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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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Foreword

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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, ρ, 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.

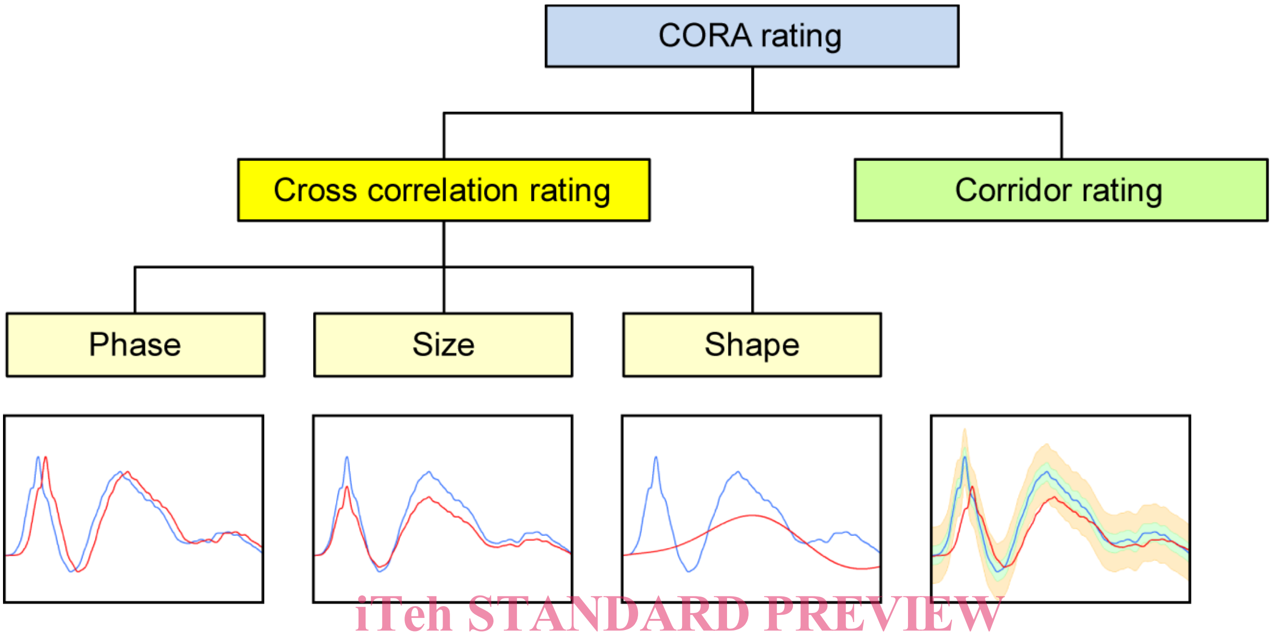

Figure 1 — CORA rating structure

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.

$$Z_{CORA} = w_{Z1} \cdot Z_1 + w_{Z2} \cdot Z_2 \tag{1}$$

$$w_{Z1} + w_{Z2} = 1 \tag{2}$$

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

$$w_{Z2a} + w_{Z2b} + w_{Z2c} = 1 \tag{4}$$

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*.

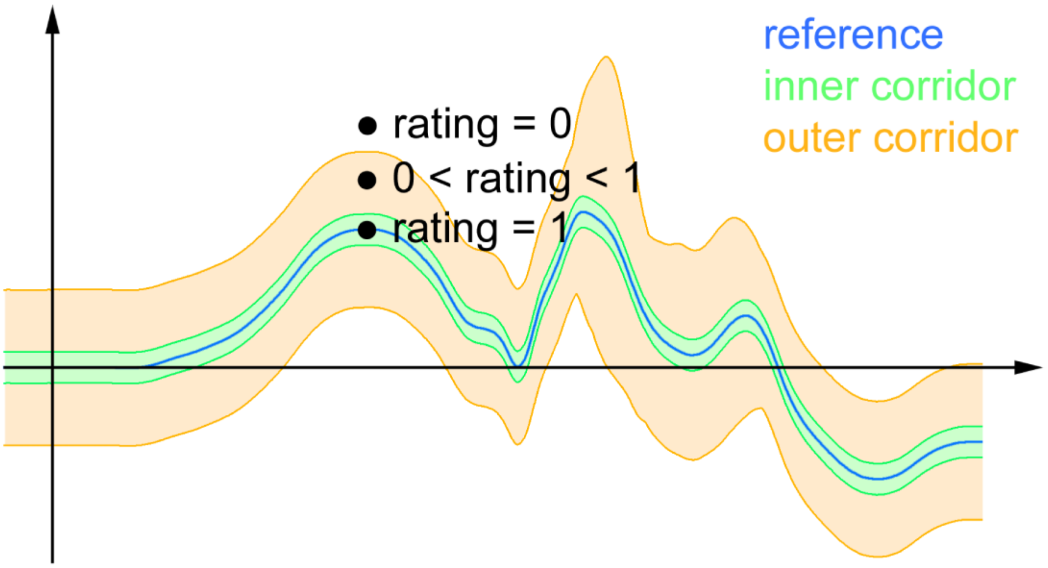

Figure 2 — Rating zones of the corridor method (corridors of constant width)[10]

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}.

$$T_{norm} = \max\left\{\left|\min(T)\right|, \left|\max(T)\right|\right\} \tag{5}$$

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.

$$\delta_i = a_0 \cdot T_{norm} \qquad 0 \le a_0 \le 1 \tag{6}$$

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

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).

$$\delta_i(t) = T(t) \pm \delta_i \tag{8}$$

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

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 $\delta_i \leq |T(t) - C(t)| \leq \delta_o$. 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.

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

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