TECHNICAL SPECIFICATION

ISO/TS 18571

First edition
2014-08-01

Road vehicles — Objective rating metric for non-ambiguous signals

Véhicules routiers — Mesures pour l'évaluation objective de signaux non ambigus

Reference number
ISO/TS 18571:2014(E)

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Published in Switzerland

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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.

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).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 22, *Road vehicles*, Subcommittee SC 10, *Impact test procedures*.

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, the validity and predictive capabilities of these models 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 American Institute of Aeronautics and Astronautics (AIAA),[1] the American Society of Mechanical Engineers (ASME) Standards Committees on verification and validation of Computational Solid Mechanics[2] and Computational Fluid Dynamics and Heat Transfer,[3] the Defence Modelling and Simulation Office (DMSO) of the United States Department of Defence (DoD),[4] the United States Department of Energy (DOE),[5] and various other professional societies.[19] [20]

One of the critical tasks to achieve quantitative assessments 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.[6] [16] [17] Developing quantitative model validation methods has attracted considerable researchers' interest in recent years.[11] [12] [13] [15] [17] [18] [23] [24] [25] [27] 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.

This Technical Specification is the essential excerpt of ISO/TR 16250:2013[10] which provides standardized calculations of the correlation between two signals of dynamic systems, and it is validated against multiple vehicle safety case studies.

Road vehicles — Objective rating metric for non-ambiguous signals

1 Scope

This Technical Specification (TS) provides validation metrics and rating procedures to be used to calculate the level of correlation between two non-ambiguous signals obtained from a physical test and a computational model, and is aimed at vehicle safety applications. The objective comparison of time-history signals of model and test is validated against various loading cases under different types of physical loads such as forces, moments, and accelerations. However, other applications might be possible too, but are not within the scope of this Technical Specification.

2 Normative references

There are no normative references used in this document.

3 Terms and definitions

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

3.1
filtering
smoothing of signals by using standardized algorithms

3.2
goodness or level of correlation
similarity of two signals

3.3
interval of evaluation
time domain that is used to calculate the correlation between two signals

3.4
rating
rating score
calculated value that represents a certain level of correlation (objective rating)

3.5
sampling rate
recording frequency of a signal

3.6
time sample
pair values (e.g. time and amplitude) of a recorded signal

3.7
time-history signal
physical value recorded in a time domain; those signals are non-ambiguous

4 Symbols and abbreviated terms

CAE	Computer-aided engineering

CORA	Correlation and analysis
DTW	Dynamic time warping
EEARTH	Enhanced error assessment of response time histories
SME	Subject matter expert
a_0	Relative half width of the inner corridor
b_0	Relative half width of the outer corridor
C, $C(t)$	Analysed signal (CAE signal)
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}
DTW	Dynamic time warping distance
$DTW_{opt}\,(i, j)$	Cost of the optimal warping path
d	Local cost matrix to perform the dynamic time warping
$d(i, j)$	Local cost function to perform the dynamic time warping
$dtw[i, j]$	Cumulative cost matrix
Δt	Interval between two time samples
δ_i	Half width of the inner corridor
$\delta_i(t)$	Lower/upper bounds of the inner corridor at time, t, (curve)
δ_o	Half width of the outer corridor
$\delta_o(t)$	Lower/upper bounds of the outer corridor at time, t, (curve)
E_M	Magnitude score
E_P	Phase score
E_S	Slope (topology) score
ε_M^*	Maximum allowable magnitude error
ε_P^*	Maximum allowable percentage of time shift
ε_S^*	Maximum allowable slope error
ε_{mag}	Magnitude error
ε_{slope}	Slope error
i	Index number of time shifted and truncated CAE curve, C^{ts}
i_k	Index number of k-th warping path of curve, C^{ts}

i^w	Index number of warping path of CAE curve, C^{ts}
j	Index number of time shifted and truncated test curve, T^{ts}
j_k	Index number of k-th warping path of curve, T^{ts}
j^w	Index number of warping path of test curve, T^{ts}
k	Index number
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
k_Z	Exponent factor for calculating the corridor score between the inner and outer corridors
m	Time steps moved to evaluate the phase error
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
n	Number of data samples of time shifted and truncated curves (C^{ts} and T^{ts})
n_w	Number of data samples of the optimal warping path
n_ε	Number of time shifts to get ρ_E
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)
R	Overall ISO rating
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
T, $T(t)$	Reference signal (test signal)
T_{norm}	Absolute maximum amplitude of the reference signal, T
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	Time signal (axis of abscissa)
t_{end}	Ending time of the interval of evaluation
t_{start}	Starting time of the interval of evaluation

t_0 Time zero of an event (e.g. test, crash, impact etc.)

