Deliverable D 4.1
Virtual Certification: State of the art, gap analysis and barriers identification, benefits for the Rail Industry

Project acronym:	PLASA 2
Starting date:	01/09/2018
Duration (in months):	26
Call (part) identifier:	H2020-S2RJU-CFM-2018
Grant agreement no:	826151
Due date of deliverable:	14 – 30/10/2019
Actual submission date:	04-12-2019
Responsible/Author:	Michael Juris (DB)
Dissemination level:	PU
Status:	Issued

Reviewed: (yes)

Document history		
Revision	*Date*	*Description*
1	30-10-2019	First draft
2	04-12-2019	First formal issue
3	05-05-2020	New section 10.6, update section 11

Report contributors		
Name	Beneficiary Short Name	Details of contribution
Mac-Lan NGUYEN-TAJAN	SNCF	
Phil GARNER	BT	
David JAKOBI	SIE	
Eva TERRON	CAF S.A.	
Ion SOLABARRIETA	CAF I+D	
Michael JURIS	DB	

Table of Contents

Table of Figures

1. Executive Summary

This document of the Shift2Rail/Cross Cutting Activities project PLASA 2 gives an overview on current virtual approaches in the approval processes (authorisation and customer acceptance) of railway vehicles, sub-systems and components. It presents the different virtual approaches and their requirements. Furthermore, it shows how and at which level these approaches are implemented, analyses the barriers, which hinder the dissemination of virtual approaches and outlines the benefits when introducing them.

Basis for the results in this deliverable is a state-of-the-art analysis of standards in the railway sector, which already allow the use of virtual testing. Examples include the fields of running characteristics, aerodynamics and crashworthiness. Findings from past railway-specific projects in the FP7/TrioTRAIN framework, that dealt with the improvement and propagation of virtual methods, are also included in this document. Additionally, results from current and past Shift2Rail projects, such as PINTA or CONNECTA, are also taken into consideration. Some information on the use of virtual testing for the approval of other systems in similarly safety-critical industries such as the automotive, the aircraft, the spatial and the nuclear sectors, is also given.

Virtual Testing in general is the use of simulations, HiL (Hardware in the Loop) and SiL (Software in the Loop) test rigs or a combination of them and can be used instead of or in combination with field tests in the approval process. These tools need to be verified and validated. The verification and validation process, in this context, is always based on a comparison to a reference object, which could be the real physical equivalent or a so-called benchmark object. In order to assess this comparison and to determine if the model is a valid representation of the real system, specific acceptance criteria, which differ greatly in the reviewed fields, need to be fulfilled. It is shown that variability and uncertainties as they exist in the real world, need to be sufficiently considered in a simulation procedure.

Different scenarios for the integration of virtual testing in order to demonstrate conformance to requirements in the approval process are conceivable, depending on the level to which virtual testing is implemented:

- Full virtual testing – either the use of models/simulations or SiL and HiL
- Partial virtual testing - a blend of virtual testing and field tests
- Extension of Approval – using models for already homologated systems/products to validate changes in terms of design change of system/product or change in operational environment

The barriers that can be identified when trying to introduce virtual testing are diverse. Among others, the analysis in the different fields clearly shows a lack of harmonisation and standardisation that complicates the dissemination of virtual testing.

The implementation of virtual methods can help to reduce significantly the life-cycle costs (LCC) of a vehicle due to savings in the approval process. In addition, an increase in the capacity of the railway transport system is possible, as well as an increase in the reliability of a vehicle. Virtual tests also provide the possibility to analyse safety-critical situations without risks.

All in all, the results in the deliverable show, that virtual methods are implemented, but on different levels in the various fields in the railway sector. Some fields are a kind of pioneer and exploit the technically possibilities and provide accepted verification and validation approaches, which can be adapted. The benefits of virtual testing are obvious and at least the purely technical barriers could be overcome with increasing computational and research power. However, there is a need for harmonisation of the processes to support the acceptance of virtual methods.

2. Abbreviations and acronyms

AC/DC	Alternating / direct current
AsBo	Assessment Body
CCA	Cross Cutting Activities
CFD	Computational Fluid Dynamics
CSM-(RA)	Common Safety Method-Risk Assessment
CWC	Characteristic Wind Curve
DeBo	Designated Body
ECN/ETB	Ethernet consist network / Ethernet train backbone
EMC	Electro Magnetic Compatibility
EoA	Extension of Approval
ERA	European Union Railway Agency
FEM/FEA	Finite Element Method/Finite Element Analysis
HiL	Hardware in the Loop
HST	High Speed Train
IP	Innovation Program
LCC	Life-cycle costs
MBS	Multi-Body Simulation
NASA	US National Aeronautics and Space Administration
NNTR	Notified national technical rules
NoBo	Notified Body
NSA	National security Agency
S2R	Shift2Rail
SiL	Software in the Loop
TCMS	Train Control and Monitoring System
TRL	Technology Readiness Level
TSI	Technical Specification for interoperability
VC	Virtual Certification
VT	Virtual testing
WP	Workpackage
WRM	Wheel Rotation Monitoring
WSP	Wheel Slide Protection

Field Tests	are tests executed on the production train on a real railway track in operational conditions.
Certification	is a third-party attestation related to products or systems provided by a certification body.
Homologation/Authorisation	is the granting of approval by an official authority. In context of the European railway industry Homologation/Authorisation is the granted approval by NSA/ERA for placing products on the market. In some cases, the word homologation is used for subsystem or component level while authorisation is for the whole systems (train, signalling system, …).In this document both definitions will be used equally.
Model	is a mathematical and/or physical representation of a system or a process.
Qualification	is an activity to ensure the ability of a system or tool to fulfil the requirements of the intended use.
Simulation	is the use of a similar or equivalent system to imitate a real system so that it behaves like or appears to be the real system.
Tool	is an in house or vendor framework in which one may develop or embed models enabling the execution of tests. It can be software and/or hardware and parts of the real system can be installed in the tool.
Validation	is an activity to prove the conformance of the complete functionality to specified requirements and the intended use. The validation concept ensures that the correct work product is the right product to validate. ("Are we building the right product?") In simulation context: The process of determining the degree to which a model is an accurate representation of the real world.
Verification	is a set of tasks that ensure correct implementations techniques are in place to verify that the right work product is being integrated correctly. ("Are we building the product right?") In simulation context: The process of determining that a computational model accurately represents the underlying mathematical model and its solution from the perspective of the intended uses of modelling a simulation
Virtual certification	is the use of evidence from virtual testing to support the authorisation/homologation/certification process
Virtual testing	is the use of simulations, HIL test rigs or a combination of both.

3. Background

To obtain the authorisation to circulate, a railway vehicle needs to prove its safety, performance and infrastructure compatibility through testing. This certification process according to European regulations poses two major challenges: Vehicle costs and time-to-market. Indeed, the process can take many months and cost several million euros.

Improvement in the ability to accurately model complex systems has led to simulations becoming increasingly used to verify products in most industrial fields. Simulations have been used more extensively in the railway industry as a means of design risk reduction in recent years while the majority of the evidence for Authorisation is based on field test measurements. Recent research and development projects in the railway industry have sought to enable simulation methods to be accepted as part of the Authorisation process for products. This process has become referred to as Virtual Certification.

Increased application of Virtual Certification methods – the use of simulations, or blend of simulations and test, as evidence accepted for Authorisation – has the potential to:

- significantly reduce the cost and time to market for railway products by reducing the testing time and access needs to specific configurations of the operational network;
- enable all products to be assessed with identical input parameters and characteristics, facilitating interoperability;
- offer technical benefits by enabling more specified scenario to be 'tested' and increase the knowledge of the product performance;

without compromising the safety of the railway.

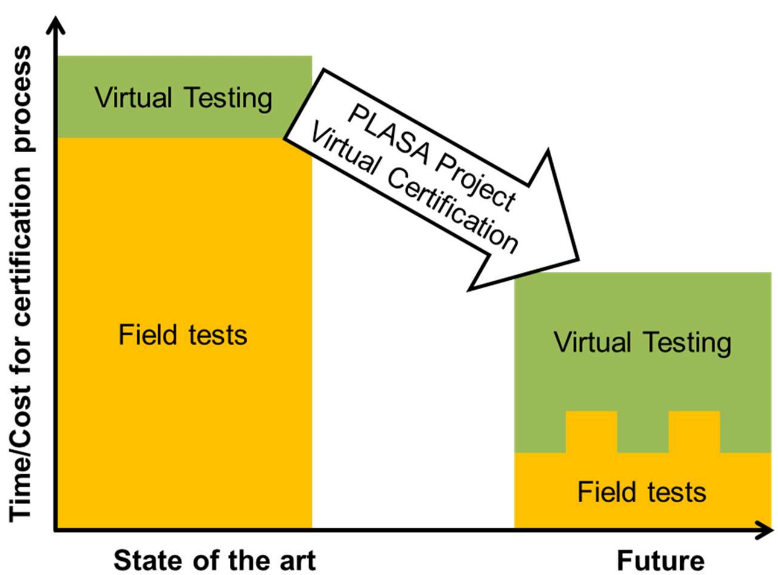

Figure 1: Objective of PLASA 2 – Virtual Certification

These potential benefits are understood by the Shift2Rail IP1 and IP2 and a number of projects are developing Virtual Certification methods as part of their workplan. The objective of this S2R/CCA project is to give an overview of the approaches, their maturity and provide a common interface to key stakeholders to ensure that the potential benefits can be realised. This will be achieved by development of a generic Virtual Certification method / process that is 'accepted' by the relevant Approval Stakeholders.
The concept of the CCA is illustrated in the diagram below.

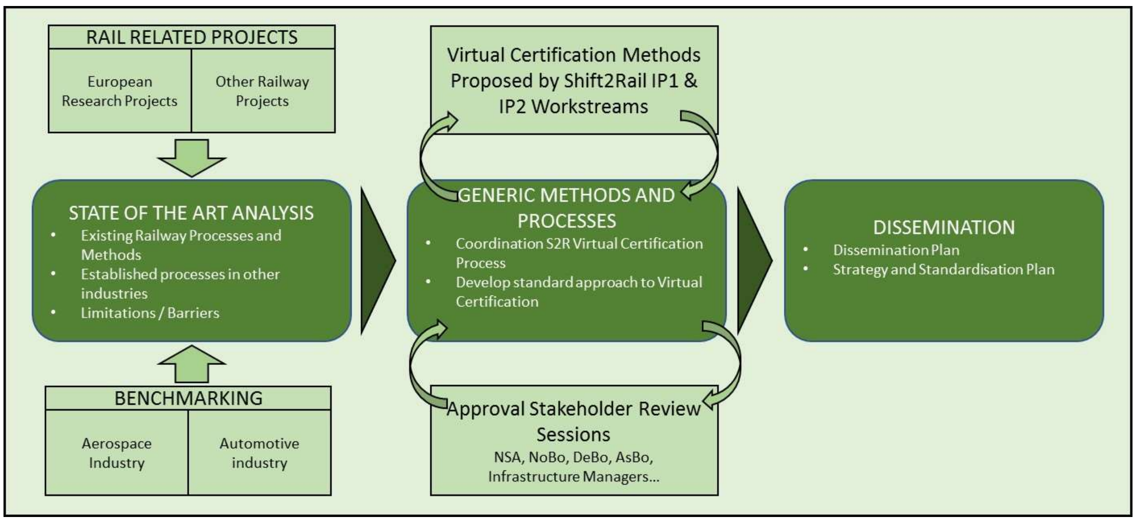

Figure 2: Concept of PLASA 2 – Virtual Certification

The project involves the following three stages:

1. State of the art analysis – review of previous and existing Virtual Certification projects in the railway industry including the perceived limitations and barriers for use in the Authorisation process. A review of applications in the automotive, aircraft, spatial and nuclear industries and the methodologies that underpin these will provide a baseline for what has been achieved in comparable industries. This will enable a baseline status to be derived from which this project can develop.
2. Generic Methods and Processes – the objective of this phase is the production of a standard framework for the application of virtual certification techniques to achieve acceptance by Approval Bodies. The communication channel with the key stakeholders (including Approval Bodies) will be used to elicit requirements to ensure that the generic methods and processes will be acceptable and to provide feedback to the S2R IP1 and IP2 on the specific approaches under development.
3. Dissemination and engagement with relevant stakeholders – this final stage is the promotion of the derived generic methods and processes through implementation of a structured plan for the engagement with the relevant stakeholders. Then a specific strategy will be developed, to present the ideas, principles and benefits for the Railway Sector using the approach of virtual certification to the identified stakeholders. This strategy shall

define how the virtual certification could be implemented into the existing authorisation process, its legal framework, processes and the associated practical arrangements.

