Recommendations

regarding the use of numerical simulations to demonstrate compliance with technical and regulatory requirements on the rail network

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Foreword

This document is the first published by the EPSF concerning numerical simulation.

It is the result of a think-tank animated by the EPSF including participants from the rail sector.

It is intended to evolve according to advances in this field.

Contents

By clicking on one of the lines of the summary, you go directly to the corresponding chapter or article

1. Scope of application of this document

This document contains instructions and recommendations regarding the use and validation of simulations (numerical, analytical, hardware in the loop etc.) for demonstrations of compliance with the technical and regulatory requirements applicable for rail systems. This is a general guide summarising the conclusions reached by experts in the railway sector, often with a view to updating future standards in order to precisely control the correct usage of simulations.

Although they are particularly focused on safety demonstrations for certification and authorisation purposes, these recommendations are intended to be sufficiently wide-ranging to be used in other circumstances: assessments, research, development etc.

However, this document is not intended to be used for the process of engineering of simulation tools, a process ranging from design through to certification. Its purpose is to ensure that simulations tools are used in such a manner as to ensure that the results obtained correspond to the real usage conditions of the equipment being tested.

2. Context

The issue of tests to be performed for rolling stock and infrastructure for safety demonstrations - with a view to obtaining authorisation or certification - has been the subject of much debate in the rail sector. The costs, safety constraints, organisational challenges (particularly finding available train access to the network) and sometimes the limitations (the difficulties encountered in trying to conduct physical tests for certain extreme conditions such as overspeed, real infrastructure configurations, atmospheric conditions, degraded modes, safety risks, etc.) of these tests have led stakeholders to find alternative ways (lab testing, dedicated test plants, numerical simulation etc.) in order to keep field tests to a minimum wherever possible.

Already widely-used in the design and pre-validation of sub-systems, numerical simulation[1] is still relatively rare in the validation phase (certification and authorisation), where trials are still generally used to provide sufficient results for compliance assessments.

More specifically, the technical specifications for interoperability (TSI) set result targets which much be reached but do not specify the means used to achieve them, other than to explicitly reference the standards or parts of standards which apply to each technical domain (braking, dynamic behaviour, current collection etc.). The norms vary in terms of the means which they deem acceptable for demonstrating compliance with the applicable standards: the regulations may stipulate compulsory testing, or else leave significant room for simulation, or else decline to specify.

Anticipating the trend for more widespread use of alternatives to field tests for compliance demonstrations, the aim of this document is to set out the conditions for accepting evidence other than test reports, included in certification files or final assessment dossiers.

[1] understood in this paper as the replacement of a decision-making process based on the measurement of *in situ* parameters by the production of results from the modeling of the behavior of this system

Numerical simulation can be used to improve our understanding of certain phenomena, enabling experts to study a broader range of cases than those covered by physical trials (limited by parameters such as weather, geographical range and configuration). For example, simulation allows us to simulate combinations of defects which may not be covered by regular trials, or to investigate how equipment functions in fail-safe mode, or to determine the limits of a specific component or sub-system. Nevertheless, the primary purpose of simulation is not to cover ever more scenarios which current tests do not address, but rather to help optimise the testing process and minimise industrial risks.

The most common approach adopted by manufacturers is to make extensive use of numerical simulations and laboratory testing to validate decisions in the design and pre-production phases, thereafter, making more targeted use of simulation to prepare, guide and minimise the actual physical trials required. Take the example of a current collection: a manufacturer with a mature tool and a robust process can use simulation to identify those load conditions whose test results do not raise interpretation issues or problems, thus drawing up a physical testing program focusing on those cases identified as 'critical' by the simulation, as well as cases corresponding to singularities which simulation alone cannot analyse satisfactorily.

Generally speaking, a certain number of essential tests (on tracks, dedicated loops or in lab conditions) are required to produce reliable numerical models, observing the correlation between these models and the measurements and observations derived from physical testing, thus ensuring that the results deliver a sufficient degree of reliability.

