WANDA validation

Version 3.6x

WANDA development team

Prepared for:

Deltares / Delft Hydraulics

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Report

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H5124

Client	Deltares / Delft Hydraulics
Title	WANDA validation

Abstract

This report is the summary of the validation of WANDA 3.6x.
WANDA simulations show a good to excellent agreement with pump trip, valve closure, SCADA controlled measurements and cavitation over a wide range of systems lengths (350 m to 330 km), pipe diameters (93.5 mm to 1.8 m), pipe materials (steel, PE, PVC and concrete) and applications (water, sewage water, oil).
The Transient Performance Indicator varies from 1.2% of the measured range for a well-established lab experiment to 5.1 % for measurements with cavitation to a maximum of 16% for a field measurement with many unknown parameters.
The general trend is that maximum pressures are slightly over predicted and minimum pressures are slightly under predicted.

References	WANDA research and development

Ver	Author		Date	Remarks	Review		Approved by	
Ver1	I.W.M. Pothof		September-2006		R.P.M. Lemmens			
Ver2	S van der Zwan		February-2008	Cavitation included	I.W.M. Pothof		W.M.K. Tilmans	

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Contents

1 Introduction

1.1 Background

The numerical models in WANDA and its predecessors have been validated since the 70s of the previous century. The primary objective of many measurement projects was to solve a particular problem, rather than to validate a software code. For this reason, measurements and numerical predictions have been compared partially and just enough to fit the purpose of the particular projects.

Several developments have been demanding for a more formal validation report, expressing the quality or at least the capability of a certain software program for simulation of fluid dynamics in pipeline systems, due to transient operations or operational control scenarios:

- Increasing trend in probability based or risk based design methodologies;
- Increasing complexity of industrial and utility pipeline systems;
- Integration of simulation models in operational control systems;
- Integration of simulation models in operator training systems.

A benchmark analysis has been conducted in a European project between 1998 and 2002, in which WANDA and three other commercially available transient simulation software tools have been benchmarked against a selected set of field and lab data. The results of this benchmark have been included for information.

1.2 Scope of work

Deltares / Delft Hydraulics has decided to collect a representative subset of the measurement reports from the past. An overview of the analysed validation measurements is given in chapter 2. A trainee has been appointed in summer 2006 to convert the old WANDA models (if available) or to remodel the systems in WANDA, version 3.60.

This database of validation measurements and WANDA models is continuously being extended by Delateres / Delft Hydraulics to maintain an up-to-date overview of the fluid dynamics simulation capabilities of WANDA.

The validation scenarios are included in the WANDA test bench, which is verified on every WANDA release.

1.3 Acknowledgements

The Industrial Hydrodynamics department (previous Industrial Flow Technology department) of Deltares / Delft Hydraulics acknowledges the Dutch Ministry of Economic Affairs (Min. EZ) for their co-sponsorship and the clients who have given permission to publish their field data.
The lab and field validation measurements in this document cover a subset of all projects in which WANDA calculations have been compared with measurements. Appendix A provides an overview of systems that have been included in this validation report to date.

2 Validation requirements

The selection criteria for inclusion in this validation report are the following:

- The measurement data must be of sufficient quality.
- The uncertainty of input parameters must be limited.
- The main WANDA application areas must be covered: i.e. sewage water, water transmission, oil transmission.
- The widest possible range of pipe diameters must be covered: 93.5 mm to 1800 mm.
- The widest possible range of system lengths must be covered: 350 m to 330 km.
- There must be balance between lab and field data: 3 lab systems and 2 field systems are included to date. One lab system is for cavitation measurements
- A variety of pipe materials must be included: PE, PVC, steel and concrete are included to date.
- A large variety of WANDA components and functionality must be covered: see appendix A, Overview of Systems.

3 Approach

The general approach for comparing the predicted and measured time series has been the following:

- The predicted steady state has been tuned to match the measurements to a reasonable degree.
- The predicted transient results have been compared with the measurements, based on visual inspection of the time series. Unknown parameters have been set to appropriate design values or marginally adjusted to obtain a visually acceptable result.
- An appropriate performance indicator, called the Transient Performance Indicator (TPI), is applied to quantify the difference between the prediction and measured time series. This TPI has a number of useful properties, which is elaborated in detail in appendix *B, Transient Performance Indicator*.