The present document constitutes the Deliverable D4.1 “Virtual Certification: State of the art, gap analysis and barriers identification, benefits for the Rail Industry” in the framework of the WP 4, tasks 4.1 – 4.3 of PLASA2 as depicted on the left of the diagram above. This state-of-the-art assessment includes reviews of past and current rail research projects, standards incorporating the use of virtual testing and the application of virtual testing in other comparable industries.

4. Objective/Aim

This document has been prepared to give a synthetic overview of how a mixed virtual/experimental approach can or could be used within the authorisation process for putting a train into service and how it can help the economic and industrial performance of the sector. The specific objectives are:

- To give a wide state-of-the-art on available technical and scientific methods and industrial processes when using simulations to validate a new design of a component, a sub-system or a whole system like a train, and to conduct a gap analysis and a barriers identification for VC in the different railway technical domains.
  - Review of previous and existing VC projects in the railway industry including the perceived limitations and barriers for use in the authorisation process.
  - review of applications in other industries (automotive, aerospace)
- This will enable a baseline status to be derived from which this project can develop.
- To outline the potential benefits to the rail industry from the applications of virtual certification.

5. Analysis of Processes

The approval of a product generally comes at the end of its design and validation process. It is hence useful to recall the main principles and characteristics of this process. Today, the most commonly used process is the V-shape model. It is described in section 5.1.

Both authorisation and customer acceptance can be considered a part of the approval process. Many of the stakeholders are involved in authorisation as well as customer acceptance, sometimes playing a different role in each of them. Section 5.2 gives an overview.

5.1. V-Model for Design/Validation

The V-Model, also known as Verification and Validation model is a sequential type model: the products produced at each step are used in the process following it. It is based on sequential steps moving first down and later upwards in a linear way to form the typical V shape.

Refer to Figure 3 for a schematic of the V-model process. The Design phases are on the left side of the 'V' while the Testing phases are on the right side (Verification and Validation). The component development / construction phase joins the two sides of the V-Model. The horizontal and vertical axes represent time or process progress (left-to-right) and level of abstraction or detail (bottom to top), respectively. The process starts with the definition of business needs or User Requirements and it becomes more detailed as it descends toward the bottom of the V. The process ends with the user acceptance testing on the upper right, after having sequentially completed all the testing stages.

This V-Model demonstrates the relationships between each phase of the design life cycle and its associated phase of testing and it differentiates between Verification and Validation Tests. In each of the design stages, the test plan that will be executed during its corresponding verification and validation stage is developed.

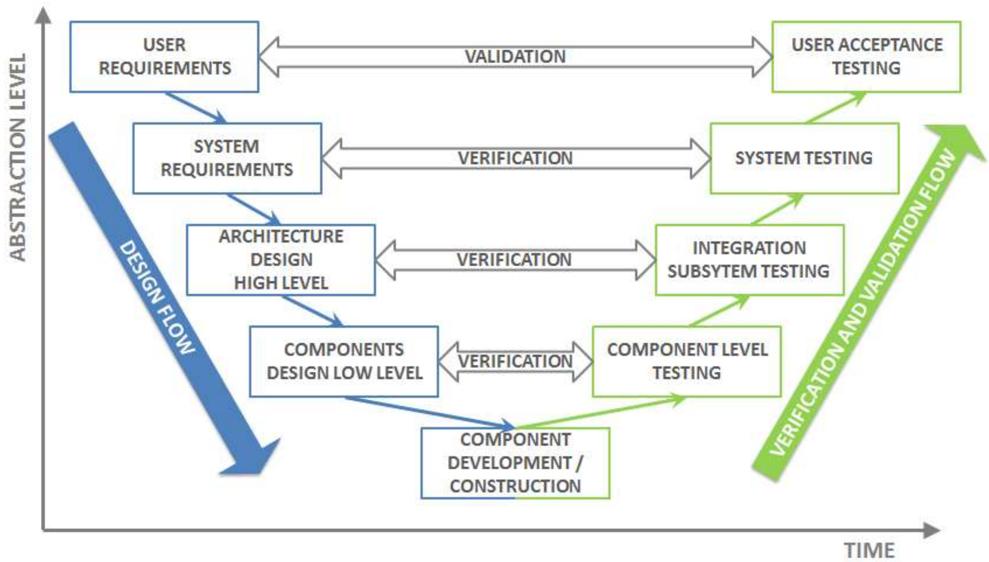

Figure 3: V-Model process

The V-Model is a highly-disciplined model. Requirements must be very clear at the start of the project because subsequent changes during later phases are usually expensive.

The different steps in the Design and Testing phases are explained in more detail in the next sections.

5.1.1 Design Phase

The Design Phase is divided in 4 steps:

User Requirements

The first step in the Design process is to collect the user or final customer requirements, by collecting and analysing the needs of the user(s). How the system is implemented is not important at this stage, but what the system is supposed to do, is important. It involves iterative detailed communication with the customer to understand and document his/her expectations and exact requirements. These involve both functional and non-functional requirements. They are all collected in the User Requirements specification. This document serves as the guideline for the system designers in the system design phase. This is a very important activity and needs to be managed well to formulate in a common language the user requirements.

System Requirements

Once the user requirements are clear, the complete system is designed. Systems design is the phase where the designers analyse and understand the business requirements and figure out possibilities and techniques by which the user requirements can be implemented. The "System

Specification" is generated. This changes the focus from what the system shall achieve to how it will achieve it.

Architecture Design (High Level)

"System Design" is produced from the "System Specification" at this stage. The System Design takes the features required and maps them to various components and defines the relationships between these components. The whole design should result in a detailed system design that will achieve what is required by the "System Specification". The interfaces between the different components are clearly understood and defined in this stage.

Components Design (Low Level)

In low-level design phase, the detailed internal design for all the components is specified. The designed system is broken up into smaller units or components and each of them is explained. Each component then has a "Component Design", which describes in detail exactly how it will perform. It is important that the design is compatible with the other components in the system.

5.1.2 Components Development / Construction

Finally, once the design is completed, each component is built and is then ready for the test phase. The path of execution continues up the right side of the V.

5.1.3 Verification and Validation Phases

The Testing Phase is divided in 4 steps, each of them correspondent with one of the design steps:

Component Level Testing

The first test level is "Component Test", sometimes called Unit Testing. It involves checking that each feature specified in the Component Design phase has been implemented in the component and can function correctly when isolated from the rest of the components of the subsystem.

Integration Subsystem Testing

As all the components inside a Subsystem are constructed and tested, they are then linked together to check if they work with each other. These tests verify that components created and tested independently can coexist and communicate among themselves.

System Testing

When the entire system has been built, it has to be tested against the "System Specification" to check if it delivers the features required. System Testing verifies that functional and non-functional requirements have been met.

User Acceptance Testing

User Acceptance testing verifies that the delivered system meets the user's requirements. It is similar to systems testing in that the whole system is checked but the important difference is the change in focus:

- Systems Testing checks that the system that was specified has been delivered.
- Acceptance Testing checks that the system delivers what was requested.

The Acceptance and thus the certification of a product comes at the very end of this process. If the design of a global system to be homologated is described with a V-shape process, each sub-system included in the global system can naturally be considered isolated, with its own "small V-shape design process".

Virtual simulations are more and more used in the design phase of the system. The models developed there can also be used for the validation and eventually reused for the final certification.

5.2. Stakeholders in the approval process

Authorisation and customer acceptance are two processes in which use of virtual testing can help decrease costs and increase planning reliability. This section gives a brief overview of the involved stakeholders. The processes will be covered in more detail in the deliverable D5.1 (Strategy and Standardisation Plan) of PLASA2.

Authorisation process

In the context of the European railway sector, authorisation is the process of obtaining permission for a vehicle or component to be placed into service. Figure 4 gives an overview of the main stakeholders involved in the process.

Figure 4: Stakeholders in the railway authorisation process

The stakeholders can be distinguished into three categories: Those who define the requirements that must be fulfilled in order to receive the permission, those who must prove compliance to them and finally the stakeholders that assess and certify compliance. A short description of these stakeholders' roles is given below.

Definition of requirements:

- Legislative Bodies: Define validation & certification process. This includes TSIs, NNTRs and safety requirements derived to meet the CSM process.
- Infrastructure Managers: Define network requirements
- Standardisation Organisations: Define the state of the art

Proof of compliance to requirements:

- Operators: Buy railway vehicles, contribute to and request authorisation and implement maintenance and operation according to requirements
- Vehicle Manufacturers: Develop and manufacture vehicles according to requirements, apply for authorisation and submit technical application file and/or certificates
- Suppliers: Develop and manufacture components according to requirements

Assessment of compliance to requirements:

- Authorisation Agencies: Assess process conformity of the railway authorisations
- Notified / Designated Bodies: Assess railway vehicle conformity to TSIs (NoBo) and NNTRs (DeBo)
- Assessment Bodies: Assess railway vehicle safety according to CSM-RA
- Independent Assessors: Assess conformity to standards

Customer acceptance process

In the customer acceptance process, the vehicle manufacturer proves compliance to the customer requirement specifications in order to obtain customer acceptance. Figure 5 gives an overview of the involved stakeholders, using the same categorisation as in the figure for the authorisation process. The colour scheme for the stakeholders is maintained in order to illustrate the shift in responsibilities.

Figure 5: Stakeholders in the customer acceptance process

In comparison to the authorisation process, fewer stakeholders are involved in the customer acceptance process. The operators (customers) have a double role, defining the requirements as well as assessing compliance to them. The stakeholders' roles are briefly described below.

Definition of requirements:

- Operators: Define the customer requirement specifications
- Standardisation Organisations: Define the state of the art

Proof of compliance to requirements:

- Vehicle Manufacturers: Develop and manufacture vehicles according to requirements
- Suppliers: Develop and manufacture components according to requirements

Assessment of compliance:

- Operators: Assess if customer requirement specification is complied
- Independent Assessors: Assess conformity to standards

6. Overview of reviewed projects and technical guidelines

The use of simulation tools in the engineering design phase has greatly increased in recent decades. As a result, the importance of virtual methods in the validation and certification process of products has increased and is still increasing. This trend affects not only the rail industry, but all industries that bring products to market that need to meet safety requirements and to limit the time-to-market.
This chapter gives a brief overview of the reviewed projects and standards which are considered in this document. More detailed insight is provided in the various sections of chapter 7, 8, 9 and 10 that summarise the different aspects of virtual testing.

6.1. Railway industry

In some areas in the railway industry, the use of simulations is already part of the state-of-the-art and regulated in the respective standards, see chapter 6.1.1. In the past, there have been efforts in the railway sector to promote these methods, but not all projects for this purpose could be fully transferred into standards, see 6.1.2. Now, in the Shift2Rail program, there are many projects to push these virtual methods, see 6.1.3.

6.1.1 Railway standards allowing the use of simulations

To analyse the state of the art concerning Virtual Testing in the railway certification process, the valid standards and guidelines that already mention the use of simulations are listed and shortly described in this section. This list may not be exhaustive but aims at giving an overview of the major standards in the railway industry related to simulations for approval.
The French National Authority, EPSF, edited a guideline for the approval process including virtual testing. In this document [O01], annexes – to be edited in 2020 – will give an exhaustive view on the TSI specifications on the use, or restriction on the use, of virtual testing for rolling stocks approval.

EN 14067: Aerodynamics

The EN14067 deals with all aerodynamic issues and requirements for railway application. Especially in the field of using numerical simulation methods for the proof of compliance with limit values, part 4 and part 6 of EN14067 play a major role. Part 4 describes testing methods, including virtual ones, for assessment of aerodynamics on open track. Part 6 describes methods, including virtual ones, and requirements for crosswind assessment. Part 5 of the standard describes aerodynamic effects of the train – tunnel interaction without details for virtual testing methods.

