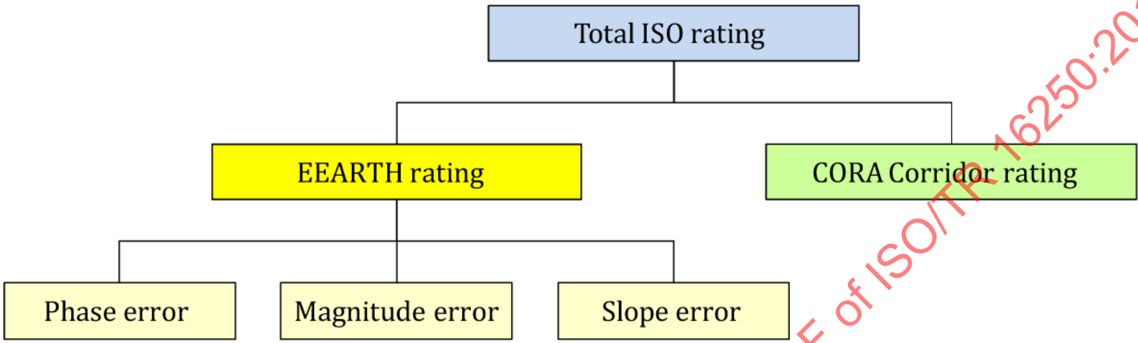


Figure 7 — ISO metric structure

Figure 7 shows the structure of the ISO metric. While the corridor method calculates the deviation between the curves with the help of automatically generated corridors, the EEARTH method analyses specific curve characteristics such as phase shift, magnitude, and shape. Hence, the ISO metric takes the advantages of the two best available algorithms.

9.1 CORA corridor method

CORA corridor rating, Z, is mainly controlled by the width of the corridors and the regression of the rating between the inner and outer corridors. As described in Clause 5, the philosophy of this metric is to use a narrow inner corridor and a wide outer corridor combined with a quadratic decline of the rating. Therefore, the number of "1" ratings is limited to good correlations only and improves the possibilities to distinguish between poor and mean correlations. Based on a sensitivity study of CORA,[17] fixed width corridors are employed and the most appropriate metric parameters are identified as shown in Table 1. All formulae of the CORA corridor rating are the same as in 5.1 ($Z = Z_1$).

Table 1 — Fixed parameters of the CORA corridor method

Parameter	Value	Description
a_0	0,05	Relative half width of the inner corridor
b_0	0,50	Relative half width of the outer corridor
k_{Z1}	2	Transition between ratings of "1" and "0" (progression)

9.2 EEARTH method

An identified issue of the EARTH metric is that when the sample points are reduced, the original EARTH magnitude and slope scores change significantly. Figure 8 shows the same set of CAE and test curves with different sampling rates, while Table 2 shows significant changes of the corresponding EARTH scores. Enhancement to the initial EARTH metric is then deemed necessary.

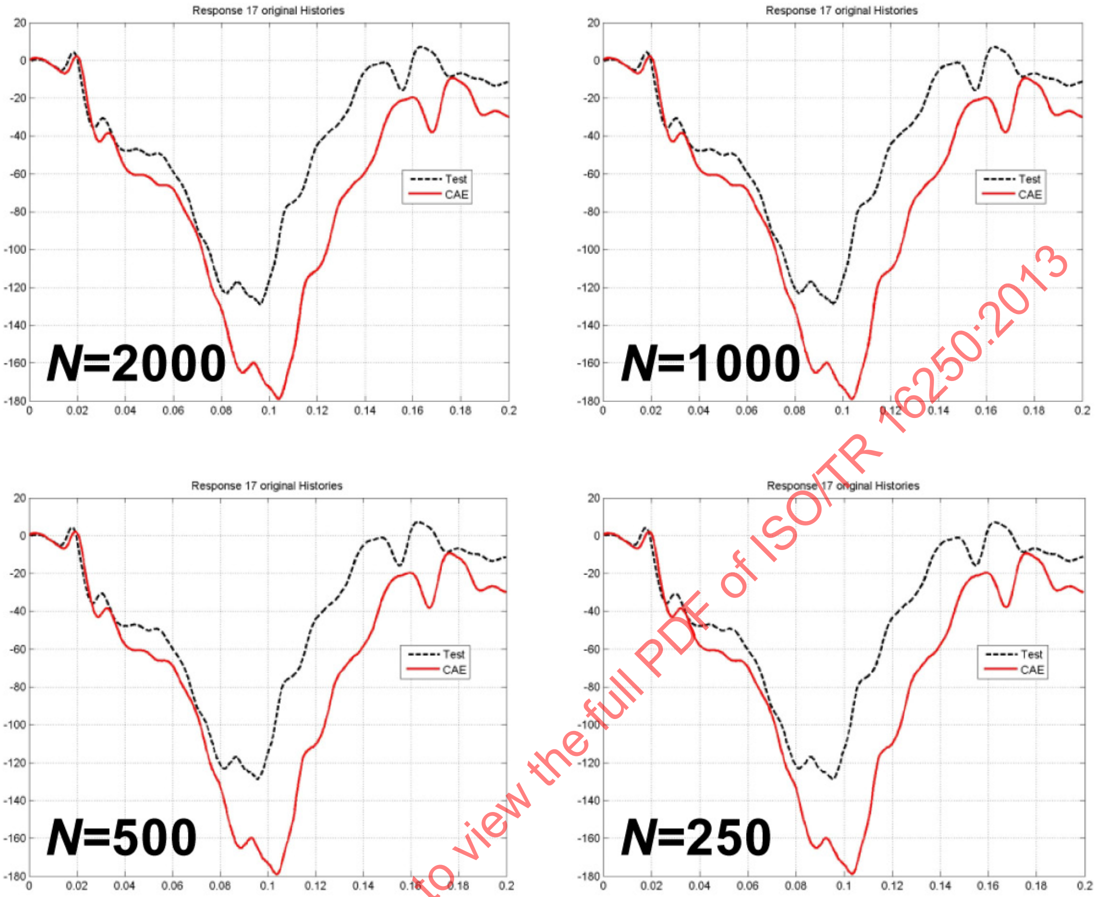


Figure 8 — A set of test and CAE curves with different sample points

Table 2 — Sensitivity study results of the EARTH scores

Sample points	Phase score	Rel. error (phase)	Magnitude score	Rel. error (mag.)	Slope score	Rel. error (slope)
2 000	0,755	0,0 %	0,455	0,0 %	0,591	0,0 %
1 000	0,755	0,0 %	0,342	24,8 %	0,618	−4,6 %
500	0,750	0,7 %	0,339	25,5 %	0,642	−8,6 %
250	0,740	2,0 %	0,290	36,3 %	0,703	−19,0 %

9.2.1 EEARTH phase rating

The EEARTH phase rating, E_P, stays the same as the initial EARTH phase score, E_P (see 6.1) because no significant issue is found from the sensitivity study as shown in Table 2.

9.2.2 EEARTH magnitude rating

The initial EARTH magnitude scores change significantly when the number of the sample points is reduced from 2 000 to 250, as shown in Table 2. Further investigation identified that the local cost function of the dynamic time warping shown in Formula (26), involving both the distance and the slope, is the main cause of this significant change in the score magnitude. Using slope in local cost function is not common, and the variability of the slopes is in general less robust. Therefore, the EEARTH calculation uses Formula (41) instead of Formula (26).

$$d(i,j)=\left(C^{ts}(i)-T^{ts}(j)\right)^2 \tag{41}$$

Figure 9 shows the same set of curves (C^{ts+w} and T^{ts+w}) as shown in Figure 8 but with EEARTH calculations, and they are now similar. Table 3 shows that the EEARTH magnitude ratings are stable when the number of the sample points is reduced.

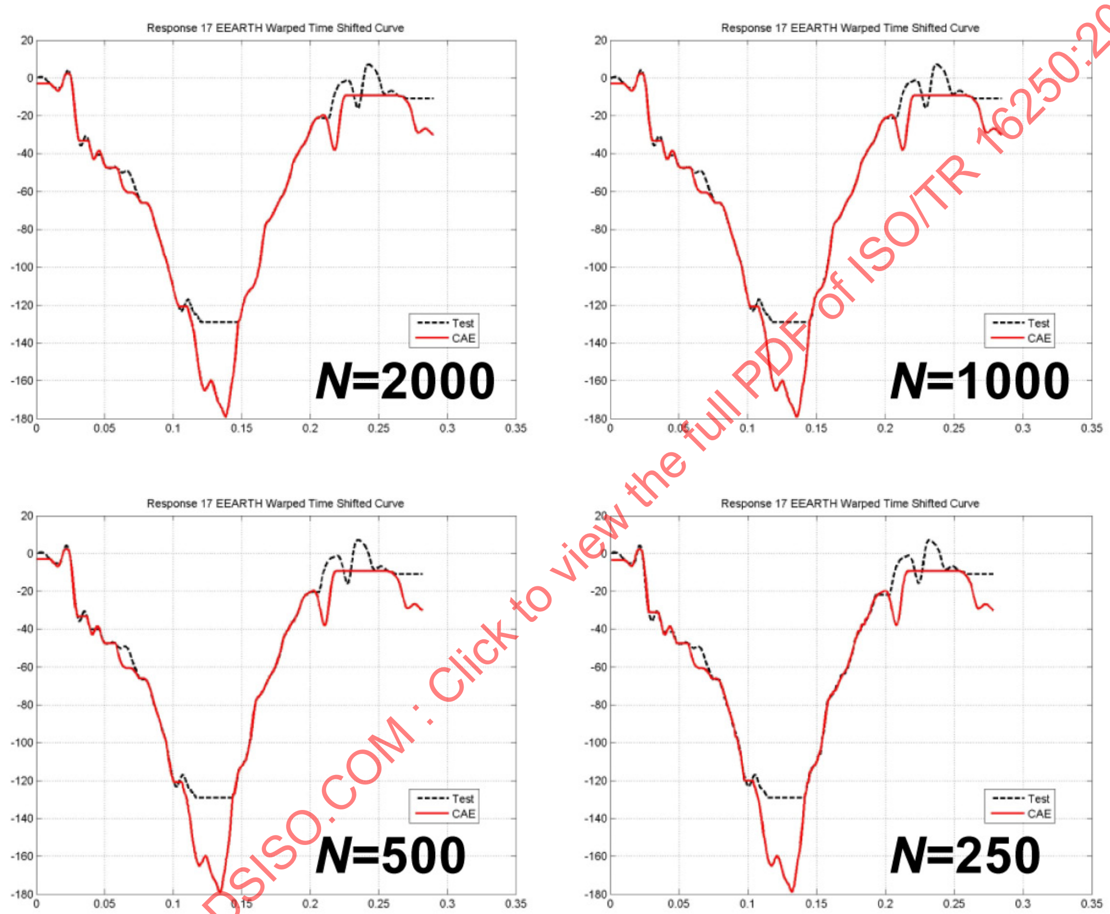


Figure 9 — A set of the shifted, truncated, and warped test and CAE curves with different sample points by EEARTH

9.2.3 EEARTH slope rating

The EARTH slope scores are also affected by the change of the sampling rate, as shown in Table 2. This is due to the implementation of the slope curve calculation and using dynamic time warping on these slope curves before calculating the EARTH slope error. In the initial EARTH metric, a polynomial fitting is first employed to smooth the time-shifted histories T^{ts} and C^{ts}, and then the derivative curves (C^{ts+d} and T^{ts+d}) are calculated from the polynomial fitting curves. This polynomial fitting is an approximation method, so it can introduce variation into the EARTH metric. In addition, dynamic time warping is performed on the resulting slope curves before calculating the slope error. DTW used here can reduce the slope differences, and the EARTH slope score may not be able to differentiate between the good or poor correlations. In the EEARTH metric, the time-shifted histories T^{ts} and C^{ts} are first divided into multiple intervals with the fixed length of 10 data points (1 ms at sampling rate of 10 kHz). If the total number of data points of the whole signal is not a multiple of 10, then the last interval shall be calculated with the remaining data points. Next, average slope is calculated in each interval to generate the slope curves (C^{ts+d} and T^{ts+d}). Therefore, the slope curves are used to calculate the slope error directly without performing dynamic time warping. The other calculations remain the same as in 6.3. Figure 10 shows the same set of C^{ts+d} and T^{ts+d} curves with different sample points using the EEARTH calculations. Table 3 also shows that the EEARTH slope ratings are not significantly affected by the change in the sampling rates.

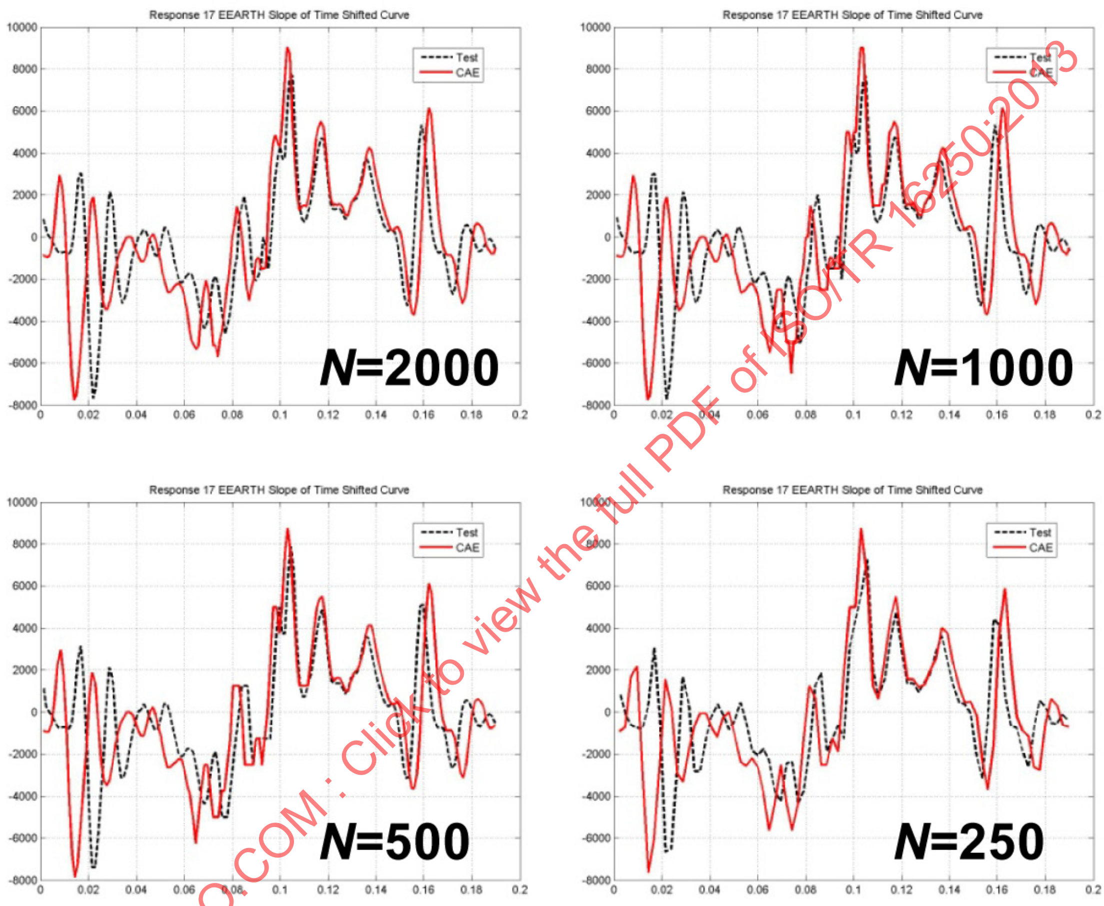


Figure 10 — A set of the shifted, truncated test and CAE slope curves with different sample points by the EEARTH

Table 3 — Sensitivity study results of the EEARTH scores

Sample points	Phase score	Rel. error (phase)	Magnitude score	Rel. error (mag.)	Slope score	Rel. error (slope)
2 000	0,755	0,0 %	0,727	0,0 %	0,511	0,0 %
1 000	0,755	0,0 %	0,716	1,5 %	0,502	1,8 %
500	0,750	0,7 %	0,708	2,6 %	0,523	–2,3 %
250	0,740	2,0 %	0,695	4,4 %	0,524	–2,5 %

9.2.4 EEARTH rating

Figure 11 shows the flowchart of the EEARTH metric. The calculation of the magnitude and slope error is simplified compared to the EARTH metric.