4 Results

The measurement time series have been obtained in 5 different systems with a total of 13 transient scenarios and 62 transient time series. The tables below summarise the validation results from different perspectives. Furthermore some typical graphs illustrate the validation results.

4.1 Overall results

In Table 4.1 the overall average results for the error in the series, the error in the maximum value, the error in the minimum and TPI are given. It is concluded from Table 4.1 that measured maximum field data are over predicted by 2.6% and measured minimum field data are under predicted by 7.9% of the measured range. These values indicate that the simulations generally show larger oscillations than reality. The under prediction in the maximum lab values is mainly caused by insufficiently stabilised steady state values in 3 out of 4 transient scenarios in system 1 (see appendix A); this is illustrated in Figure 4.1 below. The overall Transient Performance Indicator (TPI) of WANDA is 7% for simulation of field data and about 4.2% for simulation of lab data.

Table 4.1: Average performance indicators for field and lab data

	Field or lab data		
Data	field	lab	Grand Total
Average of Error series [%]	8,1	6,3	6,8
Average of Error max [%]	2,6	-0,3	0,5
Average of Error min [%]	-7,9	-1,1	-3,0
Average of TPI [%]	7,0	4,2	5,0

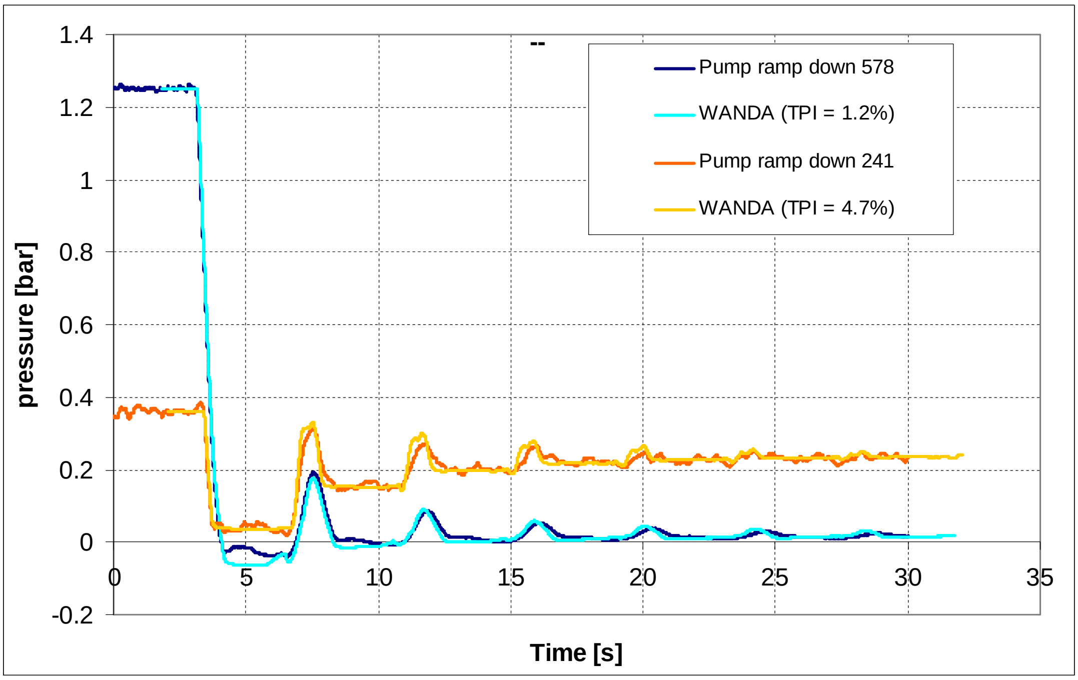

Figure 4.1 Examples of predicted and measured pressures with TPI values of 1.2% and 4.7%.

4.2 Results per output quantity

Table 4.2 shows the WANDA performance indicators for the discharge and the pressure. Table 4.2 further confirms that WANDA generally shows a small over prediction of the maximum values and a small under prediction of the minimum values. These observations are consistent for all output quantities (i.e. transient flows and pressures). The overall discharge TPI (4.8%) is slightly smaller than the overall pressure TPI (5.0%).
The lab average discharge TPI in Table 4.3 is only based on the results of system 5 from Table A.1. The reason is that for the other lab system the flows could not be recorded fast enough in the relatively small systems. Only specially prepared flow meters have the capability to record instantaneous flows at a sufficient acquisition rate (about 100 Hz). In system 5 from Table A.1 specially prepared flow meters were used. The field data have been obtained from a 15 km sewage effluent line and a 330 km crude oil pipeline, operated with drag-reducing agents; typical results are shown in Figure 4.2 and Figure 4.3 below.