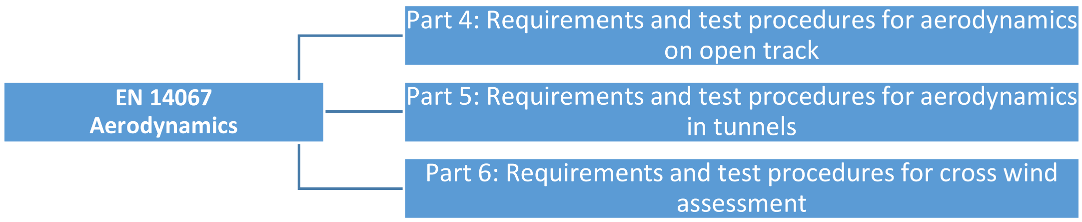

Figure 6: Structure of EN 14067

<u>EN 14067-4: Requirements and test procedures for aerodynamics on open track</u>

A train causes aerodynamic loads on objects near the track as well as on other trains it passes. These loads are an important interface parameter between rolling stock, infrastructure and operation subsystems and need to be ruled for a trans-European railway system. EN 14067-4 defines requirements, test procedures and conformity assessments to describe and evaluate aerodynamics on open tracks.
A vehicle which is approved according to EN 14067-4 meets the requirements concerning

- pressure variations beside the track,
- slipstream effects beside the track and
- loads in the track bed.

For the description and limitation of the aerodynamic pressure loads near the track, a reference case for vehicle assessment is defined. It describes the undisturbed pressure field generated by a passing train. According to this reference case, the maximum permissible peak-to-peak pressure change, depending on maximum design speed, is given. Conformity to this limit value can be provided by full-scale tests, reduced-scale moving model tests or CFD simulations.

The method for limitation and description of train-induced slipstream effects is similar in the way that a reference case for rolling stock assessment is defined and conformity of the vehicle to be assessed must be proven. This conformity can be assessed by full-scale tests or by a simplified conformity test which assesses similarities to proven compliant rolling stock, but not by simulation.

For loads in the bed, the standard refers to national regulations.

<u>EN 14067-6: Requirements and test procedures for cross wind assessment</u>

Trains on open track are exposed to crosswind which must be assessed for safe railway operation according to EN 14067-6. Safety depends on vehicle, infrastructure and operating conditions.

The crosswind stability of vehicles is defined by specific wind speeds, which are characterised by the vehicle facing a fixed wheel unloading and still withstanding the crosswind. These characteristic wind speeds are set up for different running speeds, uncompensated lateral accelerations and wind angles to the track and are referred to collectively as characteristic wind curves (CWCs).

For the calculation of CWCs on the one hand the aerodynamic and on the other hand the vehicle-dynamic characteristics of the vehicle must be set up. Depending on the maximum vehicle speed and the type of vehicle various methods with different levels of complexity are defined for the proof of crosswind stability. To determine the aerodynamic coefficients of the vehicle, reduced-scale wind tunnel measurements and simulations by CFD are allowed and are described in detail. There are three methods for determining the wheel unloading of the vehicle: First, the simple method with a quasi-static three-mass model, which is considered less accurate but conservative due to the built-in margins. The other methods are an advanced quasi-static approach and a time-dependent multi-body simulation (MBS) with consideration of a specific wind scenario (Chinese hat gust scenario). These approaches can not be carried out by experiment, but only by calculation and simulation.

After determining the CWCs of a vehicle, values of the CWC are compared with those of the so-called reference CWC to assess conformity. These are CWCs of vehicles that are regarded as crosswind stable due to their long operating experience.

prEN 17149: Railway applications - Strength assessment of railway vehicle structures

- Part 1: General requirements for strength assessments (static and fatigue)
- Part 2: Static strength assessment
- Part 3: Fatigue strength assessment

These standard projects will specify the procedure for static and fatigue strength assessment of railway vehicle structures related to base material and welded joints. This series of standards is applicable to all kinds of rail vehicles, with ferrous materials and aluminium.

The corresponding German guidelines

- **DVS 1612**: Design and fatigue evaluation of welded joints with Steels in rail vehicle construction
- **DVS 1608**: Design and strength evaluation of welded constructions of aluminum alloys in rail vehicle construction

contain information on the design and requirements for welded structure (aluminum alloy: DVS 1608, steel: DVS 1612) as well as a collection of rail vehicle specific weldment details, which have proven themselves in terms of safety, functionality, and maintenance. They apply to the design for fatigue strength of base material and welded joints. Although the DVS 1608 and DVS 1612 do not have the status of a standard, they are state of the art for strength assessment of car bodies, bogie frames and add-on components.

For the determination of occurring stresses caused by forces on the structure, two options are possible: On the one hand the stresses can be measured with sensors on the real vehicle, on the other hand the stresses can be calculated with the help of numerical simulation tools with the finite element method (FEM). Both of the DVSs define requirements for these simulations. After determining the occurring stresses they have to be compared to the allowable stresses with basically 3 optional methods (nominal stress concept, structural stress or notch stress concept). A catalogue provides assistance in the consideration of various weld joints and defines limit values. The result of the comparison is whether the structure complies with the requirements for fatigue strength or if a component could fail due to fatigue during its life-cycle.

EN 14363: Testing and Simulation for the acceptance of running characteristics of railway vehicles - Running Behaviour and stationary tests

EN14363 is a major standard for the assessment of running characteristics of railway vehicles. The running characteristics depend on the vehicle itself, but also on the operating conditions, the characteristics of the infrastructure and the contact conditions of the wheel/rail interface. EN14363 describes methods, requirements and gives limit values to assess the vehicle performance in order to get the approval. The first stage assessment tackles the following areas:

- safety against derailment on twisted track
- safety under longitudinal compressive forces in s-shaped curves
- evaluation of the torsional coefficient
- determination of displacement characteristics
- loading of the diverging branch of a switch
- running safety in curved crossings

Compliance with the limit values for these tests is usually proven by testing the vehicle on special infrastructural elements and subsequent simple calculations. These are quasi static tests while the vehicle is stationary or slowly moving.

At the second stage, the dynamic performance of the vehicle in terms of running safety, track loading and ride characteristics has to be tested. To meet all requirements for this test, the vehicle has to show safety performance under specific infrastructure und operational conditions in so-called test zones (small radius curves, very large radius curves, etc.). The standard defines limit values for the wheel/rail forces and accelerations for running safety, track loading and ride characteristics. Usually the measurement campaign is carried out by on-track tests but the use of numerical simulation instead of on-track test is permitted under controlled conditions (for example a validated model). In the 2016 revised version of EN14363, four cases of application where numerical simulations can replace on-track tests are described:

- extension of the range of test conditions where the full on-track test program has not been completed
- approval of vehicles following minor modification
- approval of new vehicles by comparison with an already approved reference vehicle
- investigation of dynamic behaviour in case of fault modes.

The high status of numerical simulations for the assessment of running characteristics was taken into account by adding the word simulation to the title of the standard.

EN 13979-1: Wheelsets and bogies - Monobloc wheels - Technical approval procedure, Part 1: Forged and rolled wheels

The EN13979-1 is about railway wheel design and sets up the requirements for monobloc wheels. Furthermore it specifies the assessment of new wheel designs, which are necessary to meet for access to the European rail network.

The requirements include geometric, thermomechanical, mechanical and acoustic conditions. For the geometric field it has to be ensured that changeability is given, which needs functional requirements, assembly requirements and maintenance requirements. The thermomechanical requirements are to control the deformations of the wheel and to ensure that the braking does not lead to a wheel break and are carried out in a laboratory and on the track. The evaluation of the mechanical behaviour is meant to ensure that no fatigue damage occurs in the wheel bridge and can be carried out by numerical methods (FEM). In contrast to this, in EN 13103 (Design method for axles with external journals) the stress analysis is performed on the basis of beam calculation. For this purpose, the standard specifies all forces to be covered as well as stress limits and safety factors. For the FE calculation method itself, the standard only mentions a few general requirements in the Annex. Concerning acoustic requirements, a new wheel design has to show conformity to a reference wheel. This can be assessed with numerical tools (FEM and TWINS (Track Wheel Interaction Noise Software)) or with measurements for the physical vehicle.

EN 12663: Structural requirements of railway vehicle bodies

EN12663-1 + A1 (2015) defines the structural requirements for railway vehicle bodies to ensure their integrity during their lifetime. It applies to locomotives and passenger metallic vehicles and can be taken as an alternative method to the one described in EN12663-2 for freight wagons.

These requirements include the definition of the loads to be sustained (from normal service loads to more specific and exceptional loads), the description of acceptance criteria (which physical phenomena are to be checked – like irreversible deformation, fatigue, stability -, limit values to use for comparison – like structural or nominal stresses, S-N-curves with a survival probability of at least 97,5 %... -, and safety margins to be applied before comparison with limit values) and some requirements on methods, test procedures and process (a validation program through physical tests and/or FEM simulations is defined, requirements on how to characterise material properties or how to apply loads during tests are given, etc.).

For a new vehicle design, some static full-scale tests, performed in laboratory, are mandatory. But some other static load cases can be validated through a full virtual method or a mix of simulations and physical tests. Additionally, when simulations for fatigue analysis do not give compliant results or if there are significant uncertainties on their results, full-scale fatigue tests are required.

For a similar structure or for an identical body with an evolution of operation conditions, a reduced test program is accepted (it can even be reduced to zero), as long as the simulations have been validated through comparisons with tests, on a similar vehicle. Very few details are given on how to validate a model or how to define a “similar vehicle”.

Uncertainties, for static analysis, are taken into account through the methods to identify input data (material properties and limit values) and through a safety factor S to be applied to the loads (or the stresses). This safety factor depends on the method used to validate the design (simulations or physical tests).

EN 13749: Method of specifying the structural requirements of bogie frames

The standard describes the requirements for bogie frames concerning structural mechanics. It applies to bogie frames of locomotives, freight and passenger wagons, trams and metros. This standard is similar to EN 12663, but with focus on the bogie frame.

For the approval of a bogieframe, the standard requires

- calculations (FEM for example),
- static and fatigue tests in a laboratory and
- onsite tests.

In general, all of these tests have to be performed – for completely new developed and for slightly modified designs. But the standard is not consequently strict and says that it is possible to reduce the tests for slightly modified designs without going more into detail. In addition, the standard mentions that it is allowed to replace fatigue tests in a laboratory by “alternative methods”.
No validation process or acceptance criteria is defined, but the static tests in the laboratory and the onsite tests on the track should be used for verification of the simulation model.

The main part of the standard is described in the informative annexes A - G. First, there is a collection of load cases (static and fatigue) which are relevant for bogie design, for example the maximal forces which are expected during a ride in a canted track. In addition, the standard gives values for the expected accelerations at the wheelset and at the bogie. It is allowed to reduce these forces, if simulation results show lower values. Second, the standard defines requirements concerning the limits, safety margins and calculation methods for the structural analysis. No stress limits are defined, but links to state-of-the-art guidelines are mentioned. Third, the standard defines the test procedures for the static and fatigue tests in the laboratory.

EN 15227: Crashworthiness requirements for railway vehicle bodies

The standard EN 15227 on crashworthiness requirements for railway vehicle bodies aims at reducing the consequences of collision accidents by providing a framework for determining the crash conditions that railway vehicle bodies should be designed to withstand, based on the most common accidents and their associated risks.

It specifies 4 scenarios that represent the most relevant collision situations with regards to their occurrence and the resulting casualties. For those scenarios, the following 5 measures for the protection of occupants must be demonstrated:

- Reduction of overriding risk
- Absorption of collision energy in a controlled manner
- Maintenance of survival space and structural integrity of the occupied areas
- Limitation of deceleration
- Reduction of the risk of derailment and limitation of the consequences of hitting a track obstruction.

Because of the impracticability of evaluating the behaviour of the complete train unit by testing, the demonstration that the measures are provided is performed by dynamic simulation. For the simulation model, variable accuracy is permissible if the survival space behaviour is correctly represented. The vehicle ends and especially the crumple zones must be modelled in detail. For many other parts, such as the middle cars of a train unit, a simplified model with equivalent mass and stiffness is sufficient.

In areas of large deformation, the model must be validated and calibrated by appropriate tests of energy absorbing devices and crumple zones that must include all interacting parts. If the key features of the design have been previously validated, a reduced validation program can be used appropriate to the degree of change.

EN 15273-2: Rolling stock gauges

EN 15273-2 provides the rules for calculating rolling stock gauges for various profiles and allows to determine vehicles' maximum dimensions. It contains a vast selection of different gauges but is not exhaustive, since all networks may define gauges according to their specific requirements.

The standard comprises of a short main part giving some general rules and definitions and a multitude of annexes describing the various gauges including the rules and means to calculate them. In the main part, the standard distinguishes gauges into different types:

Static and kinematic gauges consider the transverse displacements of vehicles or the "worst case" displacements that can occur given the vehicles kinematics. These "worst case" displacements can be replaced with optimised values if these are backed by simulation analysis reports, test reports, risk analyses, etc.

Dynamic methods for gauges are based on a reference profile for the respective network that the vehicles must not exceed. The maximum vehicle space to be occupied under normal service and fault conditions is defined in order to calculate this reference profile. It can be attained by geometric calculations as well as by simulation.