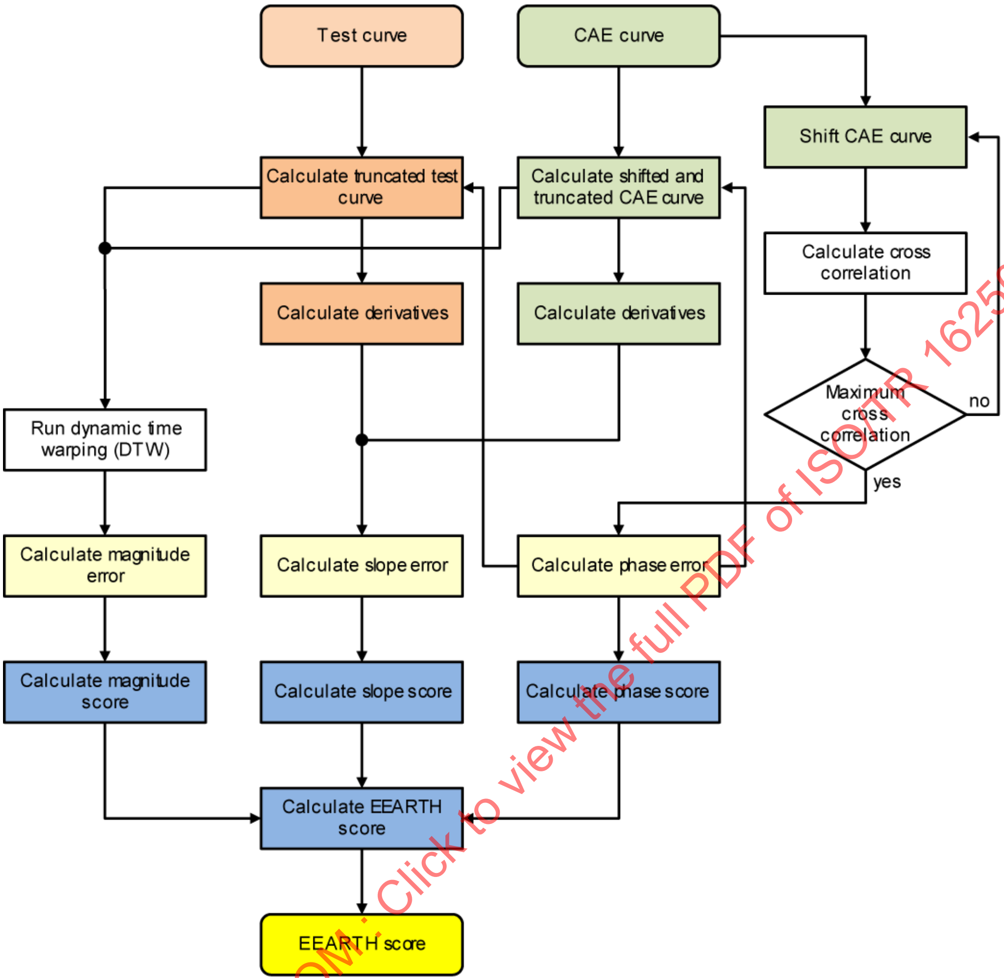


Figure 11 — Workflow of the EEARTH metric

The three EEARTH sub-scores are combined into one EEARTH score using weighting factors as described in Formula (42) and in Table 4.

$$E = w_P \cdot E_P + w_M \cdot E_M + w_S \cdot E_S \tag{42}$$

Table 4 — Weighting factors of the EEARTH sub-metrics

Parameter	Value	Description
w_P	$\frac{1}{3}$	Weighting factor of the EEARTH phase score
w_M	$\frac{1}{3}$	Weighting factor of the EEARTH magnitude score
w_S	$\frac{1}{3}$	Weighting factor of the EEARTH slope score

All predefined parameters of EEARTH are shown in Table 5. They are required to calculate the sub-scores of EEARTH.

Table 5 — Parameters of EEARTH

Parameter	Value	Description
k_P	1	Exponent factor for calculating the EEARTH phase score
k_M	1	Exponent factor for calculating the EEARTH magnitude
k_S	1	Exponent factor for calculating the EEARTH slope score
ε_P^*	0,2	Maximum allowable percentage of time shift
ε_M^*	0,5	Maximum allowable magnitude error
ε_S^*	2,0	Maximum allowable slope error

9.3 Calculation of the overall ISO rating

The merged ratings of both sub-metrics (CORA corridor and EEARTH) will provide a single number for the correlation of the analysed signals which represent the final overall objective rating. The overall objective rating, R, is calculated by combining the sub-ratings of the corridor method (Z) and the EEARTH (E). Two weighting factors (w_Z and w_E) are defining the influence of each sub-metrics on the final overall rating [see Formulae (43) and (44)]. The corresponding weighting factors are shown in Table 6.

$$R = w_Z \cdot Z + w_E \cdot E \tag{43}$$

$$w_Z + w_E - 1 \tag{44}$$

Table 6 — Weighting factors of both rating methods

Parameter	Value	Description
w_Z	0,4	Weighting factor of the CORA corridor method
w_E	0,6	Weighting factor of EEARTH

9.4 Meaning of the objective rating score

The objective rating score, *R*, ranges from "0" to "1" The higher the score, the better the correlation of the two signals. This single-rating number can be transferred to a grade that represents the goodness of the correlation by using a sliding scale (see Table 7).

Table 7 — Sliding scale of the overvall ISO rating

Rank *r*	Grade	Rating *R*	Description
1	Excellent	R >0,94	Almost perfect characteristics of the reference signal is captured
2	Good	0,80< R ≤0,94	Reasonably good characteristics of the reference signal is captured , but there are noticeable differences between signals.
3	Fair	0,58< R ≤0,80	Basic characteristics of the reference signal is captured, but there are significant differences between signals.
4	Poor	R ≤0,58	Almost no correlation between signals.

The lower and upper bounds of the different scales are calculated by using Formulae (45) and (46), respectively. Every grade is bounded by $[SC_{lower}(r), SC_{upper}(r)]$ except the fourth grade "poor" because there is no lower threshold, $SC_{lower}(r=4)$, defined.

$$SC_{lower}(r)=1-\frac{1}{25}r^2-\frac{1}{50}r \qquad r\in\{1,2,3\} \tag{45}$$

$$SC_{upper}(r)=1-\frac{1}{25}(r-1)^2-\frac{1}{50}(r-1) \qquad r\in\{1,2,3,4\} \tag{46}$$

Note that the thresholds of *R* in each grade are only valid if all the parameters (e.g. weighting factors, regression schemes, sampling rates, etc.) described in previous clauses are not altered. Furthermore, the sliding scale shall only be used for the comparison of two signals and it shall not be applied to the sub-ratings EEARTH and CORA corridor metrics separately.

10 Pre-processing of the data

During the evaluation and validation of the proposed ISO metric, it was concluded that a few basic conditions must be kept in order to obtain correct results. This must be done by the user.

Initially, the signals must be synchronized by physical meanings and by its timing. At each time step of the test signal, a value of the CAE signal is required.

10.1 Sampling rate

The proposed ISO metric was validated with signals of 10 kHz sampling rate. The sub-metrics to evaluate magnitude and slope are especially sensitive to the signal's sampling rate.

10.2 Filtering

The algorithms do not modify the original signals. It should be considered that the calculation of the correlation could be difficult when using noisy signals.

Figure 12 shows an example of the effect of filtering. Signals A and B are derived from the same unfiltered signal and differ only by the applied filter classes. The overall correlation rating of signal B increased by 6% compared to that of signal A due to the application of a higher filter class.

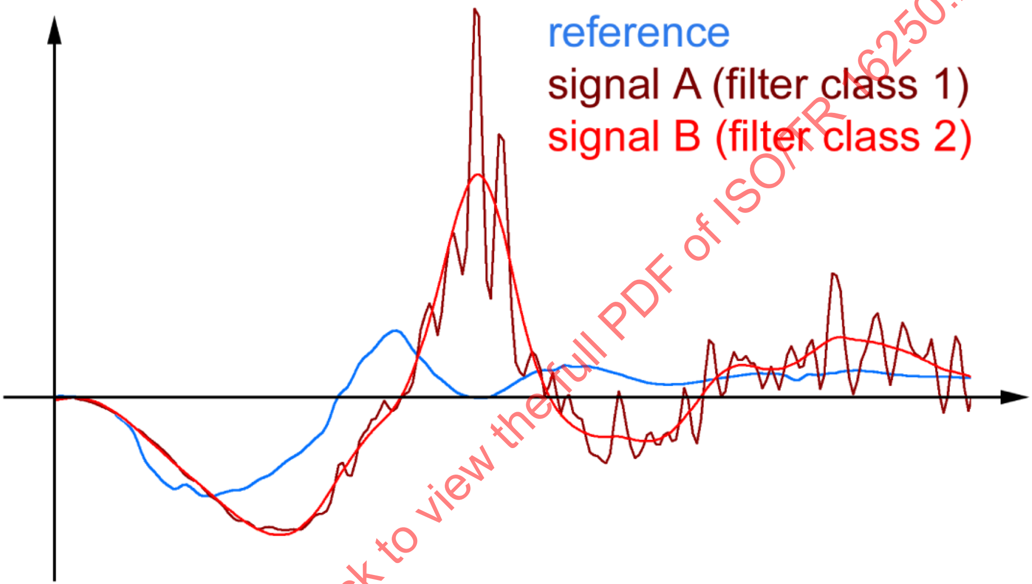


Figure 12 — Differently filtered signals[10]

10.3 Interval of evaluation

The assessment of the correlation should be focused on the relevant parts of the given signals. Typically, crash signals include pre- and post-crash phases that are not of interest and should be excluded from the rating. Therefore, an interval of evaluation shall be defined where the part of the signals are to be assessed. The interval starts at t_{start} and ends at t_{end}. An assessment of using ratings of different sub-intervals of the same pair of signals is not allowed.

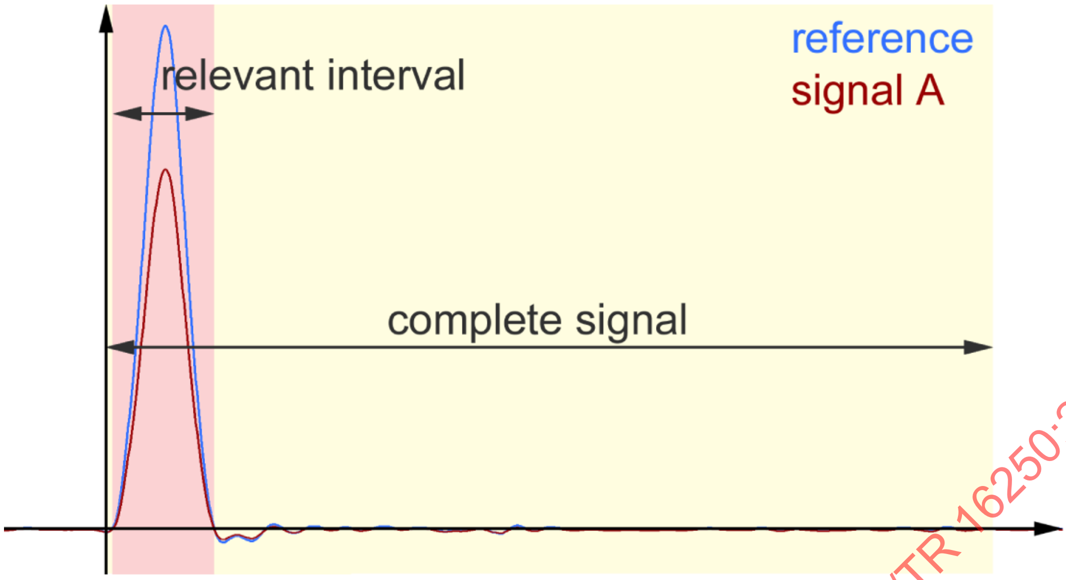


Figure 13 — Different intervals of evaluation[10]

Figure 13 depicts an example of this problem. The correlation rating is increased by 35 % when extending the interval of evaluation from the relevant part to the whole time domain.

The metric requires a minimum length of the interval of evaluation of 10 ms.

11 Limitations

This Technical Report describes a method to apply an objective metric to calculate the goodness of the correlation between two signals. As described previously, the application of such a metric requires some basic conditions. Below are a few known limitations that must be considered when applying those metrics.

11.1 Type of signals

The application of this metric is limited to non-ambiguous signals obtained in all kinds of tests of the passive safety of vehicles and the corresponding numerical simulations (CAE). The most commonly used signals in this field are time-history curves.

11.2 Metrics validation

The metrics are validated with physical loads, time-history signals of different types, and quality (e.g. forces, moments, accelerations, velocities, and displacements).

The algorithms require pre-processing of the signals (see Clause 10). Filtering criterion or method of noisy signals may affect the rating outcome. High-frequency oscillations could lead to misleading results.

11.3 Meaning of the results

As described in this Technical Report, the presented sliding scale (see 9.4) is only valid for the comparison of two signals. Any modification to the parameters, such as weighting factors, sampling rates, etc., requires a revision of the grade's thresholds. Furthermore, the defined scale is only applied to the overall objective rating, *R*, and not to its sub-metrics.

11.4 Multiple responses

This overall objective metric is defined to calculate the level of the goodness of correlation between two signals only. If more than one pair of signals (e.g. whole set of signals from various channels of a test) is considered, the defined thresholds of the sliding scale are no longer valid.

Annex A
(informative)

Child restraint example

The proposed ISO metric is demonstrated with a rear-seat child restraint system with a Hybrid III 3-year-old dummy model. A commercial child seat was used in the test of this study. Figure A.1 and Figure A.2 show the test setup and the CAE model. Sixteen tests were conducted with different configurations, including different settings of seat cushion positions, top tether routing configurations, and input crash pulses. Each test has nine responses recorded at a variety of locations of the dummy (i.e. head, neck, and chest), as shown in Table A.1. Correspondingly, 16 sets of computer outputs were generated from the model. See Reference [33].