Table 4.2: WANDA performance indicators per output quantity

	Output quantity		
Data	Discharge	Pressure	Grand Total
Average of Error series [%]	5.2	7.0	6.8
Average of Error max [%]	-2.5	1.0	0.5
Average of Error min [%]	-5.1	-2.6	-3.0
Average of TPI [%]	4.8	5.0	5.0

Table 4.3 WANDA TPI per output quantity and field/lab data

Average of TPI [%]	**Output quantity**		
Field or lab data	Discharge	Pressure	Grand Total
field	6.4	7.1	7.0
lab	4.0	4.2	4.2

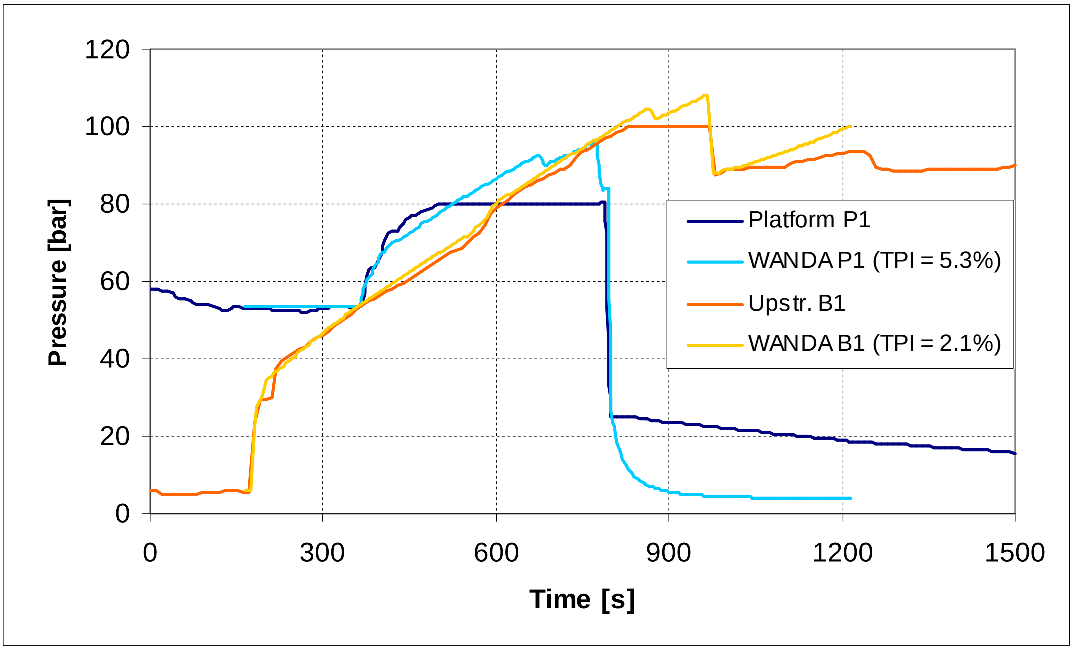

Figure 4.2: Typical WANDA performance on a 330 km crude oil transmission line (horizontal lines in measurements are cut off by the SCADA system)

