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Road vehicles — Objective rating metric for non-ambiguous signals

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

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Contents

Page

Foreword

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

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

This second edition cancels and replaces the first edition (ISO/TS 18571:2014), which has been technically revised.

The main changes are as follows:

— more descriptions about window size for Dynamic Time Warping were provided. Ten percent of data length was used as window size;

— for slope score calculation, a modified algorithm was developed. In the new algorithm, a nine-point moving average method was used to keep data point symmetry and slope curve smooth;

— in original Annex data sets, some time intervals were not consistent with variations at thousandth digit. Now, data sets were cleaned up and time interval variations were eliminated. New rating results on Annex data sets were provided and all figures and tables were updated accordingly.

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

Introduction

Computer Aided Engineering (CAE) has become a vital tool for product development in the automobile industry. Various computer programs and models have been developed to simulate dynamic systems. To maximize the use of these models, the validity and predictive capabilities of these models are 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) [2], the American Society of Mechanical Engineers (ASME) Standards Committees on verification and validation of Computational Solid Mechanics[3] and Computational Fluid Dynamics and Heat Transfer[4], the Defense Modeling and Simulation Office (DMSO) of the U.S. Department of Defense (DoD)[5], the United States Department of Energy (DOE)[6] 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[7],[16],[17]. Developing quantitative model validation methods has attracted considerable researchers' interest in recent years [11],[12],[13],[15],[17],[18],[23],[24],[26]. 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 results.

This document is the essential excerpt of the ISO/TR 16250[1] 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 document provides validation metrics and rating procedures to calculate the level of correlation between two non-ambiguous signals obtained from a physical test and a computational model and it 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 can be possible too, but are not within the scope of this document.

NOTE Annex A gives some examples of the application of this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
filtering
smoothing of signals by using standardized algorithms

3.2
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
calculated value that represents a certain *level of correlation* (3.2) (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

Note 1 to entry: Time-history signals are non-ambiguous.

4 Abbreviated terms and symbols

4.1 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

4.2 General

C , $C(t)$	Analyzed signal (CAE signal)
T , $T(t)$	Reference signal (test signal)
Δt	Interval between two-time samples
t	Time signal (axis of abscissa)
t_0	Time zero of an event (e.g. test, crash, impact)
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}

4.3 Corridor score

Z	Corridor score
$Z(t)$	Corridor score at time t (curve)
k_Z	Exponent factor for calculating the corridor score between the inner and outer corridors
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 bounds of the inner corridor at time t (curve)
$\delta_o(t)$	Lower/upper bounds of the outer corridor at time t (curve)

$N_{>0}$	All natural numbers without zero
T_{norm}	Absolute maximum amplitude of the reference signal T

4.4 Phase, magnitude and slope scores

4.4.1 General

C^{ts}, $C^{\text{ts}}(i)$	Truncated and shifted CAE curve
$C^{\text{ts+w}}$	Warped CAE curve of C^{ts}
$C_0^{\text{ts+d}}$	Derivative CAE curve of C^{ts}
$C^{\text{ts+d}}$	Derivative CAE curve of C^{ts} after averaging
T^{ts}, $T^{\text{ts}}(j)$	Truncated and shifted test curve
$T^{\text{ts+w}}$	Warped test curve of T^{ts}
$T_0^{\text{ts+d}}$	Derivative test curve of T^{ts}
$T^{\text{ts+d}}$	Derivative test curve of T^{ts} after averaging

4.4.2 Phase score

E_{P}	Phase score
k_{P}	Exponent factor for calculating the phase score E_{P}
$\varepsilon_{\text{P}}^{*}$	Maximum allowable percentage of time shift
m	Time steps moved to evaluate the phase error
n_{ε}	Number of time shifts to get ρ_{E}
ρ_{E}	Maximum cross correlation of all $\rho_{\text{L}}(m)$ and $\rho_{\text{R}}(m)$
$\rho_{\text{L}}(m)$	Cross correlation – signal is moved to the left
$\rho_{\text{R}}(m)$	Cross correlation – signal is moved to the right

4.4.3 Magnitude score

E_{M}	Magnitude score
k_{M}	Exponent factor for calculating the magnitude score E_{M}
$\varepsilon_{\text{M}}^{*}$	Maximum allowable magnitude error
ε_{mag}	Magnitude error
n	Number of data samples of time shifted and truncated curves (C^{ts} and T^{ts})
d	Local cost matrix to perform the dynamic time warping
$d(i,j)$	Local cost function to perform the dynamic time warping