Use of simulation is only explicitly defined in the annexes for the Swedish and UK gauges, which allow for dynamic calculation methods. Both provide extensive sets of requirements to simulation modeling and validation. While simulation is used as the final proof of compliance, some field tests are necessary to validate the model.

EN 15595: Braking - Wheel slide protection

This document specifies the criteria for system acceptance and type approval of a wheel slide protection (WSP) system. This standard covers the design, homologation requirements for the WSP and WRM systems and their components.

The Standard permits type testing of components through on train testing, on a test bench or a combination of both. Test benches are made up of HiL and SiL configurations. The use of test benches requires Vehicle Implementation Tests in order to demonstrate that the tested system induces the correct specific vehicle parameters and satisfies the requirements under real and artificial conditions.

The Standard suggests the use of simulations as part of the type test process in the form of HiL and SiL test rigs. It also contains a matrix of the core test cases and defines the acceptable means of validation – train test, HiL or SiL– for each. The standard mandates which hardware and software is required to be present on the test bench for each of the core test cases

The Standards defines requirements for the following models:

- Adhesion Model – a simulation to represent genuine and artificial track conditions. The model can be based on theoretical or measured data.
- Test and Performance Model - simulation model that undertakes calculations of the WSP performance in relation to the vehicle characteristics and adhesion profile being used for the test.
- Vehicle Performance Model - model used to represent the behaviour of the vehicle in relation to WSP operation, and its impact upon the overall vehicle/train stopping performance.
- Vehicle Functional Model – model used to emulate vehicle control signals that are used by the WSP to define its status.

The Models are to be validated by comparison to dry rail track test results satisfying specified levels of tolerance on key criteria. The Simulations have to demonstrate that they achieve accuracy and repeatability targets for each criteria before they can be accepted for use.

UIC 541-05:2016: Brakes - Manufacturing specifications for various brake parts - Wheel Slide Protection device (WSP)

The Standard also specifies the criteria for system acceptance and certification of a WSP system in various rail vehicles and includes the design, testing and quality assessment of WSPs and WRM systems and their components.

The Standard is applicable to Trains fitted with WSP / WRM systems which may consist of single vehicles, tractive and trailing vehicles or may be high speed trains, multiple units or commuter trains operating on any track gauge.

The standard outlines the following:

- Requirements
  - Functions
  - Design requirements
  - Installation requirements
- Certification process
- Range of tests, test methods and assessment of tests
- Designation, identification and marking of components

Appendix C of the Standard provides criteria for Classification and Certification of test benches. During the assessment process the test bench shall demonstrate its accuracy and its repeatability in accordance with the UIC Leaflet 541-00. A test report shall be prepared by the owner of the test bench and examined by the team of assessors.

Simulation facility tests should, where technically possible, be used both as part of the verification process and also to validate WSP changes. Simulation facility tests are intended to reduce the number of track tests. A simulation facility shall fulfil requirements of the Standard and the facility shall be accredited in accordance with EN ISO/CEI 17025.

Accuracy and repeatability of the simulation test bench are to be demonstrated by comparison to valid track test results. It is recommended to use a test performed during a test campaign for UIC approval of a WSP and the same WSP used in the track tests shall be installed on the test bench. Simulation accuracy is defined as the error percentage between the specific values of the simulated test and the track test. Accuracy and repeatability is to be calculated for the following specific values:

1. Braking distance
2. Braking time
3. Initial adhesion
4. Mean value of the minimum slide of all axles

The Standard specifies targets for accuracy and repeatability that need to be met for the simulation test bench results to be valid.

EN 50388:2012: Railway Applications - Power supply and rolling stock –
Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability

This Standard establishes requirements for the compatibility of rolling stock with infrastructure particularly in relation to:

- co-ordination of protection principles between power supply and traction units, especially fault discrimination for short-circuits;
- co-ordination of installed power on the line and the power demand of trains;
- co-ordination of traction unit regenerative braking and power supply receptivity;
- co-ordination of harmonic behaviour.

The Standard covers the following main topics:

1. Requirements for performance of power supply including the mean useful voltage at the pantograph for each type of power supply system taking into account the characteristics of the infrastructure
2. Harmonics and dynamic effects assessment for ensuring compatibility between the infrastructure and rolling stock.
3. System protection requirements relating to short circuits on the rolling stock and at the substation
4. Regenerative braking requirements
5. Test Methodology to be implemented including how simulations may be used to demonstrate compliance to the quality index of the power supply and harmonics/dynamic effects and therefore reduce the number of test cases on the network.

Note that prEN 50641:2017 is in development to validate the simulation tools used to demonstrate compliance to the requirements in this standard. This is described in the section below.

prEN 50641:2017: Railway applications — Fixed Installations - Requirements for the validation of simulation tools used for the design of traction power supply system

The objective of this European Standard is to specify requirements for the acceptance of simulation tools used for the assessment of design of traction power supply systems.
The simulation results allow the calculation of quality indexes requested by EN 50388:2012, Clause 8. This European Standard is applicable to the simulation of AC and DC traction power supply systems including lines defined in the TSIs.

The standard provides the minimum required functionalities and ensures that the output data of different simulation tools are consistent when using the same input data. The Standard only applies to simulations of traction power supply systems at their nominal frequency for AC and DC systems. It does not apply to harmonic, electrical safety or EMC studies over a wide frequency spectrum.

Assessment of the simulation is in two parts:

1. Validation process shall be undertaken which compares specific characteristics of the key simulation output graphs;
2. The quantitative verification of the simulation is assessed by comparing key calculated values with those given in the standard.

The verification process is based on verification using a defined benchmark example of a traction power supply system with common input data for the infrastructure, types of trains and timetable. Note: number of systems included is limited and the standard will need to be updated to cover models for all AC systems.

Validation of the tool is through the assessment of outputs using the following steps:

- Plausibility of expected outputs – a set of output graphs are to be generated and this step involves reviewing these against the expected results to ensure that certain features are present in the output. This step involves reviewing the shape of the output rather than the actual recorded values. These graphs assess:
  - Train graphs for the timetable
  - Time functions of voltage, current, speed and tractive effort for a train
  - Time function of substation current and voltage
- Verification of expected output – the results of the simulation are documented in tables defined in the EN to record the data for each trainset and for the substation
- Validation with simulated values – The output of the simulation is compared to min and max values specified in the EN. It is expected that the results are within the bounds set by the EN. It is accepted that up to 10 results may be out of tolerance as long as the shape of the output curves are correct with the exception of the parameters travelling time, UMean Useful and consumed power where only two out of tolerance values are acceptable.

The simulation tool developer is to produce a report defining the details of the software used for the simulation tool and the output of the analysis against the EN. Finally, a third party assessor is required to certify that the simulation tool is compliant and specify the types of traction system(s) validated.

Note: Railway outside the EU

In Japan, there is no standard about running safety assessment, however, the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT) provides some guides for it.
Railway companies implement running safety assessment by themselves. They define for themselves methods (models, tools, measurement/data processing…) and processes when:

- a new vehicle or a major-modified vehicle is to be introduced,
- the operational maximum running speed is to be increased

For the assessment of dynamical running safety, conventional desk-calculations, complemented with laboratory tests and simulations carried out with a tool delivered by MLIT are often used. The alternative approach is to perform field-tests.
It should be noted that most of the Japanese railway companies operate trains, own the infrastructure and rolling stock and are responsible for all the maintenance work. Consequently, they handle the whole process and data that are necessary to apply this process.

6.1.2 Previous rail related research projects

TrioTRAIN, is an acronym for Total Regulatory Acceptance for the Interoperable Network, dealing

with key railway interoperability issues. The TrioTRAIN cluster of integrated research projects in a consortium of 30 partners - railway manufacturers and companies, infrastructure providers and universities - had the objective of partially replacing the physical tests with simulations and proposing a simplification of approval processes through an optimised mix of field tests. The overall project, coordinated by UNIFE, was funded by the European Commission under the 7th Framework Program. Relevant topics for the certification of rail vehicles were separated into three different projects: Vehicle dynamics (DynoTRAIN), pantograph-catenary interaction (PantoTRAIN) and vehicle aerodynamics (AeroTRAIN). All projects had a similar structure of work packages (technical work packages were framed by the project management while a transversal regulatory acceptance and quality assurance work package “WPX” was common to the three projects).
The transversal WPX focussed on two aspects:

1. A formal logical analysis of the existing regulatory documents (TSIs and standards) to facilitate inclusion of research results by the regulatory and standardisation bodies;
2. A TrioTRAIN uncertainty framework to provide evidence on how the proposed virtual method compares with the existing one. The basic concept of the framework is the following: “A new assessment process, proposed as an alternative to a currently used process, is suitable for use under the following conditions:
   - its assessment uncertainty is demonstrated to be no greater than that associated with the currently used assessment process
     AND / OR
   - its assessment uncertainty is demonstrated to be compatible with that required by the assessment process on the basis of the “sensitivity” of the process itself to uncertainty (in other words, the new assessment process may have a higher uncertainty but the assessment algorithm is not very sensitive to it)"
     AND
   - provided it is demonstrated that safety levels are at least maintained.”

The framework was applied and demonstrated in several cases both during the project (AeroTRAIN [E04], DynoTRAIN [D02][D03], PantoTRAIN [P01][P02][P03]) and afterwards [SC06][SC07].

The following chapters present the technical content and main results of the projects to get an overview in which fields simulations are already state of the art.

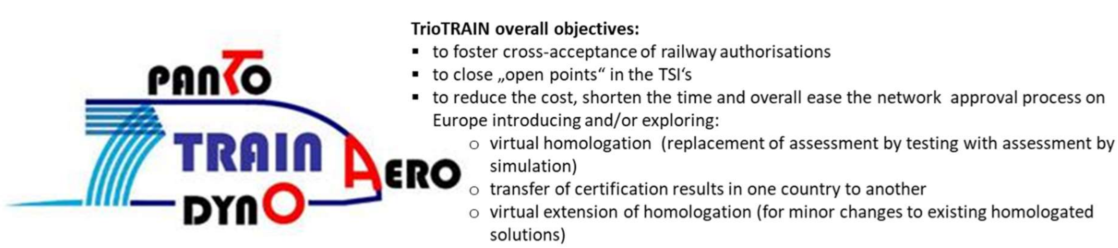

Figure 7: TrioTRAIN objectives

DynoTRAIN

DynoTRAIN was carried out from June 2009 to September 2013.

Testing for safety, performance and infrastructure compatibility is one of the most important parts in the vehicle certification process. DynoTRAIN aimed to help spread European certification and acceptance procedures to accelerate interoperable product approvals. The whole process consequently becomes more efficient, while at least maintaining the current levels of safety. DynoTRAIN showed in the field of vehicle dynamics how virtual certification can be applied in the sector. The project demonstrated how some physical tests on the track might be replaceable by virtual testing. Another important objective was to provide information for the closing of some of the 'open points' for rolling stock and infrastructure in the relevant TSIs. The results and the data gained in the project had a significant impact on the revision of the standard for safety, performance and infrastructure compatibility of running characteristics, EN14363:2016.

The six technical work packages were embedded by the organisational work packages from the global TrioTRAIN framework. Work package 1 was a measurement campaign (7500 km) for track geometry, contact geometry and vehicle reactions through the countries Germany, Switzerland, Italy and France. Work package 2 was on track quality in terms of standard deviation and peak values for short sections of track. The closing of open points concerning contact geometry and equivalent conicity was the objective of work package 3. Work package 4 dealt with network access due to track loading limits. In work package 5 (Model Building and Validation) a procedure for validation of multi-body vehicle models is proposed, which makes it possible to replace on-track tests for running safety. Work package 6 was about a virtual solution for vehicle cross acceptance processes and provides a method to assess vehicle modifications and different operating infrastructure conditions.

With the measurement campaign in Europe, DynoTRAIN has accumulated an enormous database which could be used for research projects even in the future. Furthermore, the development of a new analysis method for track quality has given a new understanding of the relation between vehicle reaction and track quality. This new technique (multi regression) has been implemented in the latest revision of EN 14363:2016. One of the other main results of DynoTRAIN is the inclusion of a validation procedure for multi-body vehicle models also in the latest revision of EN 14363:2016. This procedure will allow track tests to be replaced by simulations as part of the vehicle certification process. For new designs the cost savings will be limited, but larger savings in cost and time can be achieved for repeat builds and for vehicles with small modifications (similar vehicles).

AeroTRAIN

The work for AeroTRAIN was carried out from June 2009 to May 2012.