w Warping path

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

w_Z Weighting factor of the corridor score, Z

w_k The k-th warping path cell

Z Corridor score

$Z(t)$ Corridor score at time, t, (curve)

5 General data requirements

The metric described in this Technical Specification requires 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.

6 ISO metric

The approach of this Technical Specification is to combine different types of algorithms to get reliable and robust assessments of the correlation of two signals. The calculated score must provide fair assessment for poor and for good correlations of two signals. The two most promising metrics are identified in Reference [10] and they are CORA corridor method and EEARTH. A combined metric based on the improved CORA corridor method and EEARTH is then proposed for an ISO Technical Specification which has been fully validated using responses from multiple vehicle passive safety applications.

Figure 1 shows the structure of the overall ISO metric. While the corridor method calculates the deviation between 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 consists of the two best available algorithms.

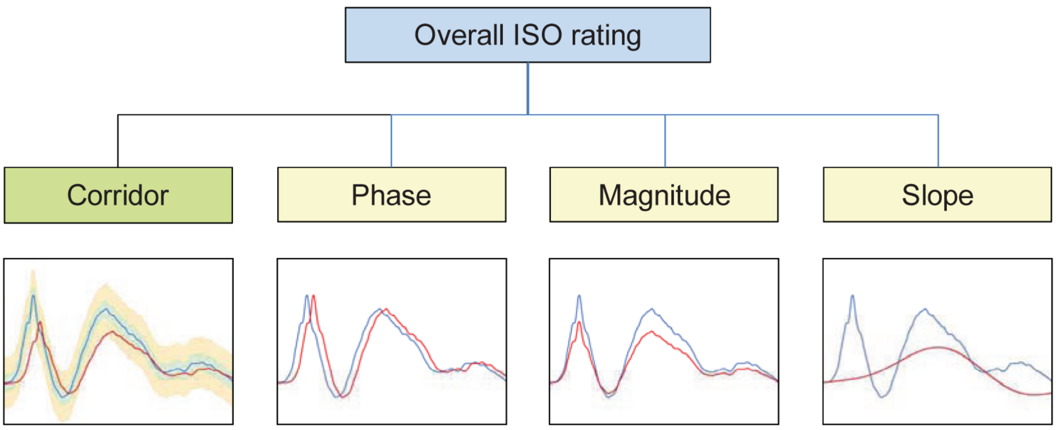

Figure 1 — ISO metric structure

6.1 Calculation of the overall ISO rating

The combination of the four metric ratings (corridor, phase, magnitude, and slope) will provide a single number, R, for the correlation of the analysed signals which represents the final overall objective rating. The overall objective rating, R, is calculated by combining the separate sub-ratings of corridor (Z), phase (E_P), magnitude (E_M), and slope (E_S). Four individual weighting factors are defining the influence of each metric on the overall rating [see Formulae (1) and (2)]. The corresponding weighting factors are shown in Table 1.

$$R = w_Z \cdot Z + w_P \cdot E_P + w_M \cdot E_M + w_S \cdot E_S \quad (1)$$

$$w_Z + w_P + w_M + w_S = 1 \quad (2)$$

Table 1 — Weighting factors of the ISO sub-ratings

Parameter	Value	Description
w_Z	0,4	Weighting factor of the corridor score
w_P	0,2	Weighting factor of the phase score
w_M	0,2	Weighting factor of the magnitude score
w_S	0,2	Weighting factor of the slope score

6.2 Corridor score

The corridor metric 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, C, is within the inner corridor bounds, a score of "1" is given and if it is outside the outer corridor bounds, the score 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. The compliance with the corridors is calculated at each specific time, t, and the final corridor score, Z, of a signal is the average of all scores, $Z(t)$, at specific times, t.