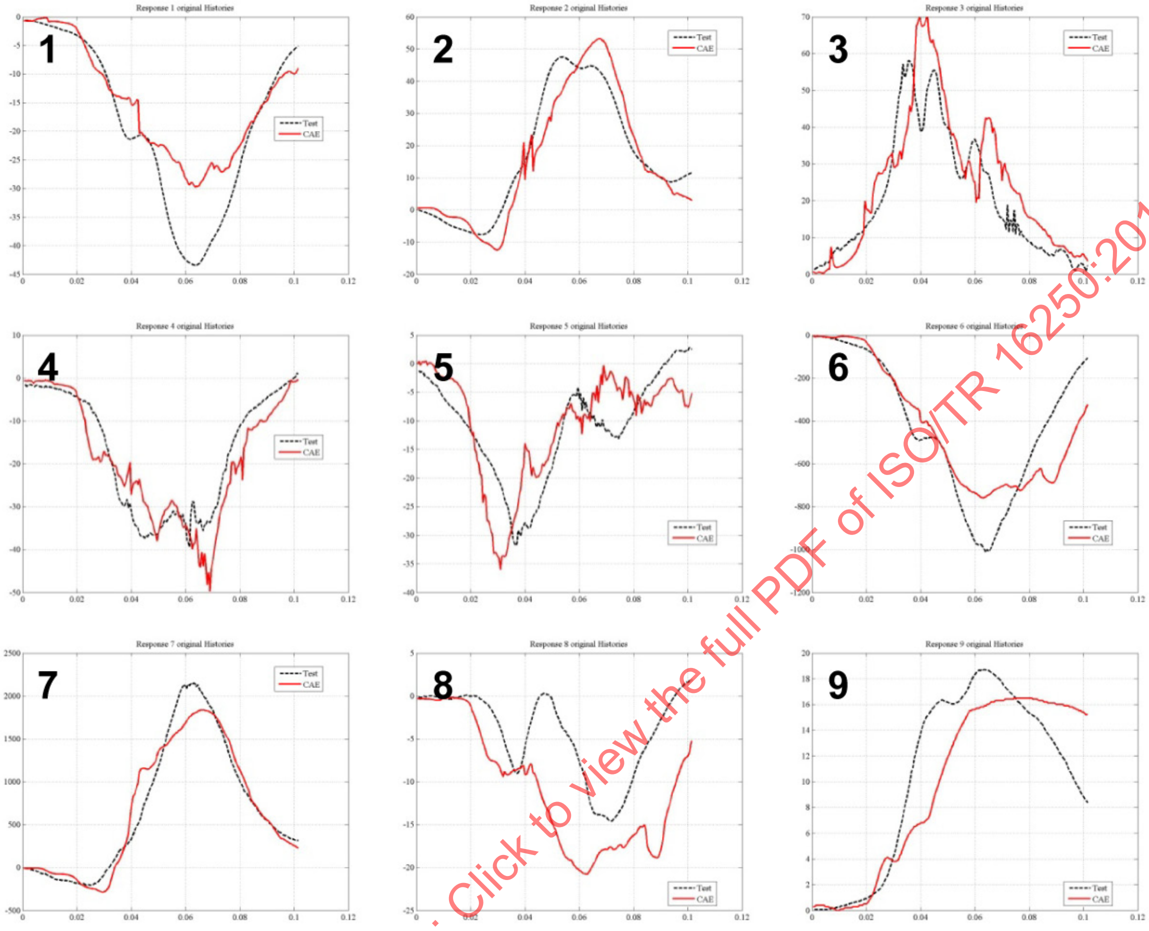
Figure A.1 — Test setup of child restraint example[33]

Figure A.2 — CAE model of child restraint example[33]

Table A.1 — Response variables

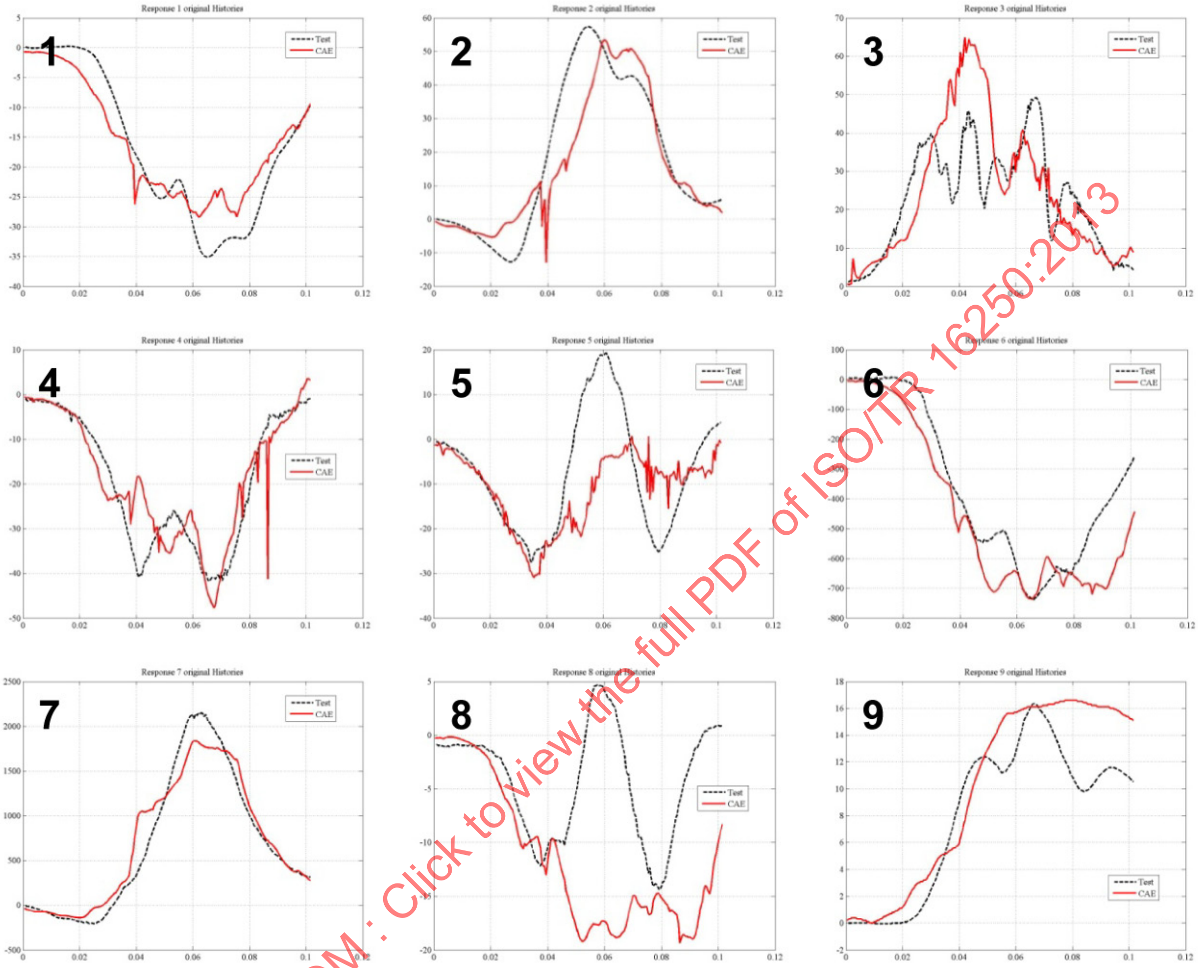
Response	Description
1	Head acceleration at *x*-direction
2	Head acceleration at *z*-direction
3	Pelvis resultant acceleration
4	Chest acceleration at *x*-direction
5	Chest acceleration at *z*-direction
6	Upper neck shear force (F_x)
7	Upper neck tension force (F_z)
8	Upper neck moment (M_y)
9	Chest deflection

A.1 Data set 1



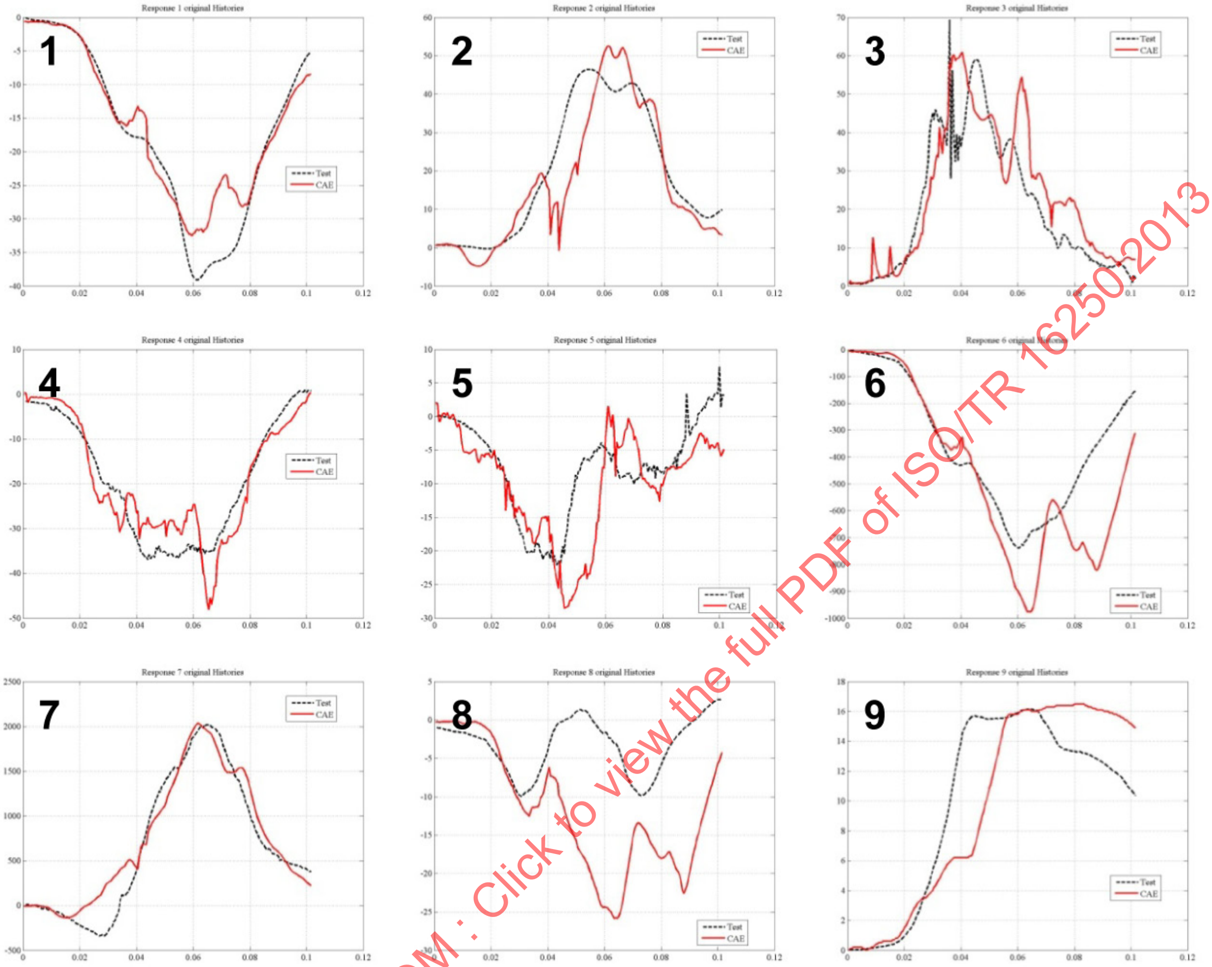
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,761	0,762	0,761	0,926	0,784	0,574
2	0,737	0,748	0,730	0,803	0,880	0,506
3	0,679	0,706	0,662	0,778	0,861	0,345
4	0,700	0,746	0,668	0,877	0,920	0,209
5	0,612	0,596	0,623	0,754	0,752	0,365
6	0,707	0,739	0,686	0,655	0,867	0,537
7	0,864	0,891	0,846	0,975	0,918	0,645
8	0,387	0,318	0,433	0,877	0,000	0,424
9	0,656	0,685	0,637	0,360	0,924	0,628

A.2 Data set 2



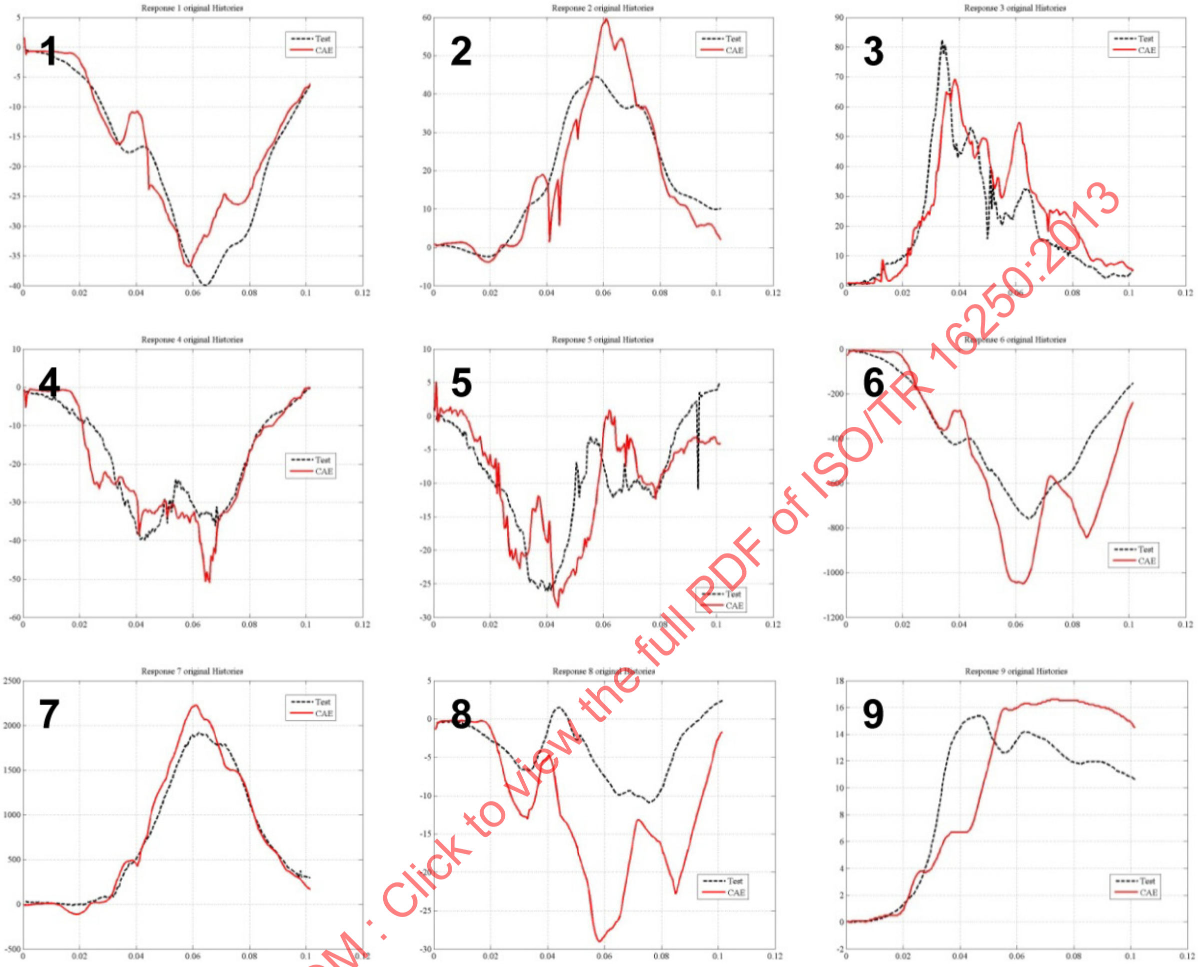
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,762	0,778	0,751	0,778	0,866	0,609
2	0,674	0,726	0,639	0,729	0,859	0,330
3	0,669	0,623	0,700	0,951	0,763	0,386
4	0,717	0,790	0,668	0,901	0,886	0,216
5	0,546	0,543	0,547	0,655	0,553	0,433
6	0,711	0,710	0,712	0,852	0,892	0,392
7	0,860	0,878	0,847	0,975	0,922	0,644
8	0,319	0,426	0,247	0,286	0,000	0,456
9	0,636	0,658	0,621	0,581	0,734	0,546