Before the start of the project, not all aerodynamic aspects were completed in the high-speed rolling stock TSI and therefore there was a great need for acceptable limit criteria. The objectives of the AeroTRAIN project were to close these open points, define limit values and, if possible, provide new test methods, for example virtual certification methods based on numerical simulations. For a successful application of the TSI, the TSI itself must be precise and complete, but also efficient in terms of time and costs. The AeroTRAIN project aimed to reduce the costs and time associated with aerodynamic certification without compromising safety.

Work package 1 was on the assessment of the ability of numerical tools (CFD) to cover the certification process regarding the “Open Air Pressure Pulse”. It was meant to replace conventional track tests which are complex, time consuming and costly. Work package 2 dealt with limit criteria for aerodynamic loads on tracks, while work package 3 was about crosswind (closing open points, investigation of CFD methods and assessing limits of experimental simulation of reference ground configurations). Work package 4 covers the “Train – Tunnel Interaction” in the context of closing open points in the TSI. Work package 5 aimed at defining a measurement procedure for less costly test configurations for the slip stream effect.

The results concerning the open air pressure pulse demonstrated that the CFD tools could be reliable to fully assess the pressure pulse at the head of the train. Because of the technical complexity of the set-up in CFD-simulations, AeroTRAIN developed a procedure in which the ability to conduct numerical assessment has to be proven by comparison with bench tests. These results contribute to the possibility of performing CFD simulations instead of on-track tests for high speed trains according to the latest version of the TSI. Concerning the closing of open points and defining limit criteria in the TSI, consensus could not completely be reached, with the consequence of no agreement on limit criteria for Cross Wind Characteristics for example. Additionally, because of AeroTRAIN, a proposal for the use of numerical simulations in place of wind tunnel tests for calculating aerodynamic coefficients with the CFD method has been developed. Based on the experimental results for the slip stream effect a revised TSI testing procedure has been outlined.

PantoTRAIN

PantoTRAIN (1 June 2009 – 30 May 2012) deals with the pantograph-catenary system, and also addresses the issue by replacing field tests with simulations or HiL tests, in order to reduce the time and the cost of pantograph certification against ENs and TSI, and also to improve the interoperability of pantograph systems across Europe, since virtual homologation techniques could also be applied to extend pantograph homologation across different national railway networks.

Indeed, the pantograph/catenary system represents one of the major barriers to rolling stock interoperability: each country in Europe has developed its own overhead line equipment in a different way, leading to different catenary and pantograph designs with variations in mechanical properties. Hence, a unified approval method, able to consider the diversity of existing solutions in Europe is a key subject that must be addressed to provide a competitive railway system. Accordingly, the high level objectives of PantoTRAIN are:

- To introduce in the current certification process of the pantograph / catenary system new procedures based on numerical simulations and HiL testing, to reduce migration time for the implementation of new interoperable solutions;
- To use the numerical and physical simulation to extend pantograph homologation to different catenary systems, thereby enhancing the interoperable use of existing infrastructure and the development of new interoperable pantographs;
- To foster the use of innovative and mechatronic pantographs, by understanding how the homologation process needs these systems and by revising the limits provided by the TSI's;
- To use the simulated behavior of new / modified pantographs or catenaries "close" to those already certified by line tests, thereby avoiding a repetition of the certification tests on the new / modified designs, and allowing to save a large portion of the costs associated with homologation;
- To foster the use of HiL testing as a more objective and less expensive alternative to line tests.

Work package 1 was on criteria to build and validate pantograph / catenary numerical simulation tools, while work package 2 was on HiL testing of pantographs. Work package 3 dealt with virtual certification for interoperability, while work package 4 was meant to enhance virtual extension of a certification for a pantograph with minor changes from an already certified one. Work package 5 focused on mechatronic interoperable pantographs.

One of the main results was a catenary database in which 3 different catenaries SNCF LN2, RFI C270 and DB Re330 characteristics were recorded. Concerning numerical simulation of pantograph / catenary interaction 3 pantographs and 3 types of catenaries were simulated numerically and on the HiL rig, with very good correlations with field measurements. Through a sensitivity analysis, general requirements of the numerical models and software were defined. It includes, for the pantographs, the deviations from their nominal specifications. A procedure to define and calibrate pantograph models, based on laboratory experiments, was proposed and recommendations on how to validate a simulation were also given. Furthermore, it was shown that the HiL technology has a clear potential to improve methods for product development and testing and to simplify homologation procedures. In addition, certification scenarios for which simulations could replace field tests were defined. Another result was the definition of a homologation map to give a consolidated view of the mean value and the standard deviation of the contact force and the value of the uplift and a measure of the safety margin achieved by a conformity assessment.

The TSI Loc&Pas and TSI ENE were revised in 2014. It is now required to analyse the dynamical behaviour of the pantograph to be approved thanks to simulations, in order to make a first verification of its compliance to the requirements. These simulations must be carried out with at least two different types of catenary. If the requirements are proved to be met with the simulations, dynamical field tests must then be carried out on a section which is representative of one of the two simulated catenaries. The use of simulations to limit the number of field tests is now being introduced in pr-EN50367.

AcouTRAIN

The research project AcouTRAIN (2011-2014) was funded under the 7th European Framework Program, too, but was not part of the TrioTRAIN cluster, even though the project pursued identical objectives and was similarly structured.

The acoustic TSI NOISE approval for new vehicles is a complex process for the manufacturing industry. According to the current method in the general case, several acoustic measurements must be carried out on every vehicle, even if the vehicle belonged to, for example, a larger series of similar vehicles. Beside this general method, a simplified method can be allowed in case of a version of a series or an upgraded or renewal vehicle. It consists in proving that the unit under assessment is less noisy than the reference type, already approved with the general method. The TSI Noise 2011 authorizes the use of physical tests and/or simulations to make this comparison but the procedure is not defined in the associated standard EN30095.

The main objective of AcouTRAIN was to improve the TSI approval process by introducing methods based on numerical simulations. These so-called virtual test methods should have been usable as cost-effective and flexible alternatives to conventional on-track test methods. The big challenge for AcouTRAIN was to integrate virtual testing methods into a certification process that was equivalent in terms of results and reliability to existing process.

In work package 1 global procedures and requirements for virtual certification of acoustic performances of freight and passenger trains were developed. The requirements form the basis for the technical content in work package 2 and 3, which dealt with the mathematical description and characterisation of rolling noise and other vehicle specific noise sources. Followed by work package 4, through which a methodology to certify simulation tools for acoustic virtual testing (calculation of pass-by and stationary noises) was developed, in order to use these certified tools for approvals. In work package 5, the methods developed for virtual approval were evaluated according to TSI Noise in terms of accuracy and cost savings. It also analysed if the virtual approval processes, defined in work package 1, met the objectives. The structures of work packages 6 and 7 were similar to that of TrioTRAIN and treated the issues of dissemination of results, project management and technical coordination.

One of the main results of AcouTRAIN was to clarify the so-called “simplified methods” of the TSI. That way, AcouTRAIN closed open points in the standards. Furthermore, first recommendations for the use of virtual testing (VT) within the scope of an acoustic certification process were proposed, for example by introducing different levels of virtual testing approaches like “Full”, “Hybrid” and “Extension of approval”. In terms of software tool certification, the available tools for the static configurations obtained globally good results and met the criteria, which were developed to decide if a tool could be certified for virtual certification of trains or not. The results of the model validation showed that the virtual vehicles, created for the different approaches, did not represent a sufficient degree of accuracy and reliability compared to the real vehicle in the on-track test. AcouTRAIN summarised that “more work is needed to validate and refine the virtual certification concept and to detail the validation of reference vehicles, including modelling updating procedures and best-practice for source representations” [A07].

6.1.3 Complementary Shift2Rail projects

The projects in the Shift2Rail program that deal with virtual methods in the certification process are referred to as complementary projects in this context. They are listed and shortly described in this section.

CONNECTA

CONNECTA (CONtributing to Shift2Rail’s NExt generation of high Capable and safe TCMS and brAkes) is a research project that belongs to IP1 (Innovation Programme 1) and it was developed from 01/09/2016 to 31/08/2018. CONNECTA aims at contributing to the Shift2Rail’s next generation of TCMS architectures and components with wireless capabilities as well as to the next generation of electronic braking systems. This project reinforced and extends the early work done in the TCMS part of Roll2Rail as well as starts the specific activities of the MAAP of Shift2Rail. It is helped in this goal by its complementary project Safe4Rail.

The high level objectives of the CONNECTA work are to pave the way to:

- Develop the general specifications of next generation TCMS and to generate the corresponding high level system architecture;
- Incorporate wireless technologies to train communication network solutions;
- Provide a train-wide communication network for full TCMS support including the replacement of train lines, connecting safety functions up to Safety Integrity Level (SIL) 4 and support of “fail-safe” and “fail-tolerant” principles, to provide an optimal train network for TCMS and OMTS (On-board Multimedia and Telematic Services) as well as communication mean for non-TCMS functions;
- Standardise functional interfaces of functions and sub systems as well as to define a generic functional architecture for the next TCMS generation;
- Facilitate the coupling of two or more consists supplied by different manufacturers and which could have different train functions;
- Develop a simulation framework in which all subsystems of the train can be simulated, allowing remote and distributed testing including HiL through heterogeneous communication networks;
- Achieve a performance improvement in safety relevant braking functions resulting in optimisation of the braking distances in safety braking;
- Optimise on-board systems by reducing the number of sophisticated pneumatic components and improving the overall LCC;
- Use an Ethernet based communication standard carrying high Safety Integrity Level (SIL) related information;
- Validate non-railway EN standards for use in safety-related railway applications.

CONNECTA was divided in 8 WP’s (Work Package), in which WP6 was fully focused on simulation. The main goal was to specify and design a certified simulation framework platform in which all

subsystems of the train could be simulated (including TCMS communications networks), assuring the same behaviour of the train, providing the same results and allowing the running of the real software of each unit.
The proposed framework allowed remote and distributed testing including Hardware in the Loop (HiL) through heterogeneous communication networks, and was completed by a toolbox to support the design, deployment, monitoring and testing of the next generation TCMS.

Specific goals defined for WP6 were:

- Specification and Definition of a standardised simulation framework
- Support virtual testing and homologation of the TCMS and its applications
- Allow local and remote homologation through heterogeneous networks and HiL
- Complete train virtualisation based on electromechanical simulations
- Test design, deployment and monitoring toolbox development
- ECN/ETB conformance testing definition and implementation

The main results obtained of the WP6 are the following:

- TRL3-4 level of achievements can be considered
- A generic process for development and validation of a simulation is proposed, following the “V-shape” life cycle defined in EN50126:2017, EN50128:2012 and EN50129:2005. This generic process reflects the development and the usage of simulation environment.
- The validity of the process is concluded that should be accepted by the certification bodies. It is necessary to differentiate between the usage of the simulation for testing of technical standard conform behaviour, safety and non-safety functionality of the tested TCMS system. A validation of the test system and the related simulation are necessary in case of the usage in regards to standard conformity declarations and to test of safety functionality, but it is not necessary for the rest of the functionalities.
- After several discussions it was concluded that not all the requirements will be possible to homologate through the simulation framework (due to technical limitations, safety reasons and not being interesting from the cost/benefit ratio point of view).
- The proposed generic process for the development and validation of a simulation could be used in the future during the homologation of non-safety functions. In the case of safety functions, it has been demonstrated that the simulation can be used during the approval process, but a real world setup would be needed in that approval process.
- A working prototype which implements a technical proof of concept is required in order to achieve a major TRL level.

CONNECTA -2 is an ongoing project with the high level objective of continuing the activities started in CONNECTA to bring the technologies to TRL5 and deploying them in two laboratory demonstrators, where the Simulation Framework will be tested.

PIVOT

The PIVOT (Performance Improvement for vehicles on track) project started in October 2017 and is planned to be completed in December 2019. PIVOT combines the development of activities in several key Rolling Stock sub-systems to con-tribute to the achievement of the key S2R Master Plan objectives (high reliability, high capacity, low cost and improved performance) within Innovation Programme 1.
It takes the Roll2Rail Lighthouse project and addresses mechanical systems within rail vehicles: Carbodies, Running Gear, Brakes, Entry Systems and Interiors including the Cab.
The objectives are:

- Explore the materials, joining techniques and manufacturing for innovative carbodies and develop a risk-assessed demonstrator specification. Develop conceptual carbody components for alternative materials (including composites).
- Provide smart solutions for running gear considering functions such as health monitoring and active suspension systems. These include new sensor system architecture and affordable hardware providing sufficient reliability and robustness. Develop a common technical specifica-tion, to innovatively use both new and existing materials and to scope the authorisation demands arising for running gear performances
- Develop next generation brake products/systems to offer attractive and efficient rail traffic both for operators and passengers.
- Provide specification of the access door systems. Perform research activities necessary for innovative conceptual design of leaves and implement new technologies, architectures and devices
- Work on the pre-project (ideation, conceptualisation and maturation process) of an adaptive train interiors and driver cabin to increase flexibility of use and adapt the train to the needs.