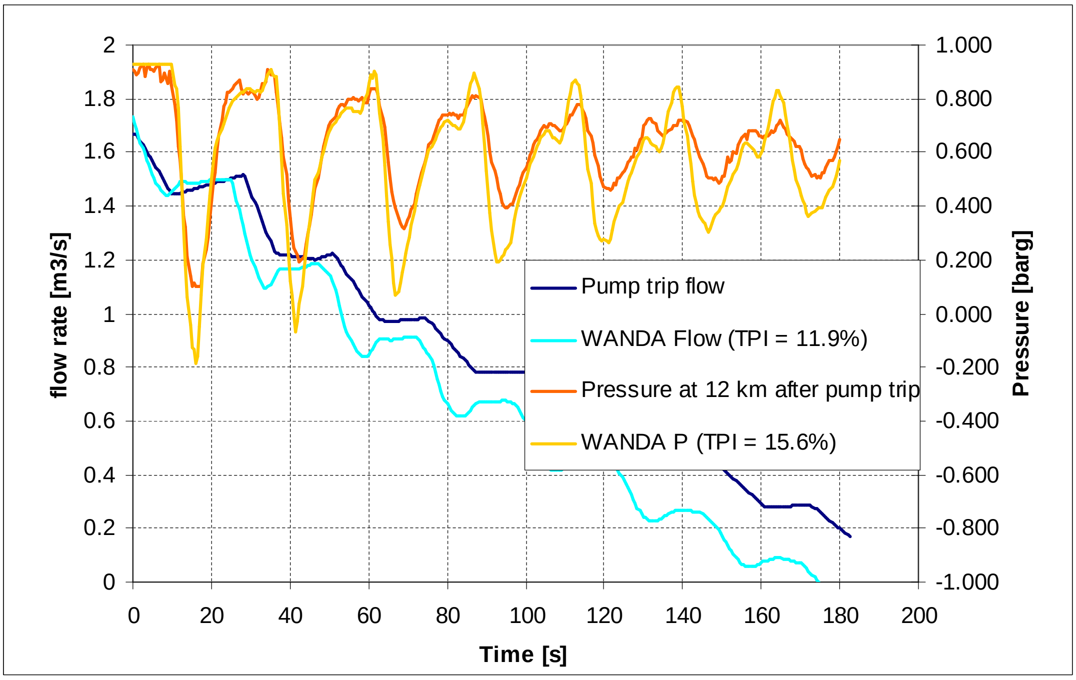

Figure 4.3: Largest TPI values in WANDA validation

4.3 Cavitation

Table 4.4 shows the results for the three transients from system 5 in Table A.1 including 5 pressure signals and 2 flow signals. In test 126 en test 129 cavitation occurs, test 123 has no cavitation. In Figure 4.4, Figure 4.5 and Figure 4.6, typical time series of the pressure are plotted for the systems. Again it can be seen that the maximum value is slightly over predicted and the minimum value under predicted. The implosion of cavitation causes pressure fluctuation and as said simulations generally show larger oscillations than reality. It can be concluded from Table 4.4 that WANDA predicts cavitation excellently. The overall TPI for cavitation is 5.1%. (In Table 4.4 test 123 has been included in the grand total, but it has no cavitation)

Table 4.4 WANDA performance indicators for the two cavitation measurements

	Scenario reference			
Data	test 123	test 126	test 129	Grand Total
Average of Error series [%]	6,4	5,9	8,2	6,9
Average of Error max [%]	-0,8	3,1	0,2	0,8
Average of Error min [%]	-0,7	-3,8	-2,3	-2,3
Average of TPI [%]	3,2	5,6	4,6	4,5