A.3 Data set 3



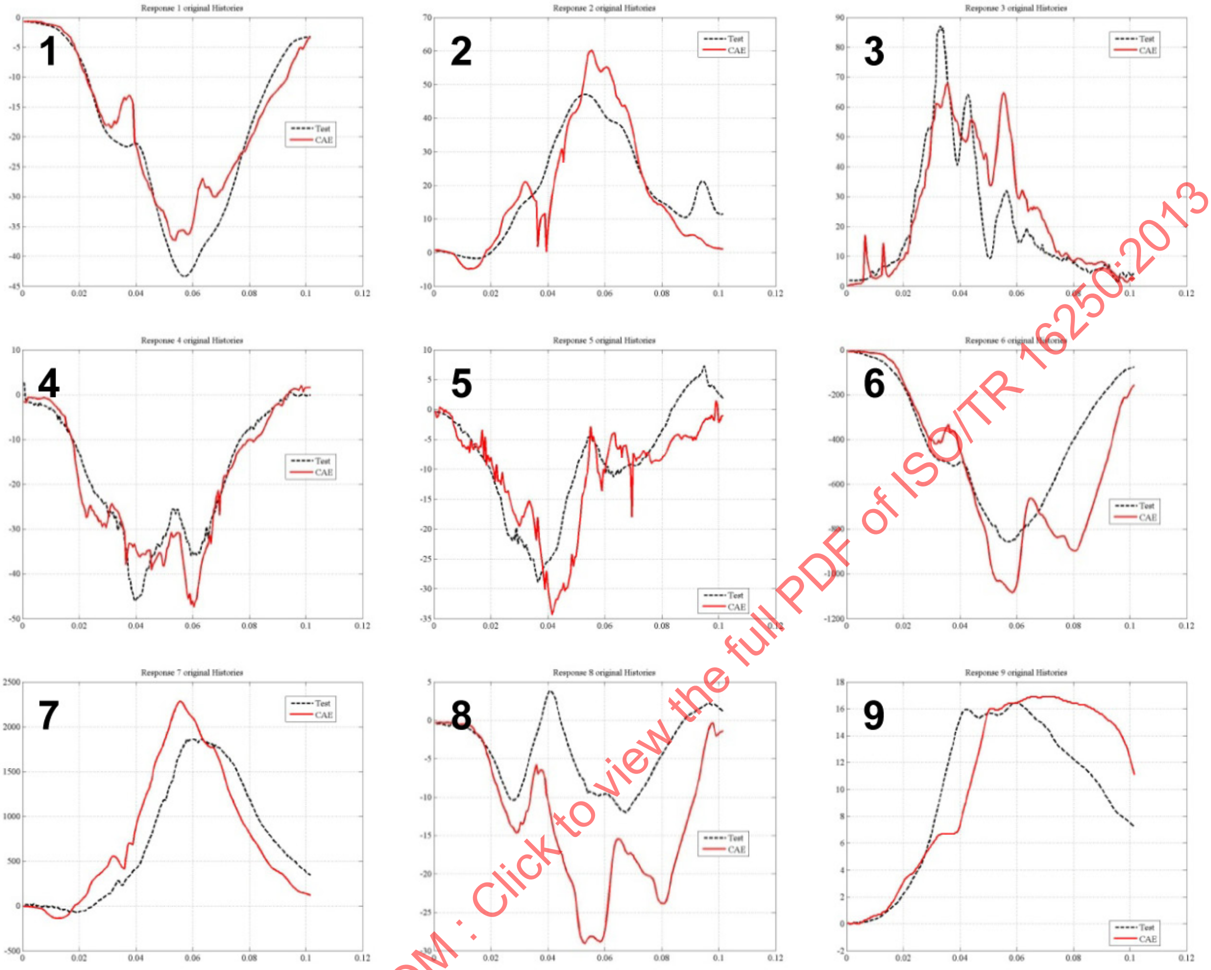
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,851	0,872	0,836	0,951	0,860	0,698
2	0,667	0,745	0,616	0,778	0,865	0,204
3	0,711	0,784	0,662	0,803	0,853	0,331
4	0,672	0,735	0,630	0,901	0,860	0,129
5	0,521	0,574	0,485	0,606	0,750	0,100
6	0,621	0,660	0,594	0,704	0,824	0,254
7	0,831	0,849	0,820	0,975	0,917	0,567
8	0,099	0,237	0,007	0,000	0,000	0,020
9	0,603	0,651	0,571	0,187	0,880	0,645

A.4 Data set 4



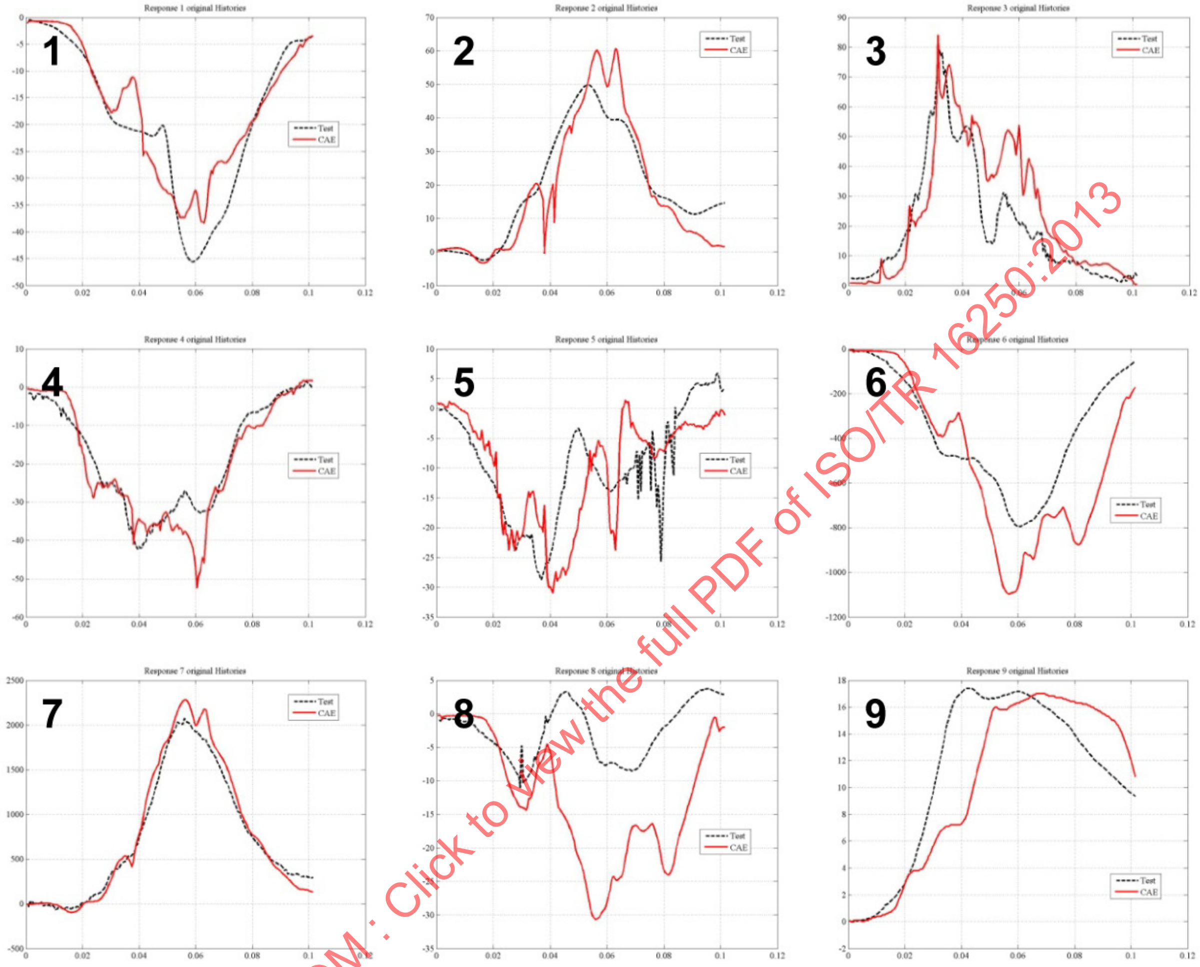
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,809	0,844	0,785	0,828	0,929	0,600
2	0,664	0,757	0,602	0,852	0,820	0,135
3	0,719	0,783	0,677	0,803	0,841	0,388
4	0,753	0,790	0,728	0,926	0,891	0,367
5	0,588	0,545	0,617	0,704	0,776	0,370
6	0,627	0,621	0,632	0,877	0,780	0,238
7	0,868	0,924	0,831	0,901	0,925	0,666
8	0,267	0,230	0,292	0,877	0,000	0,000
9	0,501	0,524	0,486	0,113	0,725	0,619

A.5 Data set 5



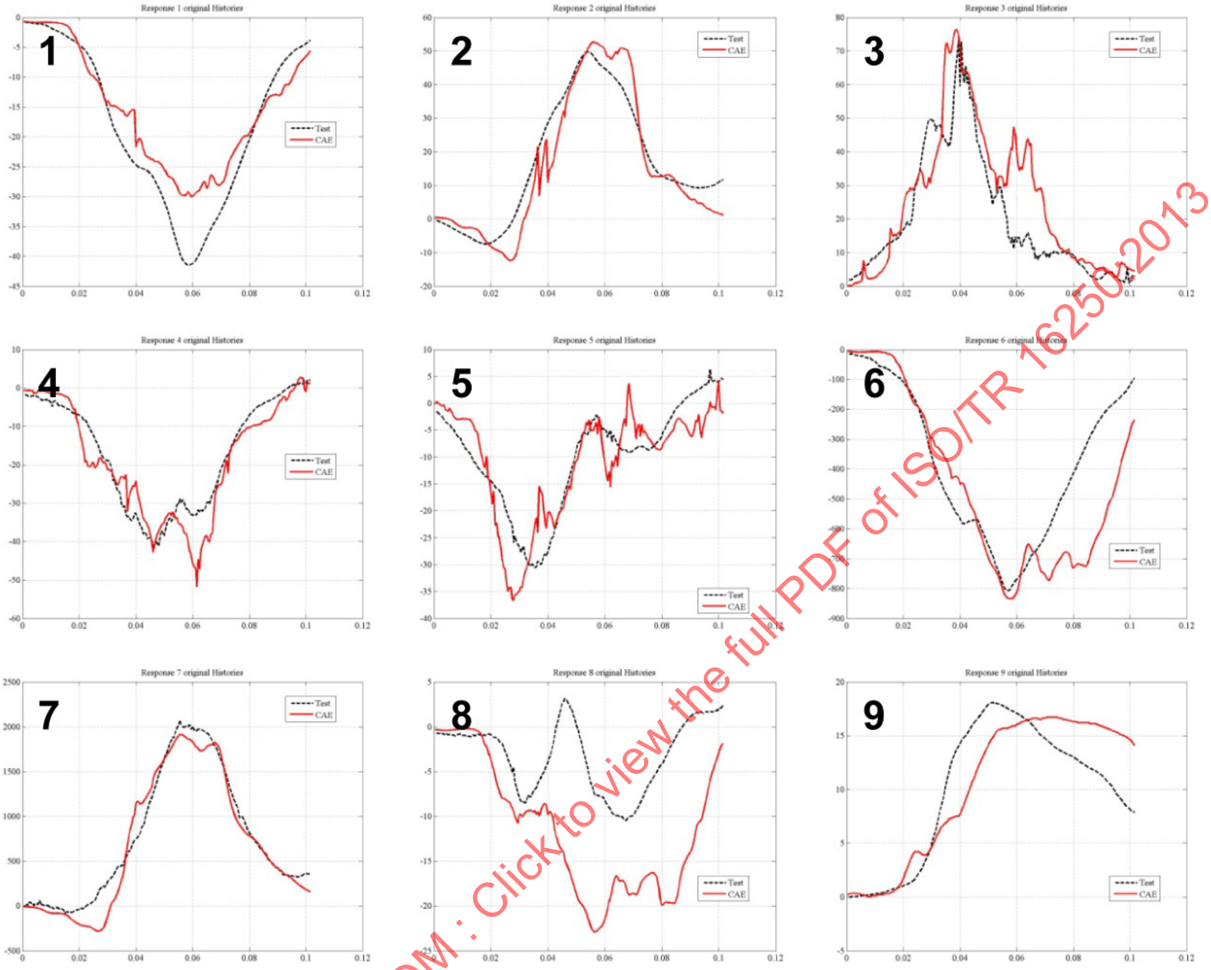
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,852	0,861	0,846	0,951	0,921	0,668
2	0,646	0,699	0,611	0,877	0,729	0,228
3	0,745	0,795	0,712	0,901	0,770	0,464
4	0,796	0,860	0,754	0,951	0,883	0,427
5	0,598	0,612	0,589	0,704	0,814	0,247
6	0,614	0,635	0,599	0,680	0,863	0,255
7	0,678	0,616	0,720	0,655	0,908	0,597
8	0,341	0,244	0,405	0,975	0,000	0,240
9	0,636	0,631	0,639	0,360	0,918	0,639