A list of validations/certifications currently requesting full scale or train tests (static and or dynamic) have been defined for brake systems, defining the items where a virtual validation and certification approach can be used and of which kind.
A pilot application for a virtual supported certification of the wheel-slide protection system is in development and criteria are to be defined for the deployment of vehicle simulation in order to reduce certification runs. The activity will include the possible improvement of the WSP at train level and their evaluation with a static and flexible virtual certification. In addition, criteria and procedures for an accreditation of simulation procedures have to be defined, if appropriate, in dependence on ISO 17025 (or similar standards).

PINTA WP8 provided a basis for the application of simulation for certification, however limited to the scope of WSP system certification. The results shall be analysed for applicability (transfer) in the context of vehicle certification with the focus on the brake system in general. If applicability (transfer) is possible, necessary modifications of the WSP test rig specifications (software or hardware) for applicability in the context of vehicle certification shall be implemented in the proof-of-concept phase before comparing the test rig results with field data.

Increasing the amount of virtual testing vs field testing of the brakes system will facilitate the authorisation of rolling stock and reduce its cost and duration. At present, HiL test rigs are used to validate/optimise WSP performance but testing is still required on the network. Simulations are not used to reduce the homologation testing for rolling stock brake systems.
The aim of this work package is to prepare for accreditation of simulation procedure necessary for virtual certification. Currently no case of successful accreditation of simulation methods is known. In the first step the possibility of accreditation according to EN17020 and EN17025 will be investigated.
The use of HiL and SiL test rigs will be assessed with a process developed to utilise the results from testing as part of the homologation phase.
The outcome of this will be a significant reduction in test duration and cost for homologation of new rolling stock brake systems. This will be achieved initially through 'right first time' due to risk reduction simulations and ultimately through the use of simulations to demonstrate compliance to standards.

The PIVOT project is on going and as described above endeavours to increase the level of virtual certification in order to reduce the field test durations. At present, simulations and HiL test benches are used as part of the overall certification process for WSP systems and the application and implementation is defined within EN 15595 which is summarised in section 6.1.1 of this report. The use of simulations and HiL/SiL rigs for brake stopping performance validation act only as a risk reduction activity and development of the application, to reduce field testing is the subject of the next stage of the project.

Run2Rail

Run2Rail (Innovative RUNning gear soluTiOns for new dependable, sustainable, intelligent and comfortable RAIL vehicles), which is an open call IP1 project, coordinated by Unife, under the technical lead of Politecnico de Milano. Among other objectives, it has proposed an authorisation strategy for active suspensions and steering, taking into account all reasonably foreseeable failure modes, and to assessing them with regard to their likelihood and impact. Indeed, even if some standards, such as EN 14363, now accept the use of simulations to prove a safe running dynamic behaviour, it is not really tailored to vehicles with active secondary and /or primary suspension components. When introducing them in a vehicle, each fault mode would then require on-track tests to be performed again, which is burdensome.
Run2rail has produced a set of distinct Safety Cases based upon EN 50129 for generic products, generic applications and specific applications (GPSC Generic Product Safety Case, GASC Generic Application Safety Case and SASC Specific Application Safety Case, respectively). A set of templates with guidelines oriented towards active suspension systems has been prepared, and these are supported by four examples, two GPSCs and two GASCs. (The SASC is too specific for an example arising from a research project.) This structured approach provides a modular, reusable set of safety-related documents. This combination of documents will help to provide potential industry exploiters with a valuable starting point for a full safety case submission.
The proposed risk-based approach was revised in the project's Advisory Group together with the relevant regulatory and standardisation bodies (ERA and CEN) for a preliminary assessment of its

feasibility which led to positive results.

PINTA1

PINTA1 was a S2R project that gathered 9 partners from 01/09/2016 to 31/12/2018. It focused on the improvement of technical and economical performances of the traction system, addressing the following Shift2Rail objectives:

- Railway system LCC reduction through reduction in validation & certification cost;
- Operational reliability increase through higher reliability/availability of components;
- Train & Line capacity increase through weight, volume and noise savings of traction equipment, with 2 main technologies that are studied: Silicon Carbide semiconductors and independent wheel motors for High Speed Train.

A subproject, related to adhesion issue, contributed in formulating new performance specifications for Adhesion Recovery Systems and improving requirements for Wheel Slide Protection test procedures, followed by new specifications for Automatic Test benches.

A specific WP5 dealt with virtual validation and certification of traction components & systems. Its high level objectives were:

- Early detection of design failures
- Do the right test at the first time
- Significant reduction of physical validation tests
- Important savings in terms of costs & time-to-market during validation
- Long-term target: 30% cost reduction
- Adaptation of norms / standards to allow virtual validation and certification

WP8 dealt with adhesion modelling and Lab & track reproduction systems.

The main results obtained so far are the following:

- A state-of-the-art on simulations of traction components and systems (mechanical, thermal, electrical simulations), as well as some considerations on the use of simulations in other industrial sectors, was conducted. In particular, it helped to identify methods to evaluate the credibility of simulations, to highlight the benefit of developing a common model repository and using a Model Based Design process over the project life and to identify some key change factors and barriers for introducing virtual testing for approval
- The list of replaceable physical tests (potentially 74 on XX for the traction system) by simulations was edited.

Some recommendations for the future developments were given:

- A good understanding of the level of reliability and sensibility of the different parameters will be a key question to be answered.
- Take into account some variability, uncertainties (ex. in electronics, the parasitic impedance of connections and cables should be considered.)

- Need to validate models for whole range of possible service conditions
- Integrate in simulation tools the measurements acquisition characteristics to facilitate the comparisons
- Develop a Model Based Design approach (platform including several models to manage complex systems, coding, reports, automatic code generation, helping the traceability
- Necessity to synchronise the virtual testing tools development with the products development

For the WSP:

- Partners have agreed on a common specification for the vehicle simulator inside the WSP test rig.
- High number of data collection at various conditions
- Simulations performed by different partners were compared to tests, with good results (less than 5% differences were observed in the braking distance)
- Some proposals for modification in EN15595 were formulated.

PINTA2 is on going with the aim of justifying the quality/maturity of simulations in order to reduce the number of tests performed at vehicle level. Comparison with experimental tests has been identified as an efficient way to demonstrate the level of prediction that is reached.

X2Rail

In the X2Rail 1 project, six selected key technologies in the field of railway signalling and automation systems (IP2) will be analysed and developed. These are

- Adaptable Communication System,
- Automatic Train Operation over ETCS (European Train Control System),
- Moving Block,
- Zero on-site Testing,
- Smart Wayside Objects and
- Cyber Security

The overall goal is to foster innovations for a flexible, intelligent traffic management and decision support system in real-time.
Work package 6 (Zero on-site testing) is regarded to be a complementary project and aims at defining a common framework for the test process and at defining a dedicated system test architecture for bench testing. The overall goal is to standardise interfaces and test processes to foster interoperability.
One task in work package 6 is to analyse the current field test activities to identify tests which can be shifted to bench-tests. In safety critical industries (here: transport, nuclear, system engineering, medical and defence), the status quo-analysis showed for bench tests:

- 50% are subsystem validation tests
- 30% are integration validation tests
- 20% are whole system validation tests.

The analysis which was conducted via survey showed for onsite-tests:

- 76 % are system validation tests
- 9% are integration tests
- 0% are subsystem tests
- The rest are non-functional and acceptance tests.

6.2. Other industries

As mentioned in the introduction, the importance of virtual methods in the certification process increases in all industries which bring products to market that need to meet safety requirements. This chapter introduces selected projects and shows examples of state-of-the art in other industries.

Simulation at NASA

The US National Aeronautics and Space Administration has released NASA-STD-7009a [NA01], a technical standard on modelling and simulation. It is designated for NASA internal use and not officially published by a standardisation organisation.

Its purpose is to reduce the risks of simulation-based decisions at NASA by ensuring complete communication of the credibility of simulation results to those making critical decisions by providing a basic set of best practices applicable to any simulation. It addresses the common aspects of simulations across all NASA activities while leaving out discipline-specific details. Hence, it covers what needs to be accomplished and communicated, not how this is to be done.

The standard contains 39 requirements that are generic in nature. They are necessary but not sufficient for the successful design, development and operation of any system at NASA. The requirements are complemented by recommendations. NASA-STD-7009a additionally provides in-depth methods for criticality assessment and credibility assessment of simulations. The provided method for criticality assessment is partly comparable to the risk assessment given in EN 50126 (RAMS). The credibility assessment aims to quantify the credibility of the simulation and its results by grading 8 largely independent factors.

The introduction of the standard at NASA received a mixed feedback. While the importance of a structured simulation process and consistent terminology was emphasised, there was resistance to using the standard because its implementation is perceived as complex and it imposes a high documentation burden.

Automotive industry

In the automotive industry, simulations are intensively used for the design and validation of components, sub-systems and systems. Today, there is a clear willing to also use simulations for the homologation of new vehicles, mainly for cost reasons.

In Europe, simulations in the approval process are therefore timidly introduced, while in some countries (for example in Canada), it is not formally accepted yet.

Example of passive safety

To homologate a new vehicle, many configurations need to be studied to check the good behaviour of a car in case of a crash. Because of the great number of mandatory scenarios, some national safety authorities, such as Union Technique de l'Automobile du Motocycle et du Cycle (UTAC) in France, admit that it is not reasonable to ask for physical tests for all the configurations to be analysed. The consumerist requirements can even be stronger, requesting even more configurations to be tested (in order to obtain the 5 stars of EuroNCAP - Euro new car assessment programme).
Thus, the car designer is now allowed to physically test only few configurations chosen by the authorities and simulate the others. For example, the crash scenario with an impact on the right side can be physically tested while the one with an impact on the left side can be simulated.

Example of mechanical fatigue design

Unlike passive safety, fatigue of mechanical components and sub-systems is nor submitted to regulatory rules, nor consumerist requirements. The car manufacturers carry a so-called "self-certification". They must set a design and validation process that is clearly defined and described, and they must guarantee that it is correctly applied. These processes and the associated methods, as well as the safety level target, is supposed to be justified by the "proven-by-use" (i.e. knowledge about safe and reliable past cars, designed and validated with these methods) and with the verification of non-discrepancy with competitors and most recent observations, i.e. the so-called compliance with the state-of-the-art.

Nevertheless, to assure the good mechanical behaviour of a car, full-scale tests such as tri-axles tests are still performed at the end of the design and validation phase. These tests help to check the fatigue behaviour of specific area (complex assemblies, new materials…) and also to check the whole system behaviour (loads on sub-systems, couplings and interactions at interfaces, etc.). It is not expected to replace those tests, because the level of confidence in simulations on a complete and complex system such as a car is not yet considered sufficient by technical experts.
For engines, the situation is the same: final full-scale tests are performed on benches (leak tests, mechanical fatigue tests, thermal-mechanical fatigue tests).

Tests are also carried out on specific tracks (proven grounds), during which many physical parameters are measured (forces, engine torque, accelerations, temperature…). The aim is not to run until wear or damage can be observed but to check the level of the loads, capture some useful information, "debug" the first version of the car (noise…) and detect potential early sign of failure that may not have been predicted by the modelling.

Finally, tests are systematically performed on real roads at the very end of the validation phase, before the homologation of the car. These running tests can be up to a cumulative mileage of

200 000 km of circulation, which corresponds to the order of magnitude of a car lifetime.

Multi-body simulations of a car running on a virtual road can be performed in order to determine time signals of loads on the wheels and at the main internal interfaces of the carbody. At present, these signals are almost used to define relevant load specifications early in the design phase.

Example of a research project: IMVITER

In the automotive sector, too, vehicles have to meet certain technical requirements before they are approved for sale in the EU. The approval for an automobile is a type approval. Although the EU Framework Directive 2007/46/EC generally allows virtual test methods for type approvals in 2010, they are not specified or explained in detail. The IMVITER (IMplementation of VIrtual TEsting in safety Regulations) project, funded under the FP7 program of the EU in the years 2009 to 2012, aimed to introduce and promote the concrete implementation of VT into safety regulations. The consortium consisted of 15 partners from Germany, France, Italy, Spain, Hungary and Greece and represented the key players involved in EC type-approval procedures for automobiles. VT in this project is considered to be the use of numerical simulation models in assessing technical requirements that either replace or at least support experimental testing methods. The main objective of IMVITER was to further introduce and enhance virtual test methods in the existing regulatory framework.