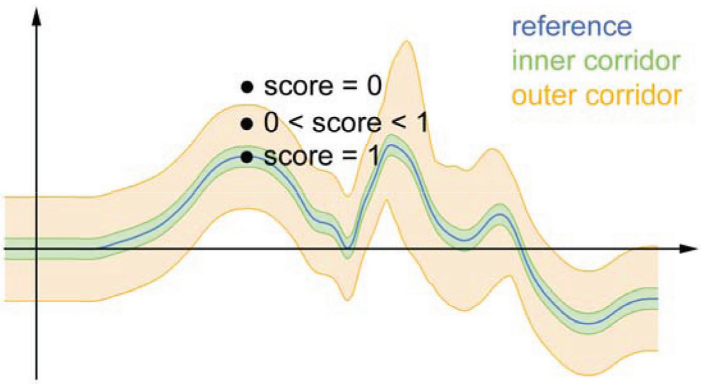

Figure 2 — Rating zones of the corridor metric (corridors of constant width)[9]

The philosophy of the ISO approach is to use a narrow inner corridor and a wide outer corridor.[14] 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. Basically the width of the corridors can be adjusted in order to reflect the specific signal characteristic. The width can be constant for the whole duration of the dynamic responses or vary at the different time intervals. This Technical Specification applies the most common approach of using constant corridor widths for the whole duration of the dynamic response.[10] [26]

6.2.1 Calculation

The parameters a_0 and b_0 define the relative half widths 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 (3) shows the calculation of T_{norm} and it is calculated within the interval of evaluation.

$$T_{norm} = \max\left\{ \left|\min(T)\right|, \left|\max(T)\right| \right\} \tag{3}$$

The absolute half width of the inner corridor (absolute distance from the reference signal to the outer bounds of the inner corridor) is defined by Formula (4). The calculation of the absolute half width of the outer corridors [see Formula (5)] is similar to that of the inner corridors.

$$\delta_i = a_0 \cdot T_{norm} \qquad 0 \le a_0 \le 1 \tag{4}$$

$$\delta_o = b_0 \cdot T_{norm} \qquad 0 \le b_0 \le 1 \quad \text{and} \quad a_0 < b_0 \tag{5}$$

Based on these definitions, the lower and upper bounds of the inner corridor are defined by Formula (6) and the lower and upper bounds of the outer corridor are defined by Formula (7).

$$\delta_i(t) = T(t) \pm \delta_i \tag{6}$$

$$\delta_o(t) = T(t) \pm \delta_o \tag{7}$$

Formula (8) shows the calculation of the corridor score 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 corridor (δ_i), then the score is set to "1". The score is calculated by Formula (8) when the absolute difference between both signals is in between $\delta_i \le \left|T(t) - C(t)\right| \le \delta_o$. If the absolute difference between both signals is greater than the half width of the outer corridor (δ_o), then the score is set to "0". The parameter, k_Z, assesses the location of the analysed signal within the outer corridor, and it applies the appropriate penalty on the rating score. A linear ($k_Z = 1$), quadratic ($k_Z = 2$), cubical ($k_Z = 3$) or any other regression relationship can be defined accordingly.

$$Z(t) = \begin{cases} 1 & \text{if} \quad \left|T(t) - C(t)\right| < \delta_i \\ \left(\dfrac{\delta_o - \left|T(t) - C(t)\right|}{\delta_o - \delta_i} \right)^{k_Z} & \\ 0 & \text{if} \quad \left|T(t) - C(t)\right| > \delta_o \end{cases} \qquad k_Z \in N_{>0} \tag{8}$$

The final corridor score, Z, is calculated by averaging all single time step score $Z(t)$ as shown in Formula (9). The parameter, N, represents the total number of sample points (e.g. time steps) between starting and ending times of the interval of evaluation.

$$Z = \frac{\sum_{t=t_{start}}^{t_{end}} Z(t)}{N} \tag{9}$$

One of the advantages of the corridor metric 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 very undesirable rating.[10]

Based on a sensitivity study of CORA[14] and as described in Reference [10], fixed width corridors are employed and the most appropriate metric parameters are identified as shown in Table 2.