3. Terminology used in this document

Hardware in the Loop (HIL): Numerical simulation of the operations of a system for which the material environment is simulated: the inputs and outputs of the test system (hardware) are connected to a computer which reproduces the environmental conditions.

Technical and regulatory requirements: All the conditions set out in the technical specifications for interoperability, and which manufacturers requesting authorisation must satisfy.

Simulation tool: All the material resources and software used to simulate the behaviour or operations of the equipment being tested.

Model for the equipment being tested: Representation of the equipment within the simulation tool (may be the object itself, in the case of HIL simulations).

Model of the environment in which the equipment operates: The representation, within the simulation tools, of the environment in which the equipment in question will be used.

Result of the simulation: Output of the simulation tool, providing a model of the tested equipment within the modelled environment.

4. General principles governing the use of numerical simulations to demonstrate safety and compliance with technical and regulatory requirements

4.1. Qualification of the simulation tool

The development and qualification of simulation tools must be part of a broader quality process (e.g. ISO9000) implemented by producers and users.

All tools must be covered by a validation plan[2] leading to its qualification for the purpose intended by the user, in coordination with the producer.

The standard validation process consists of demonstrating that the simulation results obtained using the reference scenarios – equipment with different references, properties and levels of complexity, within specified testing environments – correspond to the physical reality of the simulated phenomenon. This process allows to define the scope of representativeness of the simulation tool, with reference to its intended use.

The validation plan also includes non-regression tests for tools during version changes and updates to operating systems and host machines.

Reference objects and environments, number and representativeness must all be documented in the validation plan for the simulation tool.

A feedback log on user experiences of the tools should also be maintained.[3]

4.2. Skills required to use the simulation tool – The process

The user must verify that the tool is compatible with the purpose of the simulation and that the models are representative, as well as evaluating (qualitatively and quantitatively) uncertainty and the sensitivity of the models. Furthermore, the user is responsible for critically interpreting the results obtained (pertinence, exhaustiveness) and, where necessary, performing additional verifications on the simulation tool.

The organisation using the simulation tools is responsible for establishing and implementing quality processes for the activities concerned.

The organisation must have processes in place to guarantee their capacity to perform simulations, maintain a sufficient level of expertise among users, and maintain the independence between designers

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[2] Reference: website of the Association Française d'ingénierie système (AFIS): https://www.afis.fr

[3] This type of process is stipulated in certain standards: for example, EN 50128 - "Railway applications - Communication, signalling and processing systems," aimed primarily at product designers - requires a "Software Quality Assurance Plan." To be precise, the validation process introduces the notion of a "Software Verification Plan." It is worth noting that Standard EN50128 requires these processes to be entrusted to an "independent software assessment expert."

and validation experts. More specifically, the organisation must set out an internal validation process for the simulations performed, allocating the tasks of verification and approval to discrete individuals.

By way of an example, this may take the form of an ISO certification combined with a procedure which abides by the terms of standard EN ISO/IEC 17025 regarding the general requirements for calibration and testing laboratories.

4.3. Validity of equipment and environment models

At the very least, simulations should be covered by an accompanying document specifying the following information:

General framework:
- Purpose of this simulation;
- Reference standards (where applicable).

Validity of the numerical model:
- The individual elements which constitute the equipment being studied (e.g. for mechanical modelling: hypotheses for the representativeness of the models (periodicity, symmetry, etc.), behavioural models, type of components used, mesh density if finite elements are used, integration type, modelling of connections, modelling of the material's behaviour, resolution solver, etc.);
- The physical data which comprise the behavioural model and their identification/evaluation method (as relevant);
- The individual elements which constitute the environmental model for the equipment being studied (boundary conditions, application of different loads, internal interactions and connections, etc.);
- The calculation method (type of numerical resolution and algorithm);
- An analysis of the sensitivity of the model's defining parameters and its scope of validity.

Simulations and analyses:
- Input data (data source, uncertainty, modelling for variability, etc.);
- Method used to analyse results (and explanation for choice of method);
- Proof that the simulation was executed correctly (numerical convergence);
- Correlation of calculations to reference tests.

If multiple models are combined, this information should be provided for each model. Details of how the interface between the models (for example between rolling stock and infrastructure) is handled should also be specified.