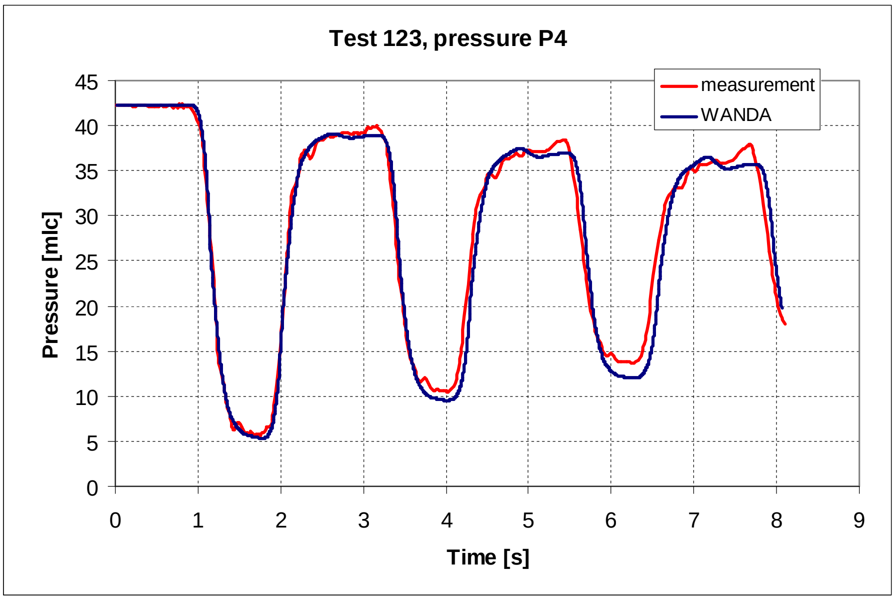

Figure 4.4 Validation results from measurement with no cavitation

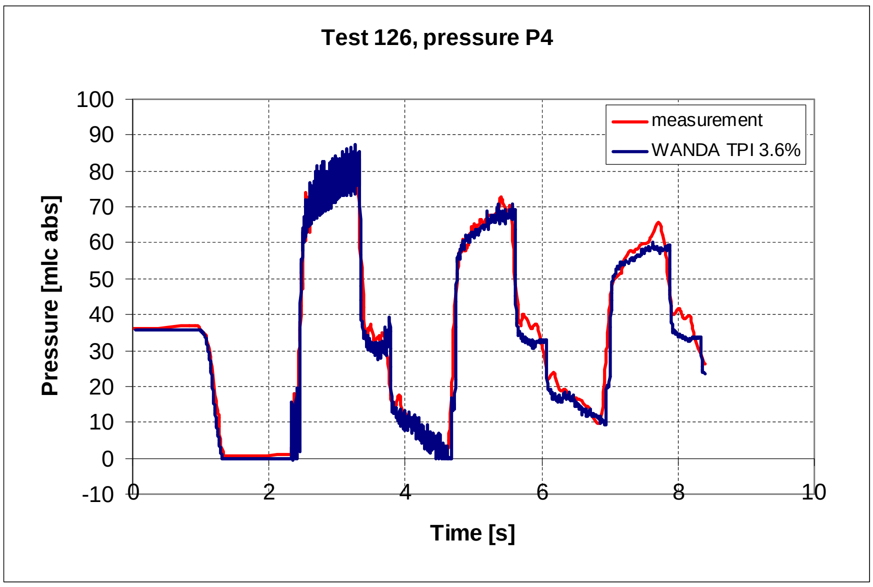

Figure 4.5 Validation results from cavitation measurement

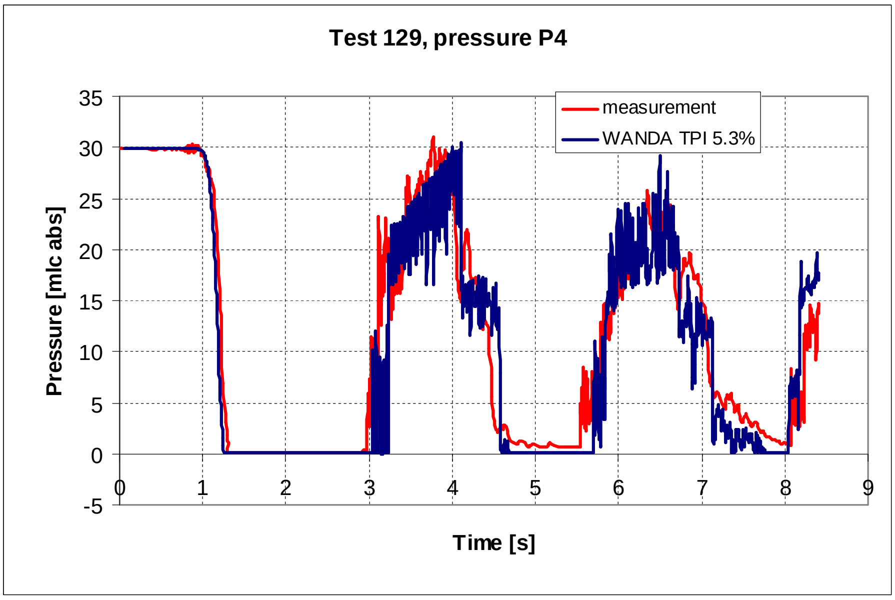

Figure 4.6 Validation results from cavitation measurement

5 Conclusions

WANDA simulations show a good to excellent agreement with pump trip, valve closure, SCADA controlled measurements and cavitation over a wide range of systems lengths (350 m to 330 km), pipe diameters (93.5 mm to 1.8 m), pipe materials (steel, PE, PVC and concrete) and applications (water, sewage water, oil).
The Transient Performance Indicator varies from 1.2% of the measured range for a well-established lab experiment to 5.1 % for measurements with cavitation to a maximum of 16% for a field measurement with many unknown parameters.
The general trend is that maximum pressures are slightly over predicted and minimum pressures are slightly under predicted.