$d_{tw}[i,j]$	Cumulative cost matrix
D_{TW}	Dynamic time warping distance
$D_{TWopt}(i,j)$	Cost of the optimal warping path
i	Index number of time shifted and truncated CAE curve C^{ts}
i_l	Index number of l -th warping path of curve C^{ts}
j	Index number of time shifted and truncated test curve T^{ts}
j_l	Index number of l -th warping path of curve T^{ts}
k	Index number of any warping path
$\tilde{k}$	Number of data samples of the optimal warping path
w	Optimal warping path
w_l	The l -th warping path cell

4.4.4 Slope score

E_S	Slope (topology) score
k_S	Exponent factor for calculating the slope score E_S
ε_S^*	Maximum allowable slope error
ε_{slope}	Slope error

4.5 Overall ISO rating

R	Overall ISO rating
w_Z	Weighting factor of the corridor score Z
w_P	Weighting factor of the phase score E_P
w_M	Weighting factor of the magnitude score E_M
w_S	Weighting factor of the slope score E_S
r	Rank of the sliding scale of the ISO metric
$S_{Clower}(r)$	Lower threshold of rank r
$S_{Cupper}(r)$	Upper threshold of rank r

5 General data requirements

The metric described in this document 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

6.1 General

The approach of this document is to combine different types of algorithms to get reliable and robust assessments of the correlation of two signals. The calculated score provides fair assessment for poor and for good correlations of two signals. The two most promising metrics are identified in Reference [1], they are the CORA corridor method and EEARTH. A combined metric based on the improved CORA corridor method and EEARTH is then proposed for this document which has been fully validated using responses from multiple vehicle passive safety applications.

Figure 6.1 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.

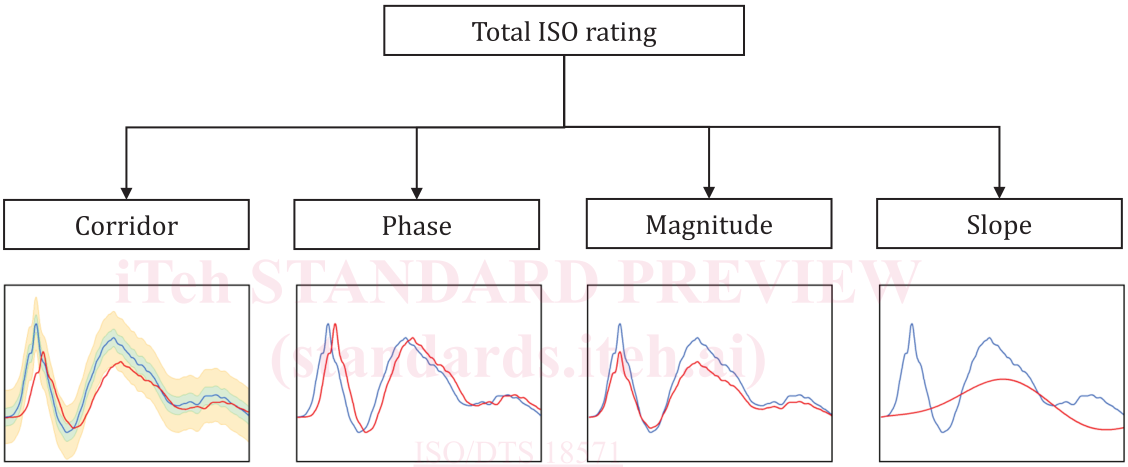


Figure 6.1 — ISO metric structure

6.2 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 (6.1) and (6.2)]. The corresponding weighting factors are shown in Table 6.1.