A.6 Data set 6



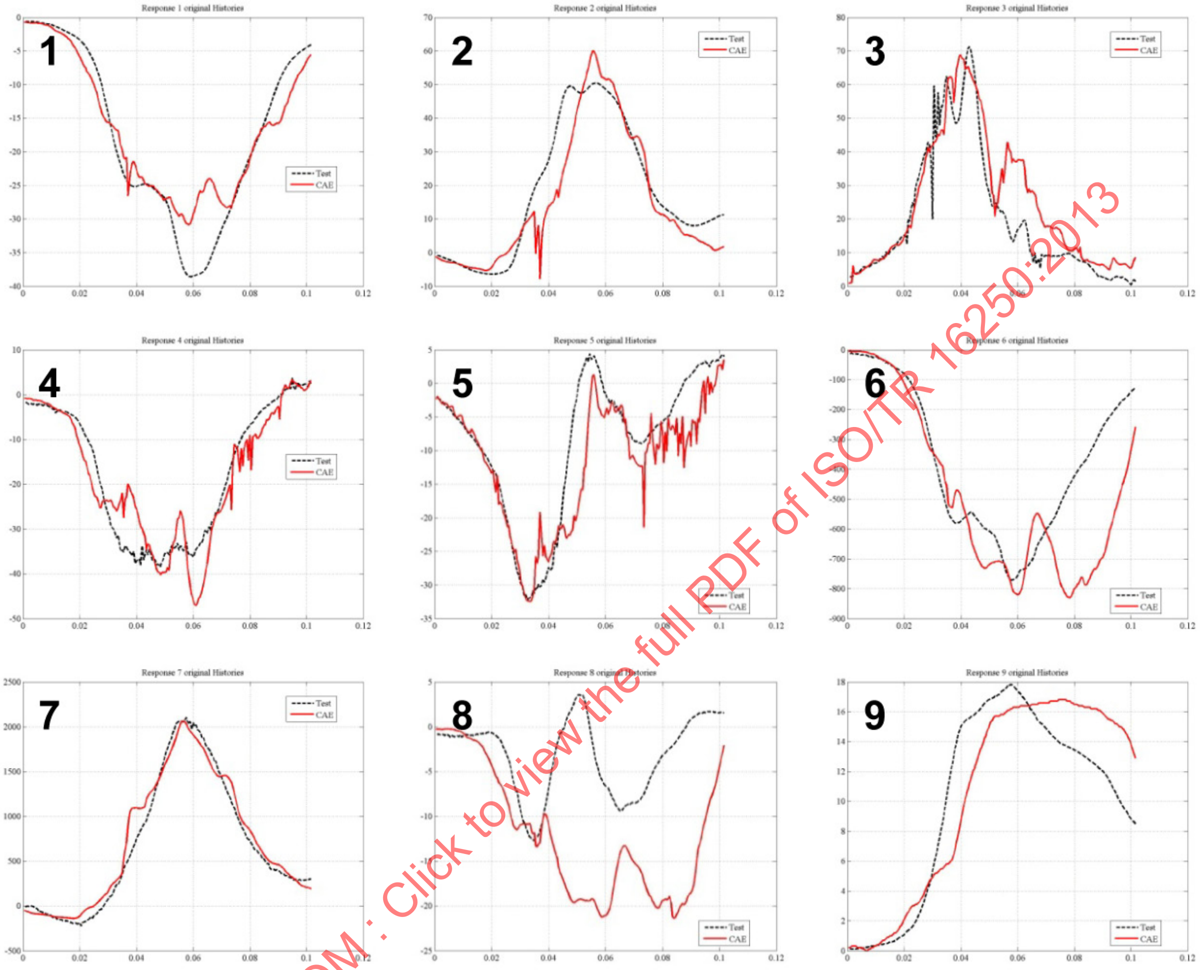
Response	**Overall ISO rating**	**CORA corridor**	**EEARTH**	**EEARTH phase**	**EEARTH magnitude**	**EEARTH slope**
1	0,768	0,814	0,738	0,877	0,881	0,456
2	0,678	0,753	0,628	0,828	0,804	0,252
3	0,661	0,742	0,608	0,828	0,789	0,207
4	0,774	0,833	0,734	0,975	0,871	0,355
5	0,539	0,552	0,530	0,754	0,662	0,175
6	0,521	0,537	0,509	0,581	0,788	0,159
7	0,893	0,947	0,857	0,975	0,934	0,662
8	0,084	0,211	0,000	0,000	0,000	0,000
9	0,643	0,670	0,626	0,261	0,963	0,654

A.7 Data set 7



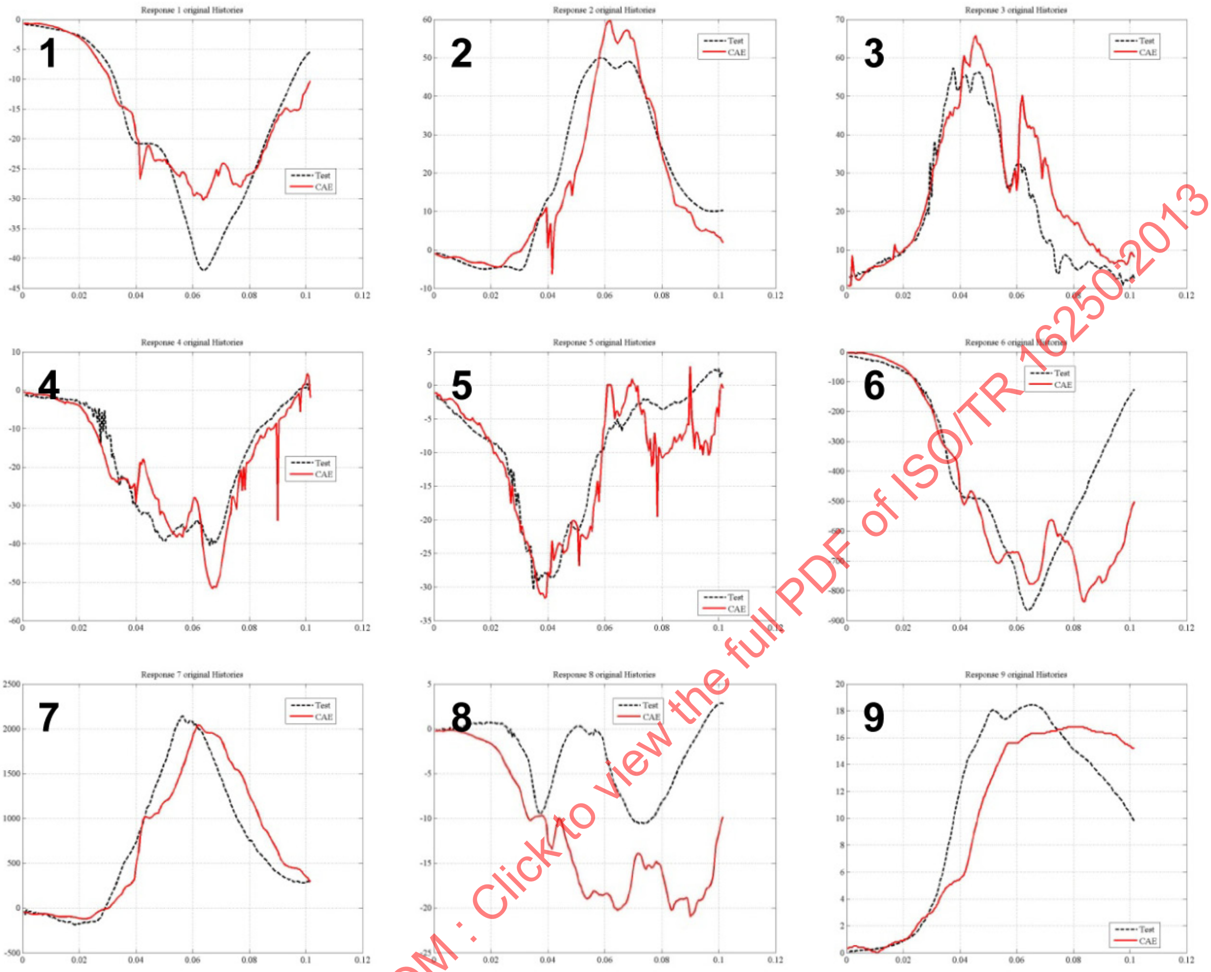
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,792	0,798	0,789	0,901	0,856	0,609
2	0,726	0,779	0,691	0,852	0,869	0,352
3	0,701	0,772	0,654	0,778	0,861	0,323
4	0,695	0,814	0,615	0,926	0,875	0,045
5	0,610	0,657	0,578	0,901	0,790	0,042
6	0,650	0,689	0,624	0,483	0,949	0,441
7	0,840	0,895	0,803	0,951	0,906	0,552
8	0,184	0,222	0,159	0,163	0,000	0,313
9	0,630	0,634	0,627	0,384	0,884	0,613

A.8 Data set 8



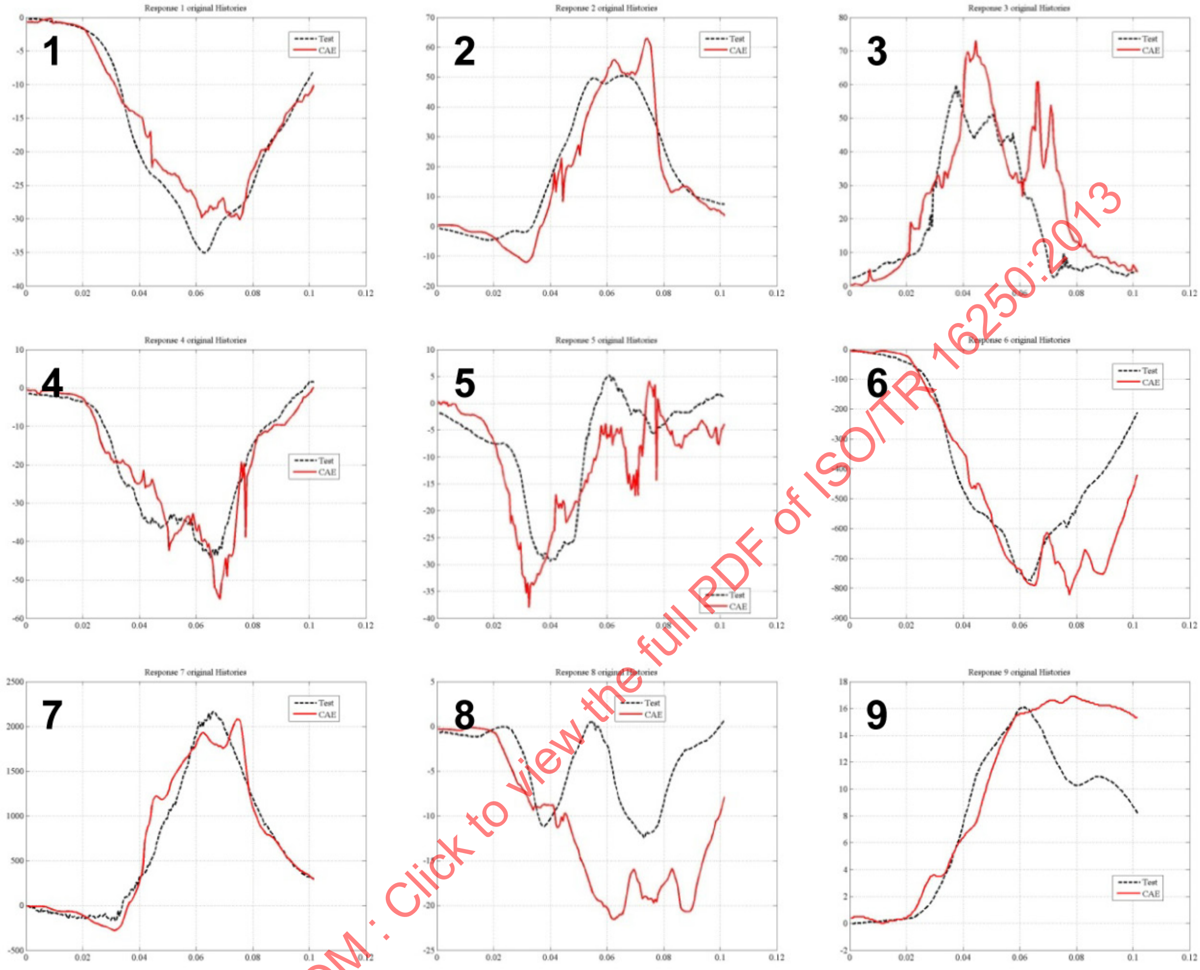
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,812	0,840	0,793	0,951	0,885	0,542
2	0,732	0,782	0,699	0,803	0,862	0,431
3	0,764	0,811	0,732	0,901	0,816	0,479
4	0,722	0,773	0,688	0,926	0,887	0,252
5	0,680	0,766	0,623	0,828	0,848	0,193
6	0,600	0,658	0,562	0,507	0,828	0,350
7	0,891	0,952	0,851	0,951	0,956	0,646
8	0,212	0,275	0,170	0,138	0,000	0,371
9	0,693	0,691	0,694	0,483	0,931	0,668

A.9 Data set 9



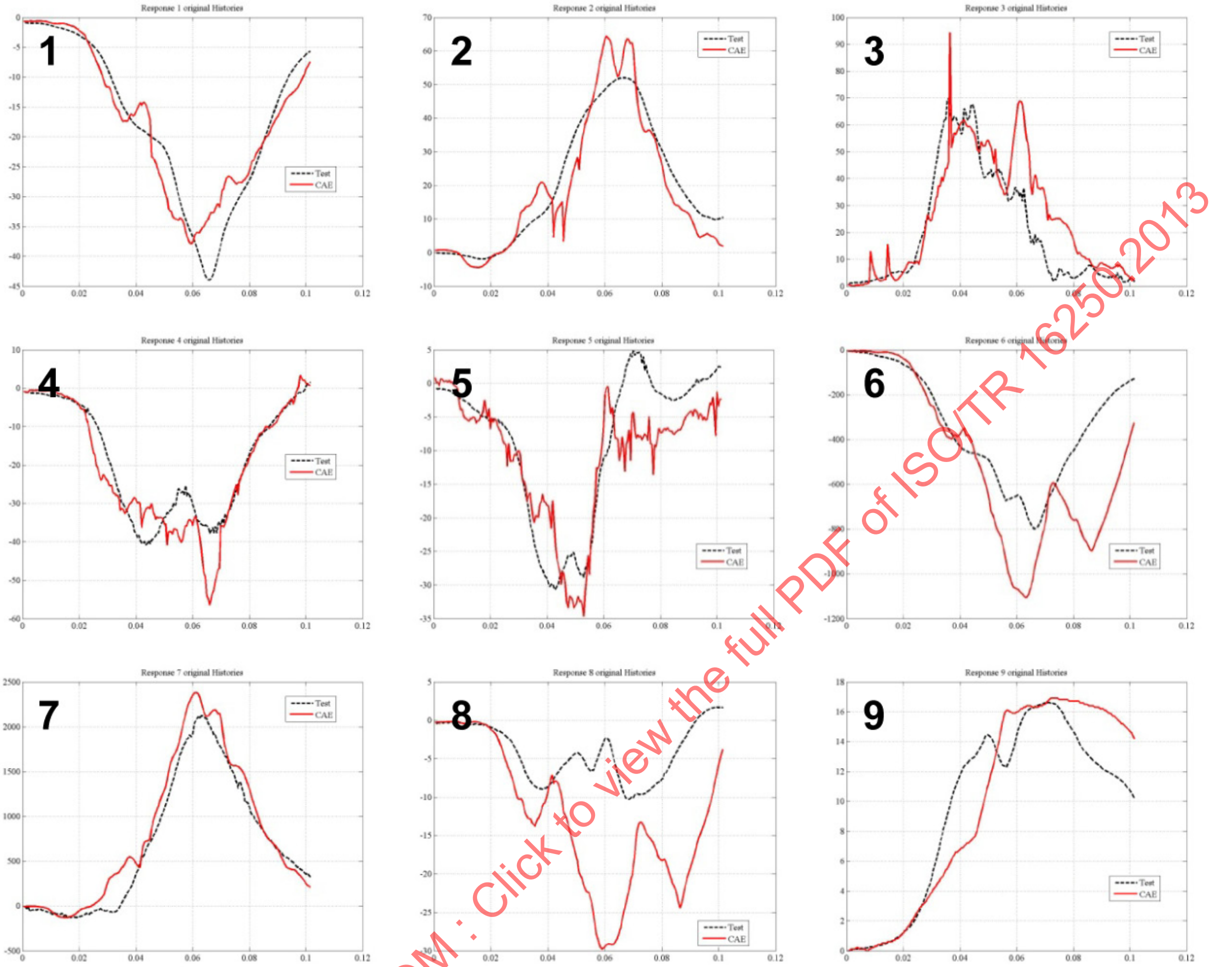
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,807	0,831	0,792	0,951	0,842	0,583
2	0,719	0,773	0,682	0,852	0,860	0,335
3	0,718	0,761	0,689	0,877	0,841	0,349
4	0,707	0,789	0,653	0,926	0,864	0,168
5	0,631	0,741	0,557	0,951	0,721	0,000
6	0,617	0,726	0,544	0,409	0,847	0,377
7	0,783	0,757	0,800	0,704	0,959	0,735
8	0,171	0,210	0,145	0,212	0,000	0,223
9	0,691	0,697	0,686	0,458	0,924	0,677