Reference

[1] Pothof, I.W.M., Stewardson, D., A statistical technique for comparing simulated and measured pressure surges, Conference Proceedings of 4th Conference on Water Pipeline Systems, BHR Group, 2001 (p. 349-361).

[2] Kranendonk, M., Validatie WANDA (versie 3.53); trainee report Marcel Kranendonk, WL report H4587.40, 2006. (in Dutch).

[3] P. Baker et al., WP6 Benchmarking analysis, benchmarking report, EC project SMT4-CT97-2188, doc. ref. 8664-51, BHRGroup, UK.

[4] Waterloopkundig laboratorium, Cavitatie door waterslag in horizontale leidingen, Rapport metingen en berekeningen, WL report M1116, 1972. (in Dutch).

A Overview of the systems

Table A.1 Overview of systems included in validation to date

System	Application	Transient Scenario(s)	Lab/field data	Description	Pipe material	Nr. of transients	Nr. of signals / transient	Validated functionality
1	Water transmission	Pump trip, Pump speed variations	Lab, Delft	650 m, ∅235mm, R&D system for gas pocket detection.	PVC	5	4	Pump (sub)model for trip and speed drive
2	Sewage effluent	Pump trip	Field, Bath (NL)	15 km, dual line ∅1.5-1.8 m,	Concrete	2	7 , 4	Pump trip.
3	Water transmission	Valve closures	Lab, Perugia	350 m, ∅93.5mm, valve downstream.	PE	2	1	Valve stroking
4	Crude oil transmission	ESD in booster station	Field	330 km, ∅20″, booster station after 220 km. Operated with Drag-Reducing-Agents (DRA).	Steel	1	5	Large portion of WANDA control components. Reduced DRA-friction. Local degassing.
5	Water transmission	Idealised pump trip with high and low pressure vessel.	Lab, Delft	1450 m, ∅100mm.	Steel	3	7	Valve stroking, cavity growth, cavitation implosion.
Totals						13	62	

Table A.2: Overview of systems to be included on short term in the validation database

System	Application	Transient Scenario(s)	Lab/field data	Description	Pipe material	Nr. of transients	Nr. of signals / transient	Validated functionality
6	Water systems	Flow deceleration by downstream pressure vessel.	Lab, Delft	50 m, ∅ 500mm.	Steel		2	Undamped check valve slam

Table A.3: Systems analysed but rejected

System	Application	Transient Scenario(s)	Lab/field data	Description	Pipe material	Nr. of transients	Nr. of signals / transient	Reason for rejection
7	Ground water production	Pump trip	Field, Seppe		Steel	1	3	Unknown initial gas pocket size, unknown dissolved gas concentrations.

B Transient performance indicator

Paper [1] has identified a number of requirements for a performance indicator of the lack-of-fit between measured and predicted transient signals, which are the following:

- it should account for bias (systematic error between measurement and prediction)
- it should account for overshoot
- it should be scaled to a percentage scale so that time series of completely different magnitude can be compared, independent of the unit system.
- it should account for the fact that a more fluctuating measurement is more difficult to predict.
- It should account for the way the prediction results are used in practice.

The paper proposes the following performance indicator, called Transient Lack-of-Fit (TLoF):

$$TLoF = w_1 \cdot \left|e_{\max}\right| + w_2 \cdot \left|e_{\min}\right| + w_3 \cdot e_{ts} \qquad (2.1)$$

where

w_i		weights assigned to e_{max}, e_{min} and the time series error. The sum of the weights must equal unity.
e_{max}	$= 100 \cdot \dfrac{\max\limits_t \left(x_p(t)\right) - \max\limits_t \left(x_m(t)\right)}{\sigma_{Xm}}$	error on the maximum value, expressed as a percentage of the measured standard deviation
e_{ts}	$= 100 \cdot \dfrac{\sqrt{MSE}}{\sigma_{Xm}}$	average time series error, expressed as a percentage of the measured standard deviation
σ_{Xm}	$= \sqrt{\sum\limits_{t=1}^{M} \dfrac{\left(x_m(t) - \overline{x_m}\right)^2}{M-1}}$	standard deviation of the measured time series.
MSE	$= \sum\limits_{t=1}^{M} \dfrac{e^2(t)}{M-1}$	mean squared error
$e(t)$	$= x_p(t) - x_m(t)$	error time series, defined as the prediction minus the measurement