The concrete objectives of IMVITER were to identify physical tests that could be candidates for replacement by VT, and to develop different VT implementation levels. In addition, validation criteria for simulation models were proposed and the introduction of stochastic methods, reliability analyses and robustness optimisations was analysed. All in all, the focus was on reducing costs and the number of real tests as well as the feasibility and potential of virtual procedures. The pilot cases analysed in the project were related to different levels of technical difficulty in (simulation-) model building:

- pilot case 1: Pedestrian head impact protection case
- pilot case 2: Seat belt anchorages strength case
- pilot case 3: Towing devices strength case
- pilot case 4: Pedestrian lower leg impact case

Based on these 4 pilot cases, extensive investigations for the validation and verification of simulation models and sensitivity analysis were carried out. These have led to deriving validation metrics that previously did not exist in the safety application. Furthermore, the studies have shown that simulation models need to be validated in conjunction with the code in which they were developed, because both entities are indistinguishable from the validation point of view. IMVITER proposed 3 different types of approval approaches (Full, Hybrid, Extension of approval) with different status of simulation and assigned the pilot cases to these 3 approaches. The Cost-benefit-analysis for VT implementation identified savings in cost and time, both in short-term and long-term scenarios. This was identified for pilot case 1 even though for pilot case 3 VT would only provide advantage, if a full VT approach could be implemented, because the experimental test is almost costless.

In conclusion, because of the technological complexity of a car and the complexity of the physical phenomena such as noise, multi-physical couplings, interfaces between sub-systems, etc., one cannot generalise that simulations can be predictive and robust enough, at least at a system level. Hence, physical tests will still be necessary to validate the final design of a whole car. However, the automotive sector is working at introducing more and more simulations in the homologation process, for a mixed virtual/physical approach.
Simulations are mainly used to limit the number of configurations to be physically tested (the most severe) or the number of vehicle versions to be physically homologated (the most detrimental ones).

Nuclear power plant industry

The design of a whole nuclear plant and of its sub-systems takes many years. There are several phases of design: from basic design – where main loads are studied, main design parameters such as thickness, stiffness are set – to, at the very end, detailed design - where additional loads are studied, geometrical details are set, etc.

In the nuclear field, simulations are intensively used, as well as feedback from operation and from other past projects. Very few full-scale tests are performed.
More precisely, experimental tests are performed only when there is a significant modification in the design principles of a system. For example, for the new nuclear plant EPR that is being designed and manufactured in France, some parts of the steam generator or reactor pressure vessel internals design are significantly different from the past ones, so bench tests are performed. In fatigue analysis, for example, if simulations show that there are areas where the "usage factor" is in-between 0,5 and 1 (the admissible value is 1), then, the area is considered as a "solicited area", and during operations, monitoring is mandatory. The objective of this monitoring is not to detect potential defaults but to verify that the loads that were used during the design phases are conservative. The number of cycles is also recorded progressively.

There is one systematic field test that is performed at the end, whatever the degree of modification of the design is: once the nuclear plant has been manufactured, a hydraulic test is performed (the pressure is set to $1,3*P_{ref}$) that enables to verify that there is no leakage.

In the nuclear field, the responsibility for safety is in the hand of the operator. For each new nuclear plant project, the design needs to be justified and a risk analysis is also performed. The risk analysis is performed using both deterministic and probabilistic approaches. Regarding the design justification, a record is produced. It includes a technical note from Framatome, the nuclear plant designer and manufacturer, checked and validated by EDF, the operator. It is then sent to the National Safety Authority that gives or not the authorisation for operation after the review with the technical support of IRSN (Institut de Radioprotection et de Sûreté Nucléaire) or notified bodies (Apave or Bureau Veritas), a third independent party, which checks and gives a final judgement.

AFCEN – an international association created in 1980 gathering experts from operators, manufacturers, suppliers, consulting and training entities, etc. which aims at defining non-mandatory technical rules - edits several guidelines of good practices for the design, supervision during operation or risk analysis of the different sub-systems of a nuclear power plant [AF01].
But: it is important to underline the fact that the details of the methods to be used are not specified in national or international requirements. This allows an agile adaptation of the methods to the scientific state-of-the-art as well as to the international nuclear experience.

The software used for certification purposes can moreover be open source (see for example the finite element software code_aster and the uncertainty code OpenTURNS) or commercial. In all cases, the purpose is to allow a continuous progress approach. In some technical areas, the strategy can also consist in emphasizing the use of different softwares by different stakeholders to gain robustness in the process. As an example, for mechanical studies, Framatome uses the commercial FEM software Systus edited by ESI Group, code-aster is developed and used by the French operator EDF, while IRSN uses the software Cast3M developed by CEA, the research institute on nuclear science, when a counter-expertise is required.

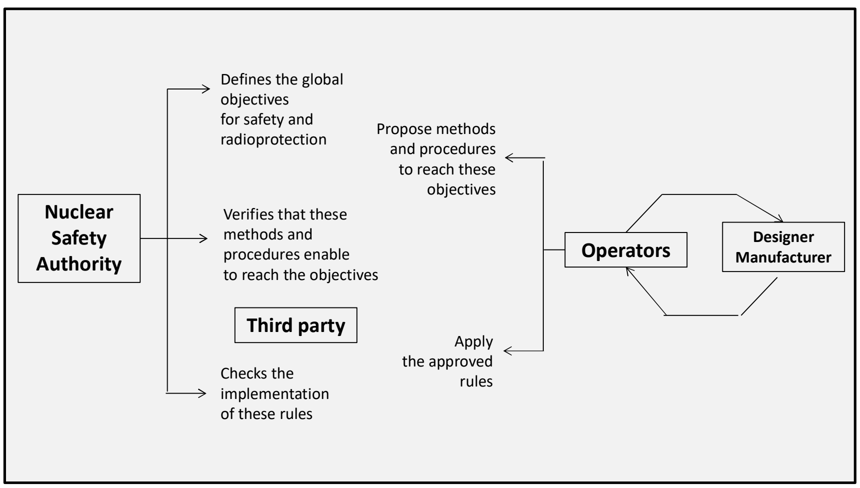

Figure 8: Stakeholders in Nuclear power plant industry

At the European level, research on simulations in the field of nuclear power plants was conducted in the NURESAFE project, which is part of the Horizon 2020 framework programme of the European Union. The aim was to move towards “high-fidelity” simulations. [N01]

NURESAFE aimed at increasing the prediction capability of computations used for safety demonstrations of nuclear power plants. This could be achieved through a common multi-physic simulation scheme, attained by dynamically and 3-dimensionally coupling the codes simulating the different physics of the problem. The software is based on the NURESIM (Nuclear Reactor SIMulation) European reference simulation platform. [N01]

The NURESAFE project also produced state of the art analyses for verification, validation and uncertainty quantification. However, they cannot be considered in this document because the respective deliverables (D32.31.2, D32.32.1a and D32.32.2) are confidential and can only be accessed by the participants of the project.

Aircraft industry

The aircraft industry applies virtual certification methods. The industry uses numerical modelling, SiL and HiL tools in order to provide validation evidence to satisfy design requirements. The process to enable this virtual certification has two key steps:

1. Communication of intended means of compliance with the relevant certification bodies;
2. Verification and Validation of the tools and simulations used to confirm validity of the outputs as evidence of conformance.

The definition of the means of compliance is documented in Validation Plans during the design phase of the project. The means of compliance is reviewed with the relevant certification/approval bodies to confirm that the proposed approach is acceptable. The process of verification and validation to enable the use for certification is also agreed with the relevant certification/approval bodies.

Verification and Validation of the tools and simulations is required to be documented in order to validate the outputs that are generated as being accurate and representative. This process considers the input requirements definition for the tools, development of simulations/models and the evidence of valid outputs. The report is also to consider the process elements such as configuration and change management, test execution and reporting and competence of people.

Bombardier Aerospace use HiL tools for the execution of tests for product conformance evidence. The process starts with HiL tools for the verification of single systems and then integrate the systems together to develop a full functional integration rig capable of testing all functional integration requirements for the product. The rig incorporates the system control units with embedded software, representative wiring between the Units and simulations of the system plant and the operational environment. The single system HiL tools are used for risk reduction purposes before the systems are integrated into the full HiL rig which is used for certification evidence.

7. Requirements for Virtual Testing

The objective of virtual testing is to reduce the duration of testing of the train in the field. This can be achieved in two ways; (i) virtual testing can be used as risk reduction by ensuring issues are identified early and therefore the field tests are more likely to be successful in fewer iterations; and (ii) the results from virtual testing are accepted as conformance evidence to design requirements thus removing field tests from validation plans.

This section comprises requirements for virtual testing and provides examples from the projects, standards and industries reviewed in chapter 6. It should be understood as a mere collection of potential requirements and shall not be confused with the proposal for a generic approach that will be developed at a later stage of the PLASA2/VC project. Initially, this section describes the different kinds of virtual testing tools utilised, both software and hardware related or a combination of both. This is followed by a summary of potential requirements for verification of tools, verification and validation of models and credibility evaluation methods for virtual testing.

7.1. Virtual testing tools

When implementing virtual testing, different kinds of tools can be distinguished. Virtual tests can range from pure numerical simulations on a PC through to test rigs incorporating control units and hardware used in the actual product. The employed blend of numerical and physical components in the virtual test depend on numerous factors such as cost, time, phase of the development lifecycle, pedigree of the tools available, complexity of the system, and availability of relevant data for the system and operational environment. The tools can be generally categorised into the following groups:

- Numerical Simulation
- Software in the Loop
- Hardware in the Loop
- Full scale test rigs

7.1.1 Numerical Simulation

Numerical simulations are the most utilised virtual testing and virtual certification technique in the rail industry. Their application is supported by one or all of: pedigree of the software package used for the calculation (e.g. ANSYS / Nastran / Hyperworks Tools for FEM; Simpack / Vampire for MBS); Standards governing the development and implementation of models; or ‘proven in application’ bespoke software such as the SNCF developed OSCAR software for pantograph and power supply interaction modelling.
Previous rail research projects AcouTRAIN, PantoTRAIN, AeroTRAIN and DynoTRAIN all developed models for use in virtual testing. Many of these projects influenced the development of Standards which allow for the use of numerical modelling and calculations as part of the certification process. The following standards, as examples, allow the use of numerical simulation:

- Power supply systems – EN50388
- Bogies and running gear, running resistance – EN15827, EN14363
- Structures – EN15227, EN12663, EN13749, EN13979-1
- Gauging – EN15273
- Aerodynamic performance – EN14067

The use of numerical simulations for certification purposes is usually supported with test evidence at system or product level to validate that the model provides an accurate representation of reality.

Numerical Simulation is distinguished from HiL/SiL testing in that it does not include any components of the real system. Such components could be hardware (case HiL) or software that is already compiled for use on the actual hardware of the system to be tested (case SiL). Instead, the numerical simulation consists only of models or codes that are an abstraction of the real system including its software.

7.1.2 Software in the Loop (SiL)

In SiL testing, the real software code compiled for use on the real hardware is embedded in a model simulating the system environment and other interfacing systems. This technique has the significant benefit of enabling software testing to commence prior to the control system hardware being available. It also allows software developers to follow a 'develop–build–test–rectify' process to enable the software maturity to be more advanced at the start of HiL or system testing on the manufactured product. This approach also makes it easier to automate execution of test cases which can deliver significant time and cost benefits to the validation process.

SiL is applied widely in the rail industry in the software development process but it is used as a risk reduction activity rather than a means of demonstrating conformance to the design requirements. The key limitation to the use of SiL tests for the replacement of field tests lies in the ability to accurately represent the hardware components of the control units and interfaces between the sub-system models that are necessary for the operational environment simulation.

7.1.3 Hardware in the Loop (HiL)

HiL uses the real subsystem/components (Hardware and Software if applicable) fully coupled with a real time simulation of the operating environment. HiL test rigs can incorporate one or more system controller units into a rig with simulated operating environment and interfacing systems. HiL tests offer a significant opportunity for the reduction of field tests as well as improving the robustness of products due to the ability to test controlled combinations of inputs more readily and to complete increased number of repeat test cases at a relatively reduced cost.