A.10 Data set 10



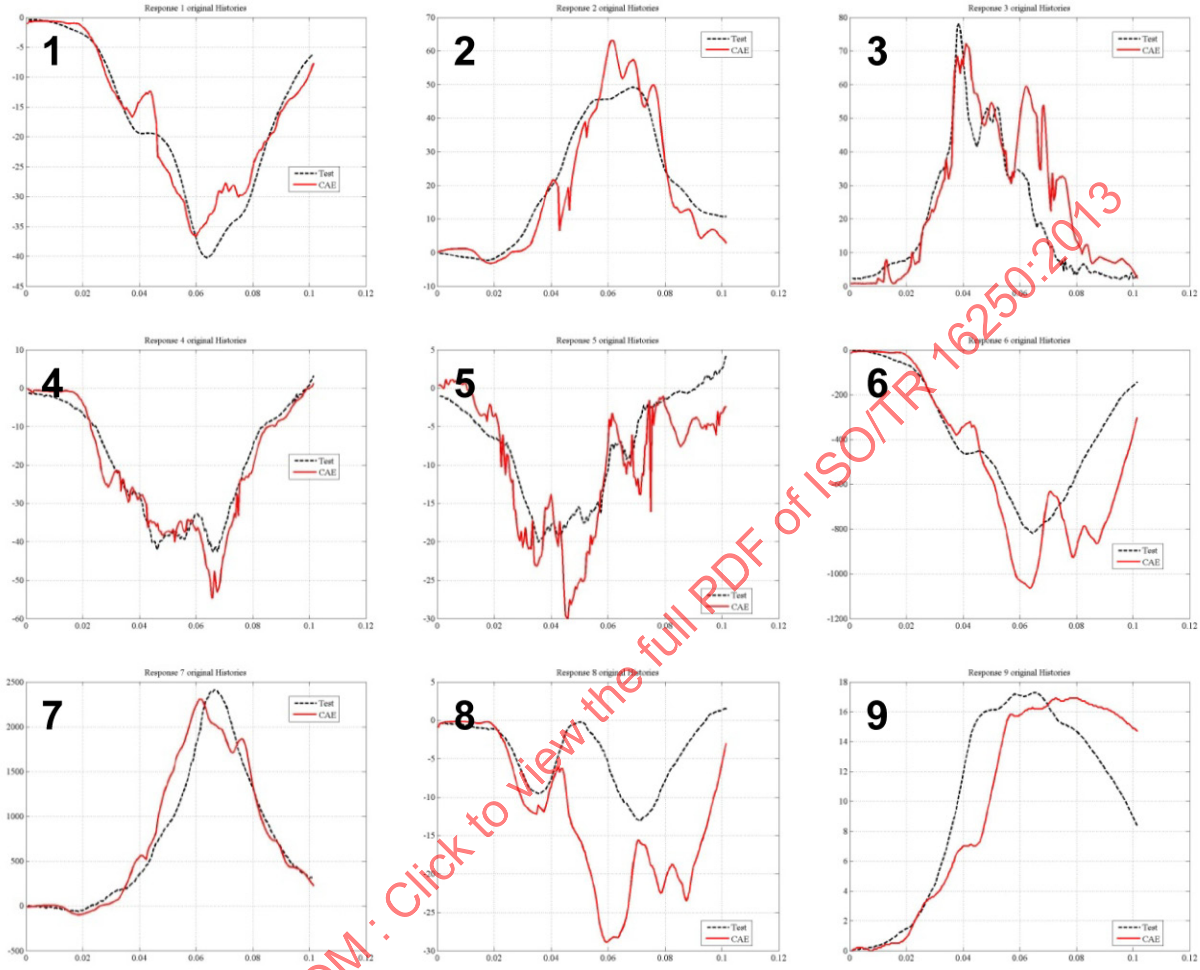
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,856	0,891	0,832	0,926	0,938	0,633
2	0,689	0,759	0,642	0,852	0,855	0,217
3	0,617	0,663	0,586	0,631	0,826	0,302
4	0,720	0,829	0,648	0,877	0,923	0,143
5	0,471	0,495	0,455	0,828	0,489	0,050
6	0,659	0,729	0,612	0,581	0,918	0,338
7	0,831	0,886	0,795	0,926	0,930	0,530
8	0,218	0,308	0,158	0,212	0,000	0,261
9	0,639	0,656	0,628	0,507	0,739	0,637

A.11 Data set 11



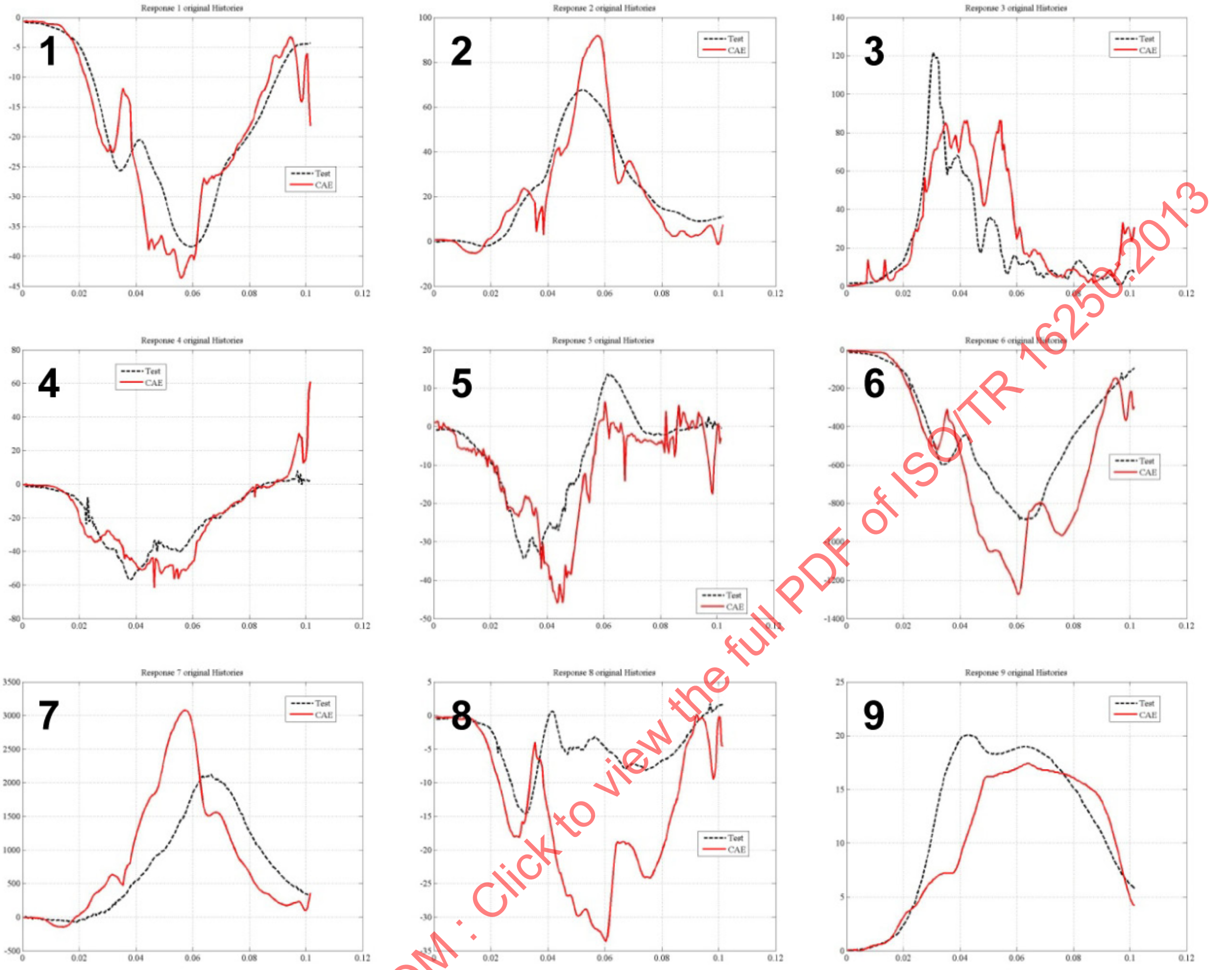
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,842	0,880	0,817	0,852	0,917	0,682
2	0,692	0,773	0,639	0,951	0,831	0,135
3	0,620	0,717	0,556	0,729	0,818	0,121
4	0,725	0,790	0,683	0,926	0,855	0,267
5	0,578	0,645	0,533	0,951	0,562	0,086
6	0,532	0,586	0,496	0,729	0,658	0,102
7	0,843	0,872	0,823	0,926	0,947	0,598
8	0,166	0,284	0,087	0,261	0,000	0,000
9	0,648	0,701	0,612	0,360	0,906	0,571

A.12 Data set 12



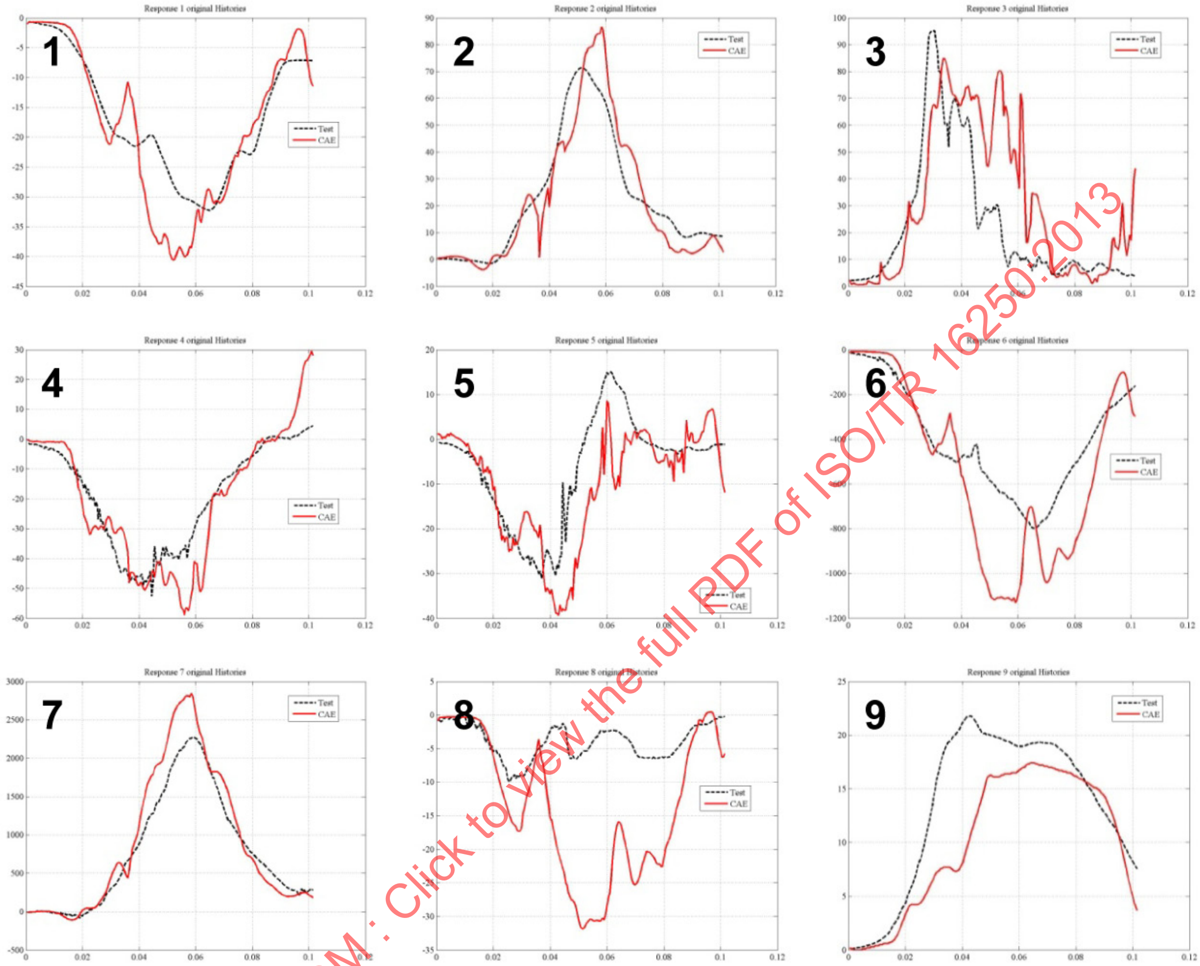
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,840	0,881	0,814	0,901	0,924	0,615
2	0,698	0,770	0,649	0,877	0,835	0,236
3	0,670	0,787	0,591	0,852	0,844	0,077
4	0,820	0,872	0,785	0,951	0,914	0,489
5	0,516	0,527	0,509	0,975	0,553	0,000
6	0,581	0,612	0,560	0,729	0,814	0,137
7	0,829	0,869	0,802	0,828	0,960	0,618
8	0,331	0,353	0,315	0,828	0,000	0,119
9	0,677	0,685	0,672	0,335	0,963	0,718