This TLoF parameter does meet all of the above requirements. The TLoF indicators of different time series of different typical critical operations are aggregated by simply calculating the average value of the TLoF indicators. However, the main disadvantage of this performance indicator is the fact that the scaling to a percentage using the standard deviation is not intuitive. A much more intuitive scaling is obtained if one would divide by the measured range instead of the standard deviation. This transients performance indicator (TPI) is defined as:

$$TPI = w_1 \cdot \left|e_{\max}\right| + w_2 \cdot \left|e_{\min}\right| + w_3 \cdot e_{ts} \qquad (2.2)$$

where

e_{max}	$=100\cdot\dfrac{\max_t\left(x_p(t)\right)-\max_t\left(x_m(t)\right)}{Rnge}$	error on the maximum value, expressed as a percentage of the measured range
e_{ts}	$=100\cdot\dfrac{\sqrt{MSE}}{Rnge}$	average time series error, expressed as a percentage of the measured range
$Rnge$	$=\max_t\left(x_m(t)\right)-\min_t\left(x_m(t)\right)$	range of the measured time series

The TPI definition allows to assign weights to the three type of errors. We decided to assign the following weights

Table B.1: Weights of maximum, minimum and time averaged errors

parameter	value
w_1	0.3
w_2	0.3
w_3	0.4

These values are consistent with the design practice and reflect that the extreme transient values typically extreme pressures are together more important than a correct prediction of the evolution in time.

C EC benchmark

A benchmark analysis has been conducted and reported in EC project SMT4-CT97-2188, Transient Pressures in pressurised conduits for municipal water and sewage water transport [2]. This project has been performed from 1998 to 2002. Four commercially available simulation software packages were included in the benchmark analysis. The university of Lisbon (EC-project partner) has performed the WANDA simulations.

Table C.1: Ranking of performance indicator values, from EC project (1 = smallest error; 4 = largest error)

network	*tests*	*Parameter*	*Comm. 1*	*Comm. 2*	*Comm. 3*	*WANDA*
UoP LSP	1	h1	2	3	1	4
UoP LYP	1	h1	2	4	3	1
		h2	3	4	2	1
UoPP	1	h1	2	3	4	1
UoP SR	1	h	4	3	2	1
UoP SA	1	h	4	2	3	1
UoL Net	No Leak	T1	3	4	2	1
		T2	2	4	3	1
		T3	2	4	3	1
	Leak 6.1	T1	2	4	3	1
		T2	2	4	3	1
		T3	2	4	3	1
UoL single	No Leak	TR1	2	4	3	1
		TR2	3	4	2	1
		TR3	3	4	2	1
	Leak Up1	TR1	3	4	2	1
		TR2	3	4	2	1
		TR3	2	4	3	1
LNEC	Closure	Transducer	4	3	1	2
Francis 140	Load Reject	Transducer	4	1	2	3
DH J1181	Trip 12	D1800_flow	2	3	4	1
		D1800_P1	1	3	2	4
		D1800_P2	4	3	2	1
		D34_N_P	4	3	2	1
		D61_N_P	4	3	2	1
		D34_Z_P	2	3	4	1
		D61_Z_P	4	2	3	1
DH J1180b	Speedup 13	D1800_flow	4	3	2	1
		D1800_P1	4	2	3	1
		D1800_P2	4	2	1	3
		D34_Z_P	3	4	2	1
	Speeddn 16	D1800_flow	2	3	1	4
		D1800_P1	3	4	2	1
		D1800_P2	1	3	2	4
		D34_Z_P	2	1	3	4
		D61_Z_P	2	1	3	4
	Trip 17	D1800_flow	2	3	1	4
		D1800_P1	1	3	2	4
		D1800_P2	4	3	2	1
		D34_Z_P	1	3	2	4
		D61_Z_P	2	3	1	4