$$R = w_Z \cdot Z + w_P \cdot E_P + w_M \cdot E_M + w_S \cdot E_S \quad (6.1)$$

$$w_Z + w_P + w_M + w_S = 1 \quad (6.2)$$

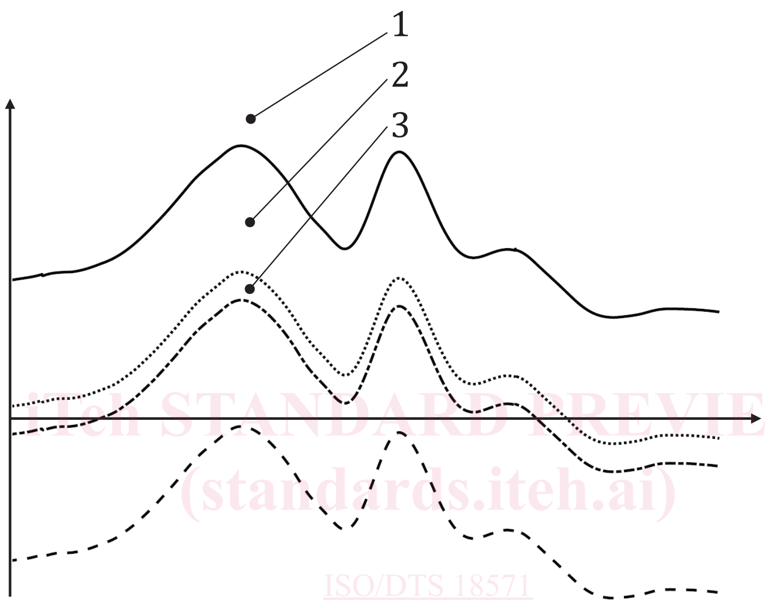
Table 6.1 — Weighting factors of the ISO sub-ratings

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

6.3 Corridor score

6.3.1 General

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 corridors 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 6.2. 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.



Key

1 rating = 0

2 0 < rating < 0

3 rating = 1

Figure 6.2 — 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 document applies the most common approach of using constant corridor widths for the whole duration of the dynamic response[1],[25].

6.3.2 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 shall 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 (6.3) shows the calculation of T_{norm} and it is calculated within the interval of evaluation.

$$T_{\text{norm}} = \max\{|\min(T)|, |\max(T)|\} \tag{6.3}$$

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 (6.4). The calculation of the absolute half width of the outer corridors [see Formula (6.5)] is similar to that of the inner corridors.

$$\delta_{\text{i}} = a_0 \cdot T_{\text{norm}} \qquad 0 \le a_0 \le 1 \tag{6.4}$$

$$\delta_{\text{o}} = b_0 \cdot T_{\text{norm}} \qquad 0 \le b_0 \le 1 \quad \text{and} \quad a_0 < b_0 \tag{6.5}$$

Based on these definitions the lower and upper bounds of the inner corridor are defined by Formula (6.6) and the lower and upper bounds of the outer corridor are defined by Formula (6.7).

$$\delta_{\text{i}}(t) = T(t) \pm \delta_{\text{i}} \tag{6.6}$$

$$\delta_{\text{o}}(t) = T(t) \pm \delta_{\text{o}} \tag{6.7}$$

Formula (6.8) 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 (6.8) when the absolute difference between both signals is in between $\delta_{\text{i}} \le |T(t) - C(t)| \le \delta_{\text{o}}$. 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 score. A linear ($k_{\text{Z}} = 1$), quadratic ($k_{\text{Z}} = 2$), cubical ($k_{\text{Z}} = 3$) or any other regression relationship can be defined accordingly.

$$Z(t) = \begin{cases} 1 & \text{if} \quad |T(t) - C(t)| < \delta_{\text{i}} \\ \left(\dfrac{\delta_{\text{o}} - |T(t) - C(t)|}{\delta_{\text{o}} - \delta_{\text{i}}} \right)^{k_{\text{Z}}} & \\ 0 & \text{if} \quad |T(t) - C(t)| > \delta_{\text{o}} \end{cases} \qquad k_{\text{Z}} \in N_{>0} \tag{6.8}$$

The final corridor score Z is calculated by averaging all single time step score $Z(t)$ as shown in Formula (6.9). The parameter N represents the total number of sample points (e.g. time steps) between starting and ending times of the interval of evaluation.

$$Z = \frac{\sum_{t=t_{\text{start}}}^{t_{\text{end}}} Z(t)}{N} \tag{6.9}$$

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[1].

Based on a sensitivity study of CORA[14] and as described in Reference [1], fixed width corridors are employed and the most appropriate metric parameters are identified as shown in Table 6.2.

Table 6.2 — 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)

6.3.3 Step by step procedure

First, 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 sample points.