As a general rule, model validation should be backed up by correlation with one or more real tests. In this case, the explanatory note accompanying the simulation should specify the methodology used to establish this correlation, including details such as the testing conditions, the degree of precision/uncertainty of the measurements and the representativeness of the boundary conditions.

4.4. Validation of simulation results

If the simulation tool is qualified, the user's aptitude verified and the equipment models (and where necessary the environment models) have been validated, the simulation results are considered to be representative of the real behaviour of the equipment in question within the scope of application specified in the numerical simulation dossier.

For simulation results to be acknowledged as proof of compliance, there are two possibilities:
- The applicable reference documents and/or standards define the conditions in which simulation can be used;
- The applicable reference documents and/or standards do not directly deal with the use of simulations.

In the first scenario, if the standards and/or regulatory requirements have been respected then the simulation results will be accepted.

In the latter scenario:
- There may be generally-accepted principles in fields where the knowledge and tools available provide a sufficient degree of reliability to dispense with physical trials, allowing the simulation results to be accepted;
- In other cases, a risk analysis taking the following criteria into account must be conducted:
  - Scope of the simulation: Does the simulation cover all of the conformity demonstrations required in the field in question or is it to be considered in conjunction with other test results in cases involving complex configurations (fail-safe modes, excess speed, values measured, etc.),
  - Criticality of the simulation: You need to specify the safety considerations associated with each demonstration. While the evidence provided must still comply with the applicable reference standards, the degree of reliability expected from a simulation performed to establish noise levels, system performance indicators or pantograph/overhead line behaviour may be different from that required of a simulation designed to validate dynamic behaviour or braking.

4.5. Content of the demonstration file when using numerical simulations

In addition to those elements relating to the numerical simulation (cf. Paragraph 4.3), the following documents must be included in the application file:
- A summary of the validation plan for the simulation tool;
- A user declaration confirming compliance with the validation plan for the tool;
- A summary of the processes in place to guarantee the organisation's capacity to perform simulations, maintain a sufficient level of expertise among users, and maintain the independence between designers and validation experts.

5. Specific conditions for Hardware In the Loop

The concept of “Hardware in the Loop” (HIL) simulations is based on using real components or pieces of equipment in direct interface with numerical simulation models. This represents a specific manner of implementing simulations.

In the standard implementation model, both the equipment and the environment are studied. While the simulation unfolds, the environmental model provides stimuli to the model for the equipment being tested. In return, the latter updates its own outputs which then have consequences for the environmental model. The system is looped and sequenced, the results of the simulation are updated by a numerical solver for each "time interval." Since the "time" reference is not critical, the duration of a "time step" is variable and can be adapted to the calculation capacities of the computer running the models.

The limitations of "classic" simulation are primarily linked to the availability of the model and the extent to which its behaviour corresponds to the real equipment. If the object of study is a complex system, such an on-board calculator combining electronics and a software programme, it becomes very difficult to model its all-round behaviour without making certain simplifications.

HIL thus provides a solution, using the real object rather than a model. The simulation thus generates the environment, since the interactions between the two worlds - virtual and physical - are covered by interfaces which convert numerical data into electrical signals and vice versa. The "time step" of the simulation should be adapted to the reaction time of the equipment being studied. HIL simulation is considered to be "real time.".

To put it another way, HIL simulation is a technique which allows us to trick the equipment into behaving as it would in its real usage environment. It thus becomes possible to subject equipment to all imaginable situations, including fail-safe conditions, in the interests of exhaustive testing.

The conditions for accepting the results of HIL simulations should not be fundamentally different from those which apply to "classic" numerical simulations:

- The simulation tool must be qualified, based on the same principles;
- Model validation applies only to the environmental model;
- A summary of the processes in place to guarantee the organisation's capacity to perform simulations, maintain a sufficient level of expertise among users, and maintain the independence between designers and validation experts.

Établissement public de sécurité ferroviaire – Direction des Autorisations
60 rue de la Vallée – CS 11758 – 80017 AMIENS Cedex