A.13 Data set 13



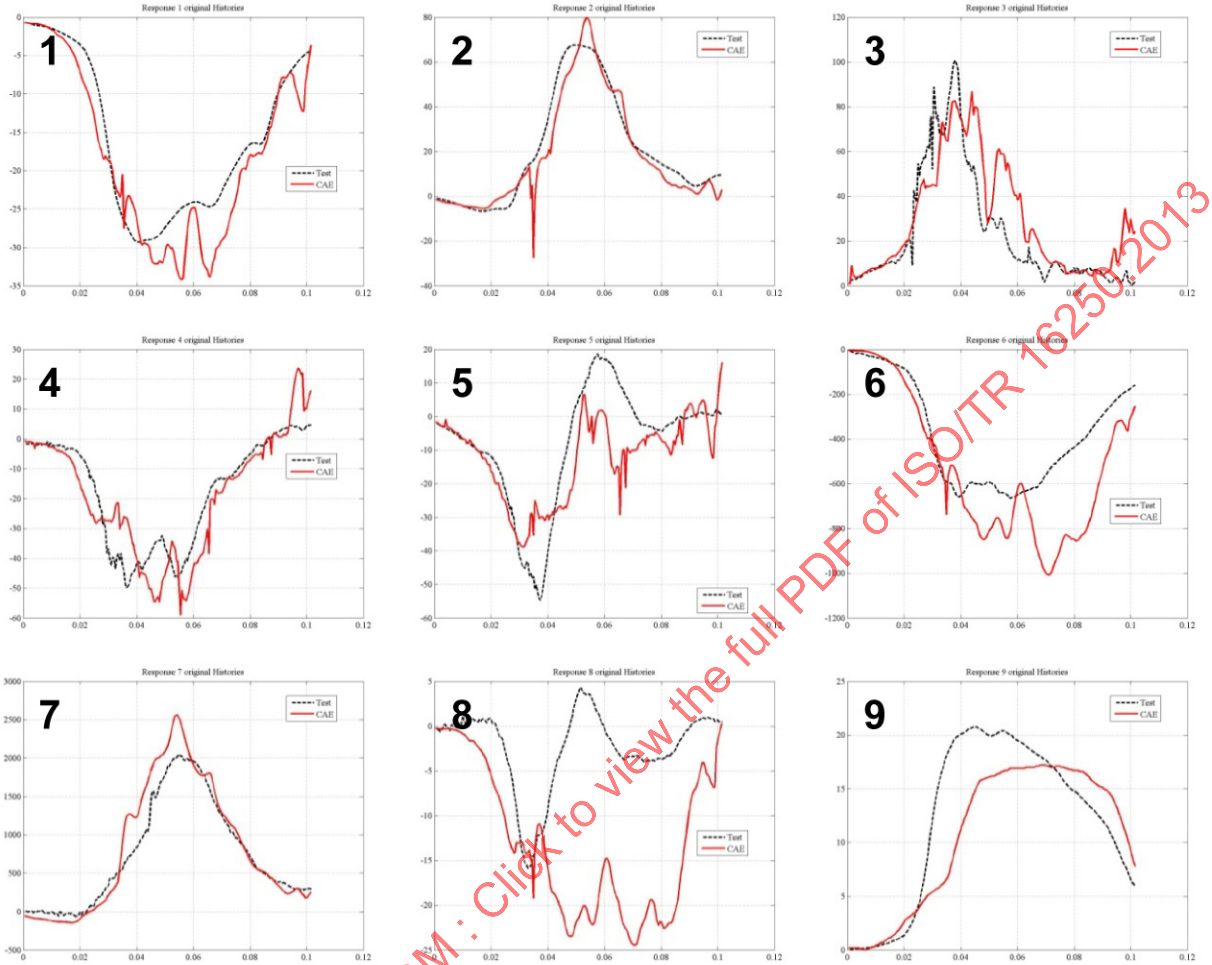
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,758	0,773	0,748	0,778	0,921	0,544
2	0,652	0,758	0,581	0,926	0,751	0,066
3	0,675	0,764	0,616	0,828	0,676	0,345
4	0,683	0,747	0,640	0,975	0,749	0,195
5	0,502	0,598	0,437	0,729	0,582	0,000
6	0,618	0,577	0,645	0,951	0,746	0,238
7	0,524	0,480	0,553	0,433	0,814	0,411
8	0,320	0,320	0,321	0,803	0,000	0,159
9	0,720	0,745	0,702	0,581	0,884	0,642

A.14 Data set 14



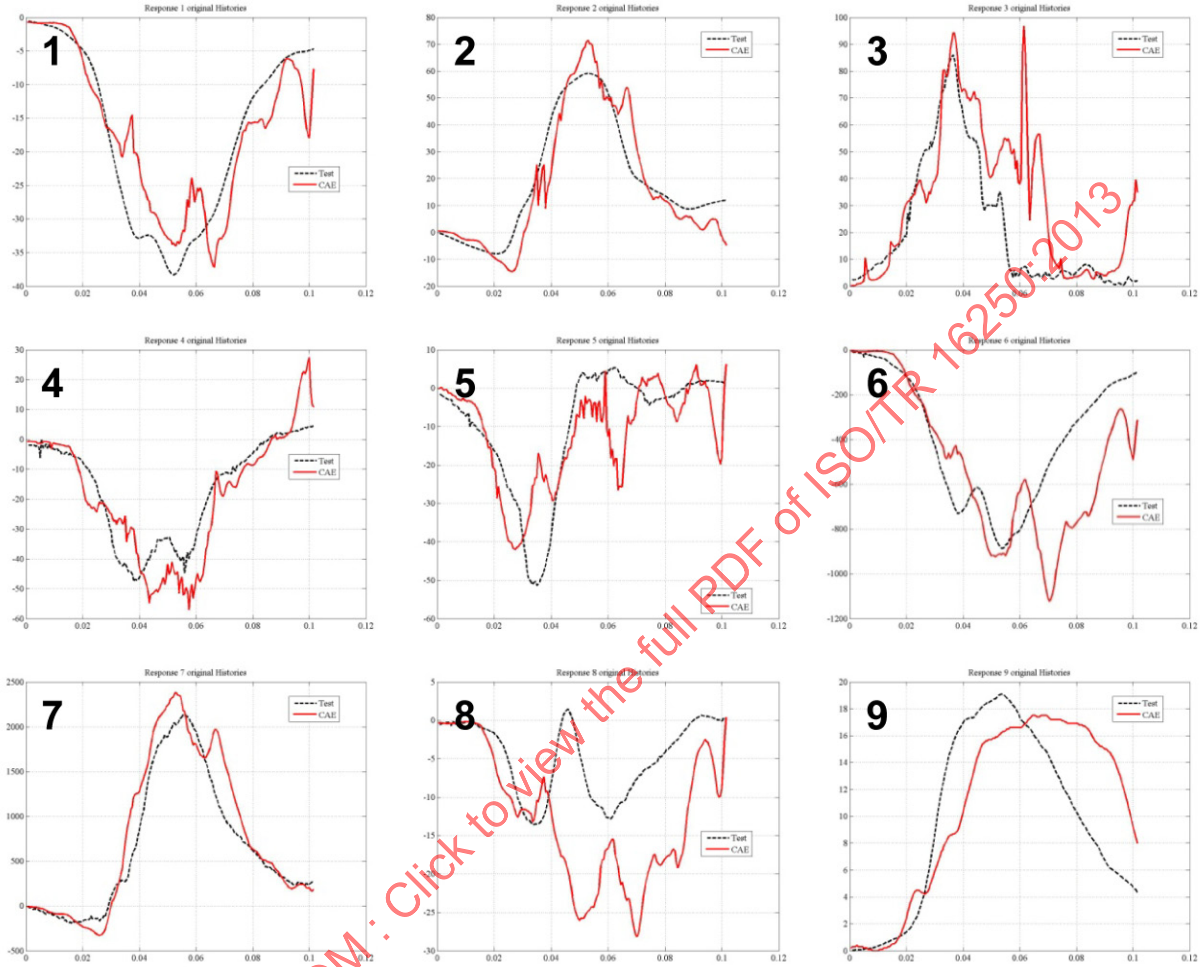
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,647	0,743	0,583	0,754	0,842	0,153
2	0,707	0,804	0,642	0,828	0,849	0,251
3	0,571	0,659	0,513	0,778	0,678	0,082
4	0,640	0,735	0,577	0,828	0,811	0,093
5	0,474	0,564	0,413	0,631	0,520	0,089
6	0,564	0,563	0,566	0,975	0,680	0,042
7	0,790	0,832	0,762	0,877	0,896	0,512
8	0,306	0,289	0,317	0,951	0,000	0,000
9	0,657	0,687	0,638	0,581	0,798	0,533

A.15 Data set 15



Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,702	0,768	0,658	0,951	0,880	0,144
2	0,760	0,860	0,694	0,877	0,867	0,338
3	0,647	0,745	0,581	0,704	0,754	0,283
4	0,617	0,678	0,576	0,828	0,838	0,063
5	0,579	0,665	0,522	0,975	0,473	0,117
6	0,483	0,518	0,460	0,655	0,709	0,015
7	0,775	0,855	0,722	0,877	0,891	0,398
8	0,211	0,254	0,183	0,458	0,000	0,091
9	0,669	0,674	0,665	0,483	0,852	0,660

A.16 Data set 16



Response	Overal ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,686	0,750	0,643	0,803	0,877	0,250
2	0,672	0,769	0,608	0,828	0,818	0,179
3	0,569	0,676	0,498	0,828	0,665	0,000
4	0,616	0,644	0,598	0,803	0,800	0,190
5	0,522	0,649	0,438	0,754	0,515	0,044
6	0,522	0,577	0,485	0,310	0,831	0,313
7	0,794	0,823	0,774	0,926	0,924	0,473
8	0,200	0,307	0,129	0,261	0,000	0,126
9	0,609	0,557	0,644	0,384	0,942	0,604

Annex B
(informative)

Sled test example

The overall objective of the study was to conduct an impartial and objective comparison of simulation codes with a focus on the associated ATD models currently available for use in frontal occupant simulation.[26] The following targets were defined:

— Generate a carefully controlled, highly repeatable set of experimental test data which can be used to validate current and future models.

— Identify areas of improvement for the dummy models.

— Gain an understanding of system level modelling in the different simulation codes.

— Create a set of frontal sled models in each of the simulation codes.

The sled testing (Figure B.1) was conducted by the National Institute for Aviation Research (NIAR) at Wichita State University. Extensive setup data were collected to facilitate detail and accuracy in model building. Three tests at each condition showed a high degree of repeatability.

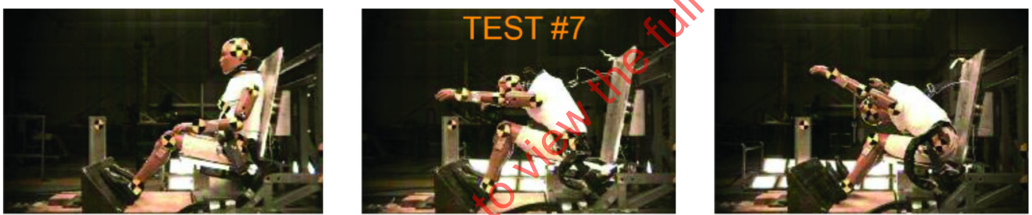


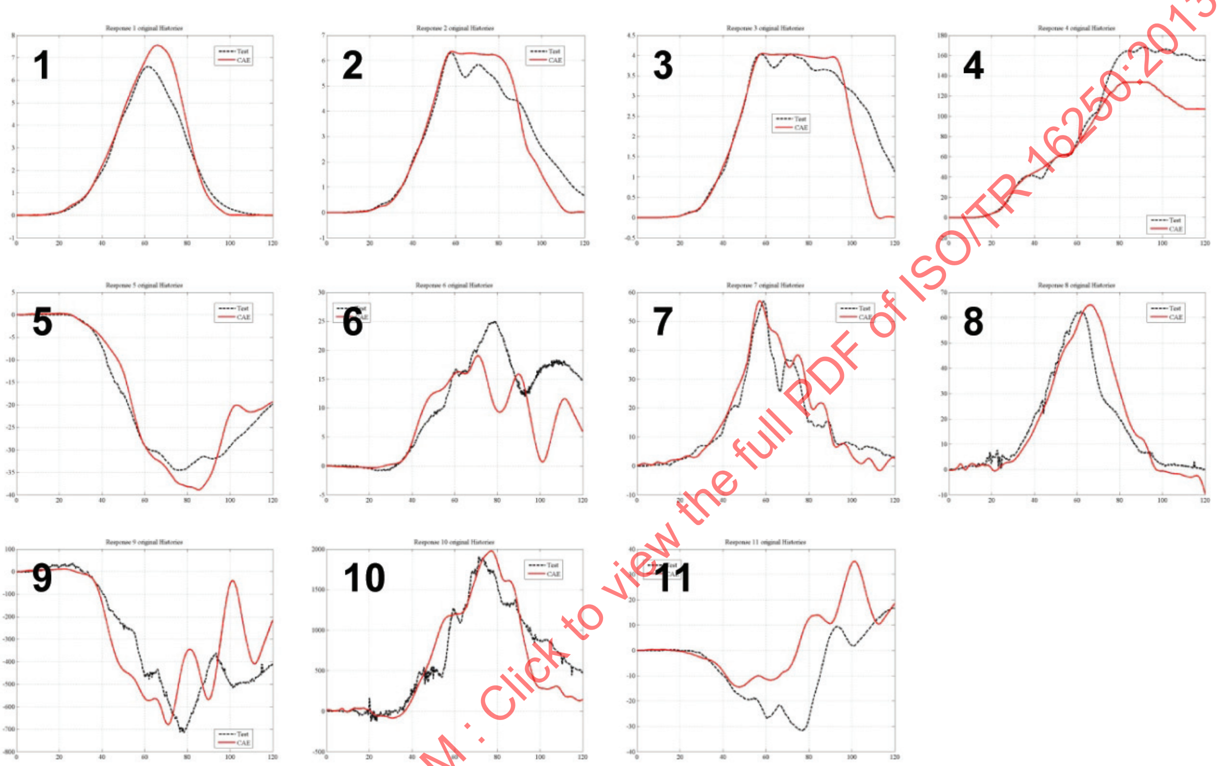
Figure B.1 — Test with Hybrid III 5th %-tile female[26]

Wichita State University compiled the test setup data, the test results and videos, and a 3D CAD model of the sled into a data package that was delivered to the participating numerical dummy suppliers. The simulation model setup and all runs for validation of the numerical dummies were the responsibility of the suppliers. When the suppliers were satisfied with the level of validation of their models for all four load cases, the models and results were sent back to Wichita State for objective rating against the test data. After the results were delivered to Wichita State, the Automotive Occupant Restraints Council (AORC) System Performance and Numerical Analysis Committee (SPNA) met individually with each of the suppliers for a deep-dive into the models, assumptions made, methodology used, and potential areas of improvement in the dummies. A selection of tests and responses are shown in Table B.1 and the subsequent clauses.