Table 2 — Parameters of the corridor metric

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_Z	2	Transition between ratings of “1” and “0” (progression)

6.2.2 Step by step procedure

First of all, the signals shall be pre-processed as described in Clause 8. 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 assessment shall be executed within this defined interval. The total score 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 corridor score.

a) Pre-process both signals according to Clause 8.

b) Calculate T_{norm} within the interval of evaluation by using the reference signal.

c) Calculate the inner and the outer corridors.

d) Calculate the corridor score, $Z(t)$, at every specific time t within the interval of evaluation.

e) Calculate the total corridor score, Z, based on $Z(t)$ and the number, N, of time samples.

6.3 Phase, magnitude, and slope scores

Phase, magnitude, and slope (or so-called topology) error assessments between the time history curves, T and C, are used as objective rating metrics[24] [28] in addition to the corridor metric described earlier. The enhanced error assessment of response time histories (EEARTH) metric combines these three assessments to the global response error.[28] It is defined as the error associated with the complete time history with equal weight on each point. Quantifying the errors associated with these features of phase, magnitude, and slope (topology) 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)[22] is used to separate the interaction of phase, magnitude, and slope (topology) errors. It aligns peaks and valleys of the two signals as much as possible by expanding and compressing the time axis according to a given cost (distance) function.[8]

The ranges of the three errors are quite different and there is no single rating that can provide a quantitative assessment alone. Therefore, a numerical optimization method is employed to identify the appropriate parameters so that the resulted phase, magnitude, and slope sub-ratings can match with SME’s ratings closely.[7] [21] Figure 3 shows the workflow of the procedures and the details of the algorithms are described in the following subsections.