6.4 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[23],[27] in addition to the corridor metric described before. The enhanced error assessment of response time histories (EEARTH) metric combines these three assessments to the global response error[27]. 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 as much as possible by expanding and compressing the time axis according to a given cost (distance) function[9].

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[8],[21]. Figure 6.3 shows the workflow of the procedures and the details of the algorithms are described in the following subsections.

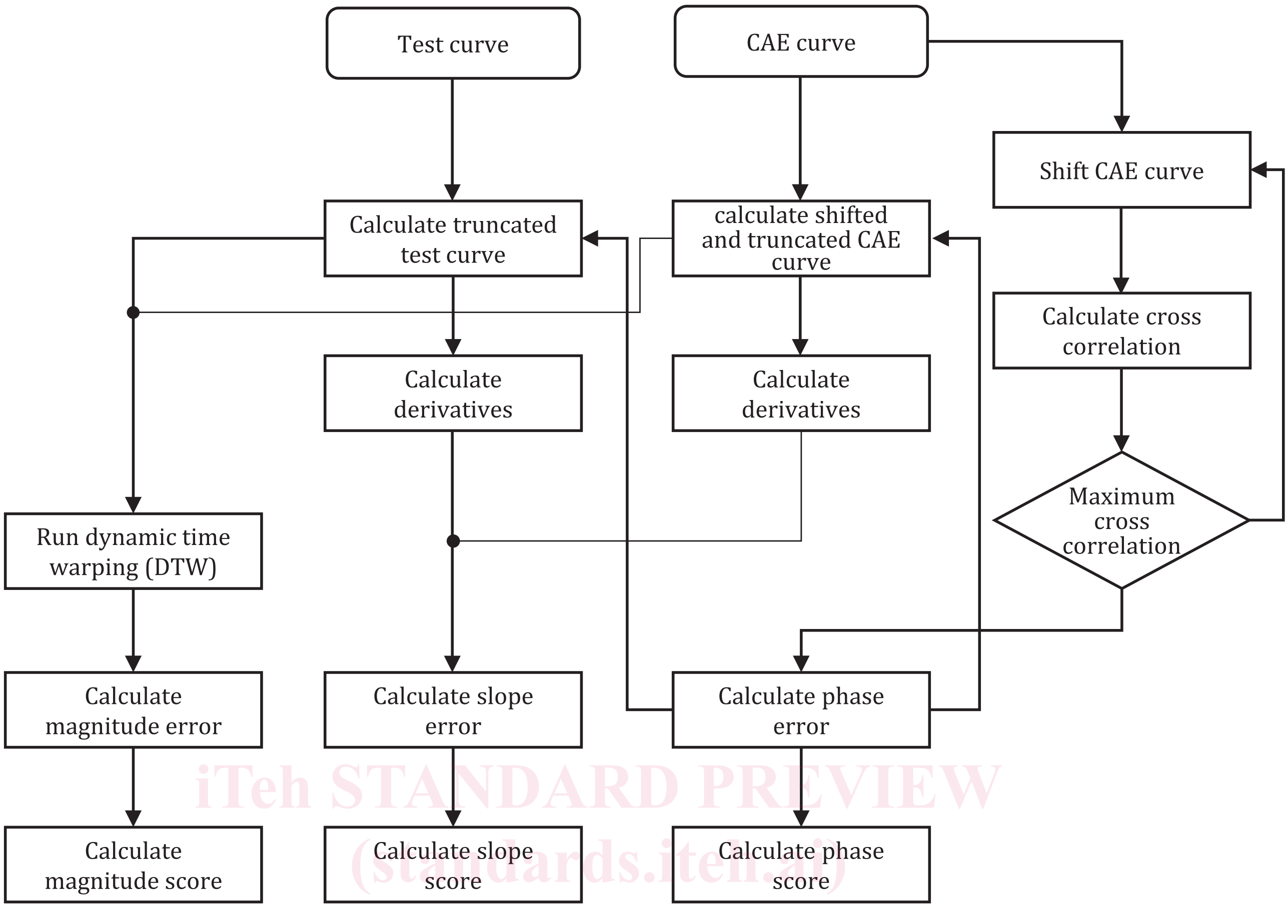


Figure 6.3 — Workflow of the calculation of phase, magnitude and slope scores

6.4.1 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 C are calculated until reaching the maximum allowable time shift limits $\varepsilon_P^* \cdot (t_{end} - t_{start})$.