Table B.1 — Response variables

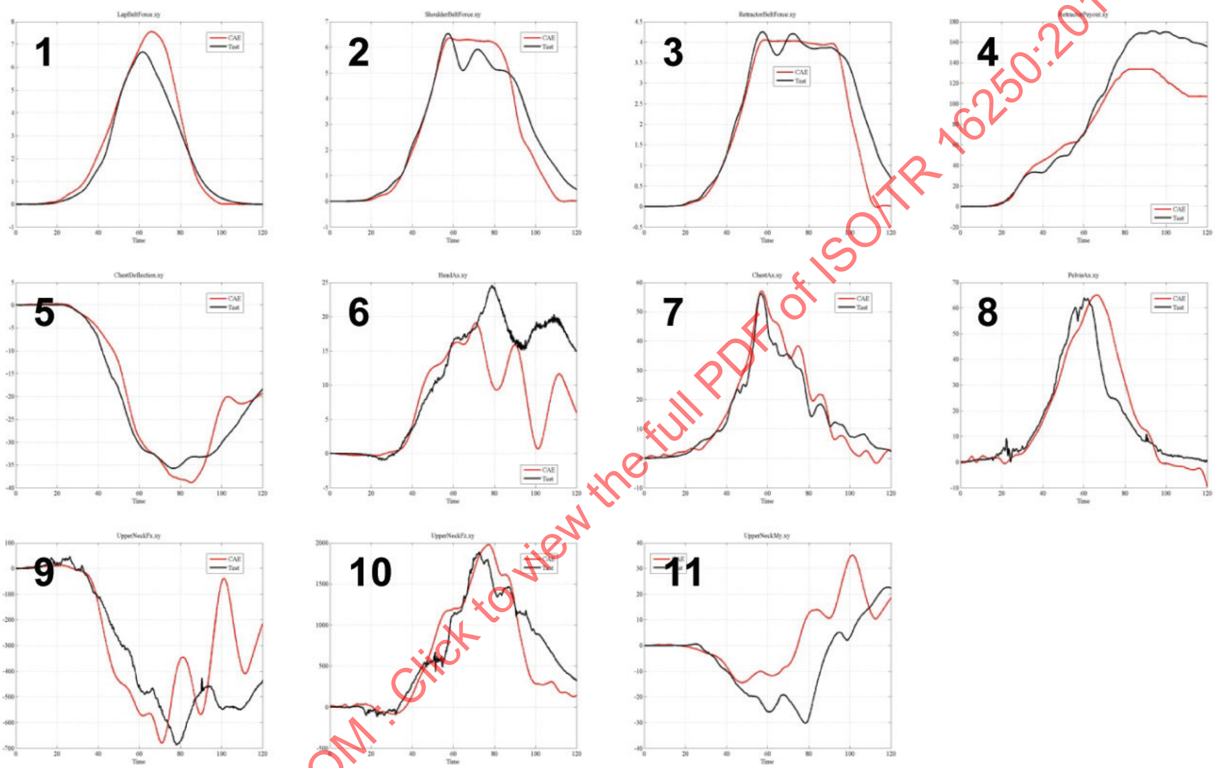
Response	Description
1	Lap belt force
2	Shoulder belt force
3	Retractor belt force
4	Retractor belt payout
5	Chest deflection
6	Head acceleration at *x*-direction
7	Chest acceleration at *x*-direction
8	Pelvis acceleration at *x*-direction
9	Upper neck shear force (F_x)
10	Upper neck tension force (F_z)
11	Upper neck moment (M_y)

B.1 Sled test 7 — Hybrid III 5th %-tile female



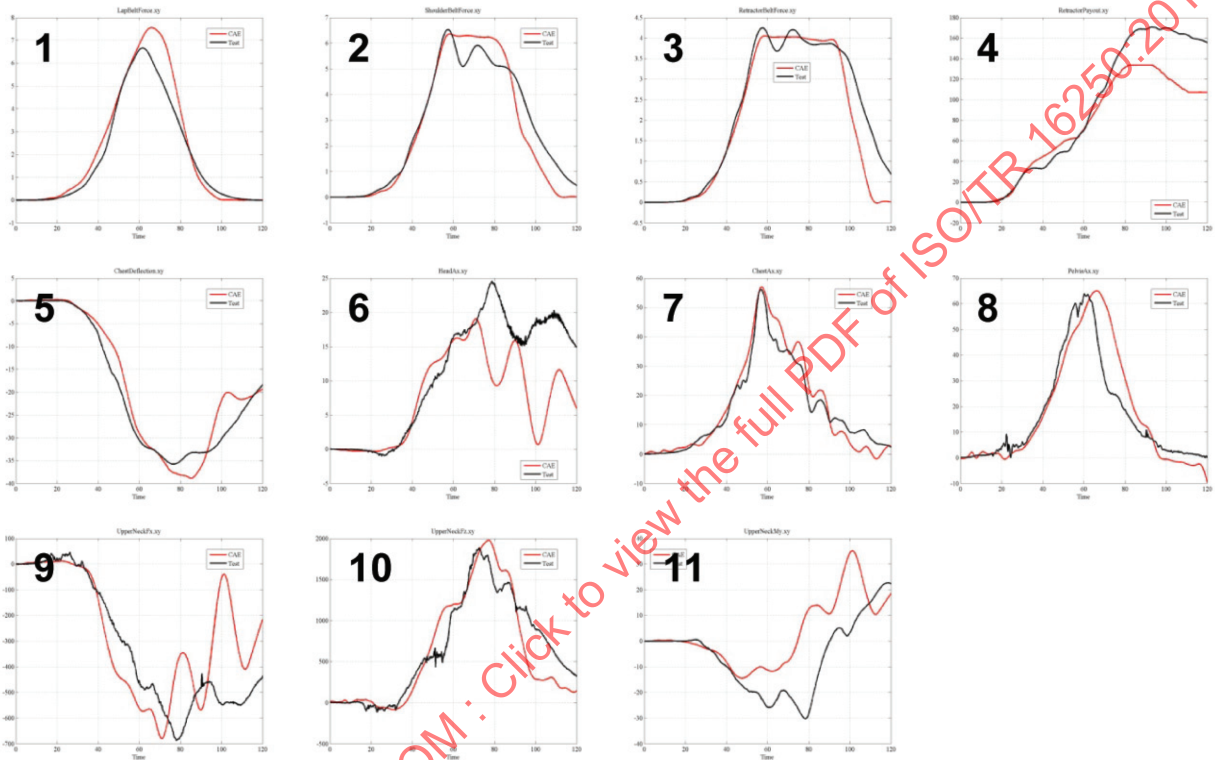
Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,906	0,915	0,900	0,950	0,943	0,807
2	0,841	0,812	0,861	0,929	0,928	0,724
3	0,798	0,822	0,781	0,821	0,930	0,593
4	0,729	0,759	0,709	0,775	0,732	0,620
5	0,842	0,856	0,832	0,988	0,947	0,563
6	0,603	0,667	0,561	0,512	0,711	0,460
7	0,845	0,895	0,812	0,975	0,929	0,532
8	0,799	0,851	0,764	0,800	0,918	0,575
9	0,593	0,619	0,576	0,504	0,850	0,374
10	0,763	0,759	0,765	0,917	0,881	0,497
11	0,456	0,545	0,396	0,433	0,239	0,516

B.2 Sled test 8 — Hybrid III 5th %-tile female



Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,892	0,892	0,892	0,954	0,947	0,775
2	0,853	0,838	0,863	0,929	0,937	0,722
3	0,845	0,852	0,840	0,867	0,950	0,705
4	0,719	0,751	0,697	0,721	0,721	0,649
5	0,851	0,863	0,842	0,967	0,965	0,596
6	0,572	0,672	0,505	0,446	0,663	0,406
7	0,879	0,907	0,860	0,988	0,948	0,644
8	0,789	0,831	0,761	0,787	0,917	0,579
9	0,566	0,617	0,533	0,500	0,835	0,263
10	0,769	0,778	0,763	0,896	0,936	0,459
11	0,463	0,481	0,452	0,379	0,459	0,516

B.3 Sled test 9 — Hybrid III 5th %-tile female



Response	Overall ISO rating	CORA corridor	EEARTH	EEARTH phase	EEARTH magnitude	EEARTH slope
1	0,892	0,897	0,889	0,938	0,953	0,775
2	0,792	0,747	0,821	0,887	0,881	0,695
3	0,780	0,799	0,768	0,813	0,904	0,587
4	0,744	0,786	0,716	0,750	0,768	0,631
5	0,858	0,864	0,854	0,988	0,973	0,601
6	0,588	0,659	0,540	0,533	0,674	0,414
7	0,843	0,868	0,827	0,992	0,906	0,584
8	0,789	0,829	0,762	0,787	0,924	0,574
9	0,587	0,637	0,554	0,546	0,835	0,281
10	0,743	0,742	0,744	0,904	0,866	0,462
11	0,437	0,533	0,372	0,412	0,191	0,513

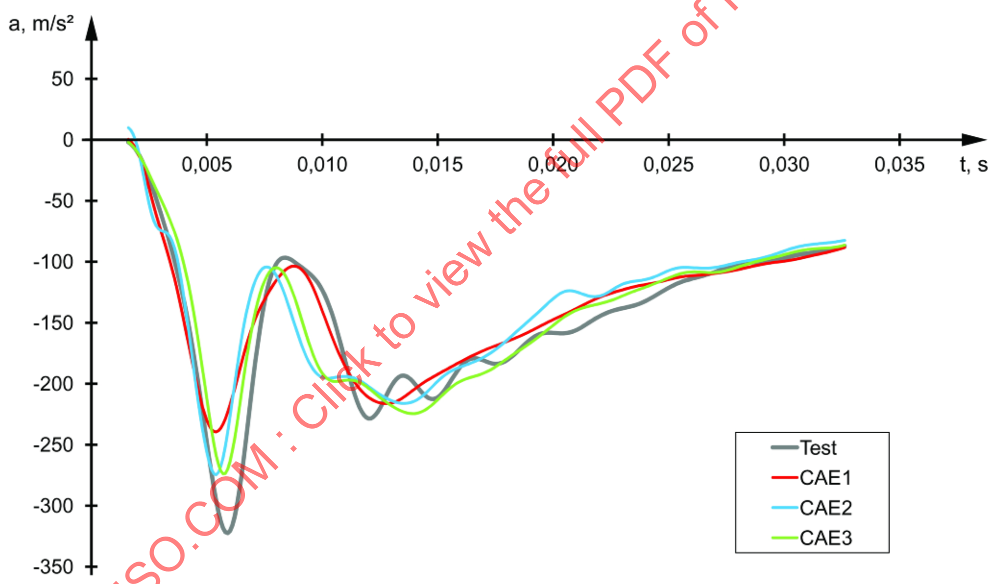
Annex C
(informative)

Case studies

This annex gives some examples of the application of this Technical Report. All responses are obtained in various tests related to passive safety of vehicles. The focus is on filtered and anonymized dummy responses. In each case, three CAE signals are compared with a test signal. As the quality of the CAE signals differs, different levels of correlation are covered by this case study. The shown data are in a digital format available (ASCII data).

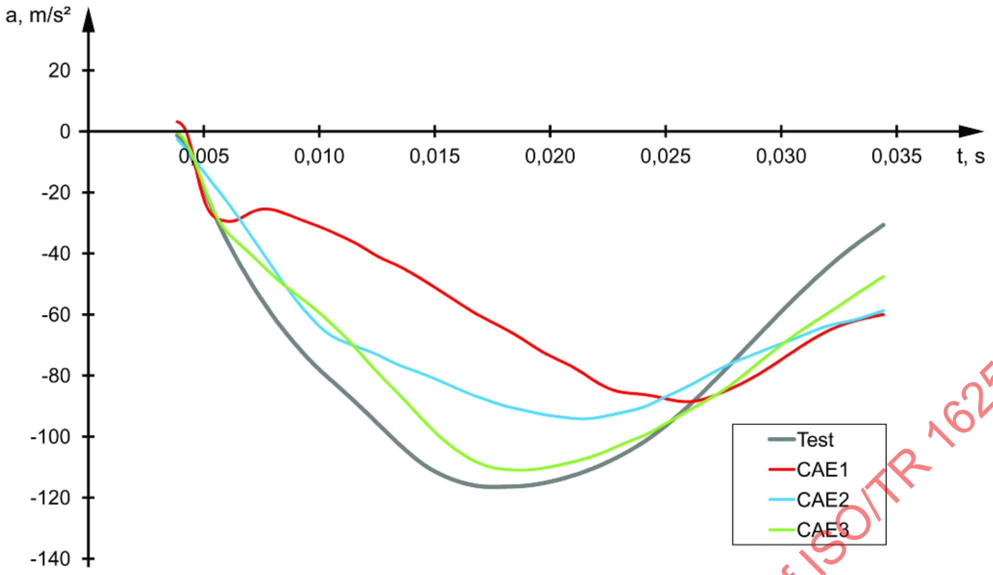
C.1 Accelerations

C.1.1 Acceleration 1



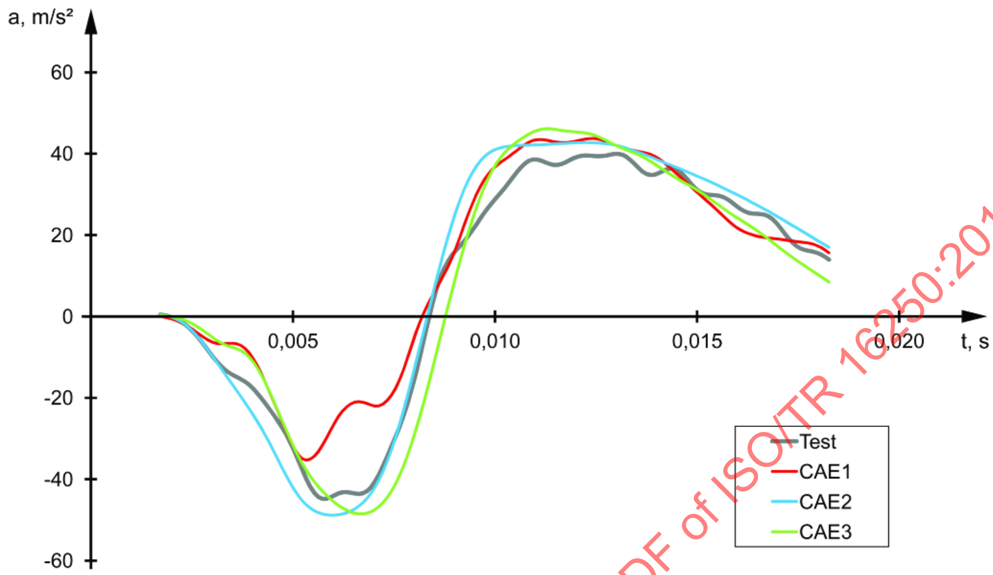
	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Good	Good	Good
Overall ISO rating, *R*	0,913	0,874	0,911
Corridor rating, *Z*	0,956	0,898	0,922
EEARTH rating, *E*	0,884	0,858	0,904
Phase E_P of EEARTH	0,936	0,904	0,968
Magnitude E_M of EEARTH	0,952	0,964	0,972
Slope E_S of EEARTH	0,766	0,706	0,773

C.1.2 Acceleration 2



	CAE1 (C_1)	CAE2 (C_2)	CAE3 (C_3)
Grade	Poor	Fair	Good
Overall ISO rating, *R*	0,444	0,691	0,850
Corridor rating, *Z*	0,406	0,642	0,845
EEARTH rating, *E*	0,470	0,723	0,853
Phase E_P of EEARTH	0,000	0,577	0,739
Magnitude E_M of EEARTH	0,679	0,825	0,965
Slope E_S of EEARTH	0,731	0,768	0,853

C.1.3 Acceleration 3



	CAE1 (C_1)	CAE2 (C_2)	CAE3 (C_3)
Grade	Fair	Good	Good
Overall ISO rating, *R*	0,785	0,859	0,818
Corridor rating, *Z*	0,725	0,816	0,749
EEARTH rating, *E*	0,825	0,887	0,864
Phase E_P of EEARTH	0,910	0,910	0,910
Magnitude E_M of EEARTH	0,898	0,931	0,909
Slope E_S of EEARTH	0,667	0,820	0,774