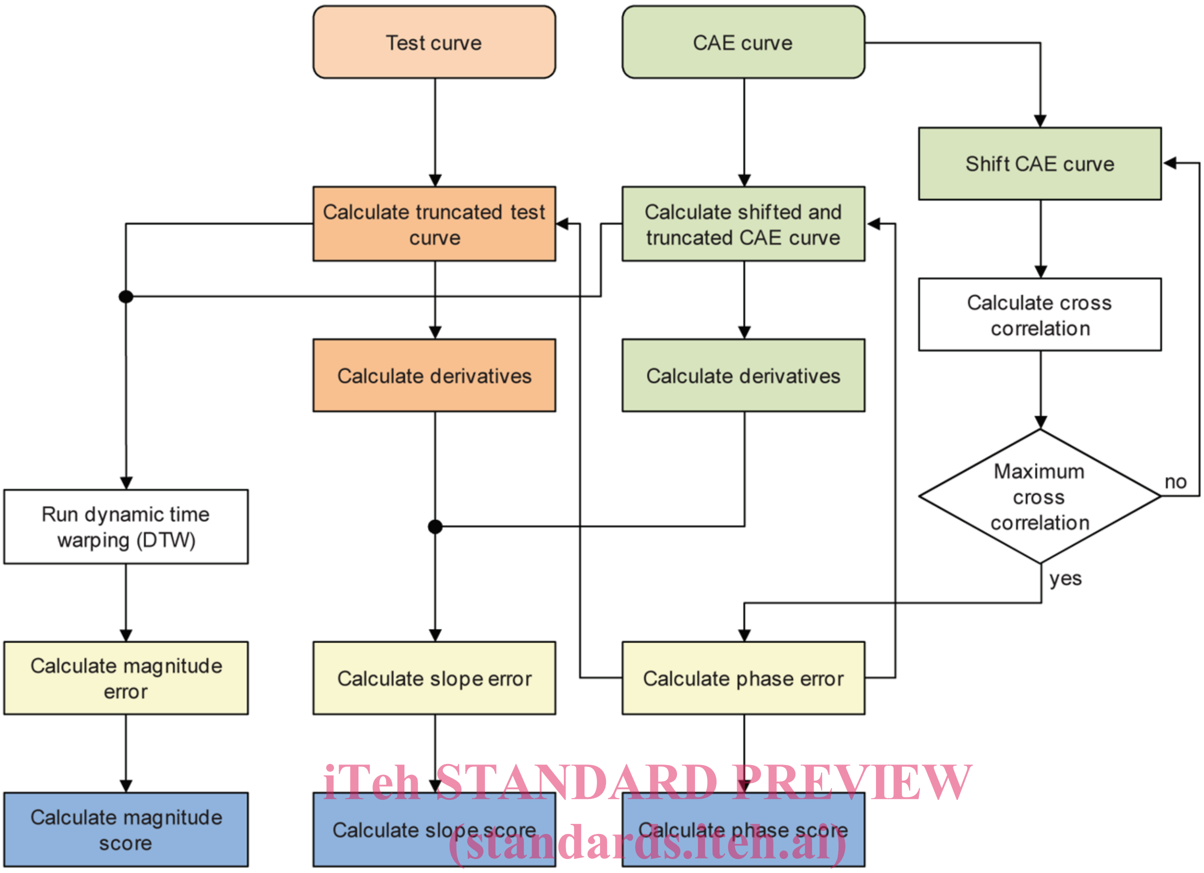

Figure 3 — Workflow of the calculation of phase, magnitude, and slope scores

6.3.1 Phase score

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

When the initial curve, C, is moved to the left by m time steps, the number of overlapping points of the two time histories after time shift, $m \cdot \Delta t$, is reduced to n $(n = N - m)$ and the corresponding cross correlation value, $\rho_L(m)$, is calculated by Formula (10).

$$\rho_L(m) = \frac{\sum_{i=0}^{n-1}\left[\left(C\left(t_{start} + (m+i) \cdot \Delta t\right) - \bar{C}(t)\right) \cdot \left(T\left(t_{start} + i \cdot \Delta t\right) - \bar{T}(t)\right)\right]}{\sqrt{\sum_{i=0}^{n-1}\left[C\left(t_{start} + (m+i) \cdot \Delta t\right) - \bar{C}(t)\right]^2} \cdot \sqrt{\sum_{i=0}^{n-1}\left[T\left(t_{start} + i \cdot \Delta t\right) - \bar{T}(t)\right]^2}} \quad (10)$$

When the initial curve C is moved to the right by m time steps, the number of overlapping points after time shift, $m \cdot \Delta t$, is reduced to n $(n = N - m)$ and the corresponding cross correlation value, $\rho_R(m)$, is calculated by Formula (11).

$$\rho_R(m) = \frac{\sum_{i=0}^{n-1}\left[\left(C\left(t_{start} + i \cdot \Delta t\right) - \bar{C}(t)\right) \cdot \left(T\left(t_{start} + (m+i) \cdot \Delta t\right) - \bar{T}(t)\right)\right]}{\sqrt{\sum_{i=0}^{n-1}\left[C\left(t_{start} + i \cdot \Delta t\right) - \bar{C}(t)\right]^2} \cdot \sqrt{\sum_{i=0}^{n-1}\left[T\left(t_{start} + (m+i) \cdot \Delta t\right) - \bar{T}(t)\right]^2}} \quad (11)$$

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 phase error, n_ε. The corresponding shifted and truncated CAE curve, C, is recorded as C^{ts} and the corresponding truncated test curve, T, is recorded as T^{ts}.

The phase score, E_P, is calculated by Formula (12). The best phase score is “1”, which means there is no need to shift the 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 phase score is “0”. In between, the phase score is calculated by a regression method. It is either linear ($k_P = 1$), quadratic ($k_P = 2$), or cubical ($k_P = 3$).

$$E_P = \begin{cases} 1 & \text{if} \quad n_\varepsilon = 0 \\ \left(\dfrac{\varepsilon_P^* \cdot N - n_\varepsilon}{\varepsilon_P^* \cdot N}\right)^{k_P} & \qquad\qquad k_P \in \{1, 2, 3\} \\ 0 & \text{if} \quad n_\varepsilon \geq \varepsilon_P^* \cdot N \end{cases} \quad (12)$$

The pre-defined parameters shown in Table 3 are identical to the definition in Reference [10].

Table 3 — Fixed parameters of the phase score

Parameter	Value	Description
k_P	1	Exponent factor for calculating the phase score
ε_P^*	0,2	Maximum allowable percentage of time shift

6.3.2 Magnitude score

The magnitude error is a measure of discrepancy in the amplitude of the two time histories. It 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 slope (topology) are minimized by using dynamic time warping (DTW).

The definition of DTW is based on the notion of warping path. Let d be the matrix $n \times n$ of pair-wise squared distances between samples of C^{ts} and T^{ts}. This matrix, d, is called the local cost matrix. The