HiL is applied in the industry for virtual testing and virtual certification purposes. In the rail industry, HiL tools have been developed for testing of train control systems, pantograph performance and WSP system validation. In these applications, the HiL tests are validated through comparison to results of tests on the real train as well as the achievement of defined acceptance criteria for accuracy, repeatability and other criteria.

PantoTRAIN defined a process for the use of HiL as part of a hybrid validation process for the interaction of the pantographs with the overhead electrification system but its use for authorisation is not yet permissible.

The Standards EN15595 and UIC541-05 recommend the use of HiL in the validation of WSP systems and the PINTA project has defined a set of requirements for developing simulations, such as adhesion models, for use in these HiL tests. The standards set out the means of validation for each of the core test cases for the system and which can be executed on HiL / SiL test rigs. Clear criteria for acceptance of the tools are defined within the Standard as well as the documentation required for the tool validation and therefore to support the use of results in the homologation.

The CONNECTA project addresses the development of HiL tests for virtual testing of TCMS architecture and software. The general strategy is a declaration of conformity on basis of a tool validation according to the standard EN 50128. [C02]

The examples of implementation of HiL for virtual certification in the rail industry are generally limited to the validation of one individual system, as defined in the WSP and CONNECTA examples. Aerospace (Bombardier) and automotive (Jaguar Land Rover) manufacturers use significant HiL rigs to validate the functional integration of all core systems within a product. These complex HiL tests are qualified and used for Virtual Certification purposes. HiL tests of this complexity are being used in the rail industry by rolling stock manufacturers but mainly as part of a risk reduction process. Functional integration rigs are developed which integrate the TCMS, system control units and train wiring to enable functional tests to be executed for risk reduction test activities prior to on train functional tests. A limitation at present is the generation and acceptance of the qualification evidence to enable approval bodies to accept the results of these tests for homologation. The validation of safety related event generation for the train drivers under certain operational conditions and functional performance of the passenger information system are examples of where test evidence from this type of HiL rig could be used for certification purposes. This is a significant opportunity for reduction of field testing in the future in the same manner currently being applied in the aerospace industry.

7.1.4 Full Scale Test Rigs

Full scale test rigs involve tests using the actual product, hardware and software, in the final configuration for testing. It is distinguished from HiL in that there is only a one-way coupling between the test bench – representing the environment – and the component: The test bench manipulates the component, but the behaviour of the component has no influence on the outputs of the test bench. The level of simulation in this virtual testing is reduced thus making it simpler to demonstrate its representativeness. Examples of full scale rigs include carbody compression rigs used for structural analysis and vehicle sway test rigs used to validate models for gauging validation in the UK. These rigs are used to provide conformance evidence to certification requirements but utilised more generally to provide comparative test data to validate models used for that purpose.

7.2. Verification of Tools

Formal verification of the tool is essential to be feasible for Virtual Certification purposes. In the context of simulation, the term tool refers to an in house, vendor or open-source framework in which one may develop or embed models enabling the execution of tests. It can be software and/or hardware and parts of the real system can be installed in the tool. In case of numerical simulation and SiL, the tool is purely software whereas with HiL, tools are a combination of software and hardware. Verification processes for both software and hardware are briefly described in this section.

For numeric simulations, before implementing a specific model, it must be ensured that the simulation tool as installed on the designated executing system (computer) correctly and accurately represents the underlying mathematical model and solutions. It consists in verifying each elementary model proposed in the library of the tool, the good behaviour when they are assembled, as well as verifying the relevancy and the correct implementation of numerical algorithms and methods. For commercial tools, the verification is mainly led by the software producer who ensures that the tool is functionally valid and provides appropriate evidence. If the tool is an in-house software, the whole process can be led by the developer/user, but a last verification by an independent assessor can be required. To verify the correct operation of a tool on the designated executing system, tool specific test-cases are applied as inputs and the tool outputs are checked against reference results provided by the software producer. This is to ensure, that even new tool releases do not contain errors and that the results are independent of the computer system on which the tool works.

The steps for verification of test rigs are different to those for numerical simulations, but have the same purpose. Before installing the object to be tested in the bench, the environmental conditions (temperature, humidity, etc.) have to be determined and compared with the required conditions - if necessary, remedial action is required. The next step is to calibrate the entire measurement chain, starting with the input quantities, then through the measurement signals to the output quantities. In this context, the uncertainty of the measuring chain can also be detected and compared to the requirements. If an acceptable level is ensured, this step is followed by the assessment of results to determine accuracy, repeatability and robustness of the outputs. The verification of sufficient accuracy can be made by comparing the (simulated) results of the bench to “reference cases”. This process is specific to the bench, but in some cases real existing reference objects can be used for this step.

All these steps should be covered by a verification plan defined upstream (for example during the development of the tools, in the left branch of the V-shape design and validation process, see chapter 5.1). The documentation aspect for verification of test rigs has a greater significance than for numerical simulations, because some parameters (e.g. calibration factors) are recorded only once and do not necessarily have to be stored in a program for reading afterwards.

If the virtual tool is made of several interacting tool components, it is necessary to verify each single tool, their interfaces and then, the assembly of the whole.

The process to verify the tool can be covered by the following areas:

1. Requirements: The expected functionalities need to be defined (input, output, type of available models, elements library, etc.), the expected accuracy should be stated, and sometimes, detailed requirements on the means can be given (type of numerical resolution, etc.). The requirements can be specified by the tool developer/owner or defined within existing Standards or Codes of Practice. The level of verification and independent assessment required to verify requirements is more onerous for tools that are not following existing, accepted Standards.
2. Software: evidence of the pedigree of the software used for development of simulations and the process for operation of the tool. It is good practice to record a feedback log on the use of the tools during previous projects, especially when the software is an in-house tool.
3. Accuracy of the output of the tool: assessment of the results to determine accuracy, repeatability and robustness of the output. The verification of sufficient accuracy can be made by comparing the simulated results to a “reference case”. This step should be covered by a verification plan defined upstream (for example during the development of the tools, in the left branch of the V-shape design and validation process, see chapter 5.1)
4. Identification of the domain of validity of the tool and its limitations
5. Documentation and quality process: formal documentation produced to record the tool development process, evidence for its accuracy, change and configuration management, competence of personnel and test execution process. It is good practice to have this documentation assessed by an independent person or organisation and this is mandated in some Standards which allow the use of such tools for certification evidence.

7.3. Verification and validation of models

The verification and validation of the simulation models is a necessary prerequisite for the application of numerical methods for approval. While the term ‘verification’ answers the question “Do we solve the model correctly?”, the term ‘validation’ serves to answer “Do we solve the right model?". This chapter is about state-of-the-art model verification and validation methods, based on the reviewed projects and standards described in chapter 6. Some of them are used in the approval process and are regulated by standards. Others have only been proposed but are not or not yet implemented in guidelines or standards. The first subchapter, 7.3.1, is about model requirements, 7.3.2 shows that verification and validation is a comparison between simulation and reality or a reference case and spotlights the different characteristics of such a comparison. Subchapter 7.3.3 goes into detail about methods and acceptance criteria for model verification and validation and presents various examples. Subchapter 7.3.4 deals with the consideration of variability and uncertainties whereby subchapter 7.3.5 deals with methods to evaluate credibility of simulations models in a larger and more global context.

7.3.1 Requirements for models

The requirements for numerical simulation models defined in the reviewed standards are very heterogeneous. They range from very detailed information to the point that quasi none are defined (ex. EN12663, EN13979).

In most cases, there is information on the level of detail of the model. In that case, the standards specify which components are to be considered in the model and where model simplifications are possible. Simplifications can be made if they have little influence on the results of the simulation model, or if they are conservatively estimated with simplification.
For example, in EN15227 for crashworthiness analysis, the first or the two first vehicles must be modelled by FEM in detail. For many other parts, such as the middle cars of a train unit, a simplified model with equivalent mass and stiffness is sufficient.

Requirements can sometimes be more detailed. For example, the standards which allow the use of FEM, sometimes define requirements which concern aspects like 2D or 3D modelling, mesh quality and allowed mesh elements types. It should be noted, that state-of-the-art FEM tools have their own quality requirements and warn the user if they are not fulfilled. Usually these quality parameters are more onerous and up to date in contrast to them defined in the standards.

If the reality can be described using different physical models, the corresponding standard gives examples of best practice and provide recommendations. For example, in aerodynamics, the standard EN 14067 suggests to use specific approaches for turbulence modelling in CFD simulations.

7.3.2 Verification and Validation by comparison

The current standards are not always precise concerning the use of the terms ‘validation’ and ‘verification’. In this report a clear distinction is made, consistent with the guideline report proposed by the CEN-CENELEC /TC256-TC9X/ survey group on “Simulation”. However, in case of the examples provided from the standards and other projects the terminology may deviate from the one defined here. An example of this is EN 15273, where even in the same standard, what is considered ‘validation’ here and in most literature is referred to as both ‘verification’ (Swedish gauges) and ‘validation’ (UK gauges). ’Qualification’ is sometimes used as well. The distinction between simulation tool and model is not always clear neither.

Verification of the model consists in verifying that the implementation is done correctly and, in the case of numerical simulations, that the numerical model can be solved in the tool and that its results accurately represent the underlying mathematical model and its solutions. In contrast, validation is the process of determining the degree to which a model is an accurate representation of the real world. Simplified, validation of the model can be described as answering the question “Do we solve the right model?”. [O02]

Verification and validation are based on the concept of comparison to a reference object. The reference object can be very different in nature:

- In the simplest case the reference object is a real physical object, the real equivalent, a railway vehicle for example. The behaviour of this real object could be described with measurements during an on-track test. But the reference object does not need to be the physical full size vehicle, in some cases it doesn't exist at an early stage or it is not available. In some cases, it is then enough to consider a scaled model and use measurements of this scaled version as the reference object for model validation.
- In a more abstract case, the reference object is a so-called "benchmark object" which does not need to have a physical representative. The behaviour of benchmark objects was not necessarily confirmed by experimental tests, but they have proven themselves and have been set up and tested by experts.
  For example, wind tunnel CFD simulations in aerodynamics have to be compared to benchmark test data described in the standard.

Depending on the scope or the results of the validation, a differentiation can be made between:

- a full validation that increases the applicability of the simulation model for virtual tests and
- a limited validation, which limits the applicability of the model.

This differentiation only exists in a few application areas in which simulations are permitted, for example in acoustics, for pass-by and stand-still scenarios.

If the virtual testing is based on the use of several separated tools, it is necessary to make the verification of each single tool as settled in 7.2, but it is often accepted that the validation of the simulation by comparison can be carried out only on the overall results.
A documentation of the verification and validation process is necessary and a proposal for this will be provided in deliverable D5.2.

7.3.3 Acceptance criteria for model verification and validation

As stated in the introduction, verification and validation means comparing the behaviour of the object to be validated with its reference object. So, it is necessary to define physical parameters which can be used for this comparison. These parameters can be derived either

- directly from the field tests or laboratory test outputs for which acceptance criteria are defined in standards or
- using physical parameters that have a high impact on those results or have a particular meaning which is important to correctly represent the system.

These parameters can be qualitative (ex. shape of curves, sequence of scenarios, etc.) and/or quantitative (peak value, mean value, amplitude, standard deviation, etc.). When the outputs are not simple scalars but time signals, spectra or matrices, it is more difficult to define simple quantitative parameters; methods to calculate a distance or a level of correlation between signals, spectra or matrices should be used (ex. cross-correlation for time signals; magnitude-squared coherence or cross power spectral density for spectra; etc.)

The comparison between simulation and reference can be carried out by assessing different parameters taken isolated; in this case, each parameter has its own acceptance criterion. Another possibility is to consider the combination of different result parameters or the combination of result parameters for different inputs and use an aggregated parameter.

Once the parameters are identified, an acceptance criterion has to be defined for each one of them. The criteria for deciding whether a simulation model can be successfully validated can be strict and purely objective, but also softer and more subjective. Examples can be found for both types. Of course, objective criteria regarding clarity and credibility are more appropriate for virtual tests for approval. However, slightly softer formulated limits, or criteria that allow a subjective (but independent) assessment, may extend the scope for successful validation for example when compared to measurements that are in some points incomplete or implausible.
The evaluation of limit values for the validation, for example for the permissible difference between model behaviour and reality, is not always clearly regulated. There are a variety of approaches. For example, as shown in Figure 9 from DynoTRAIN, a constant deviation or a variable deviation depending on the magnitude of the simulated value S_v can be considered. The final acceptance criteria are based on the experience and proposals of technical experts and should be continuously confirmed by a variety of applications.

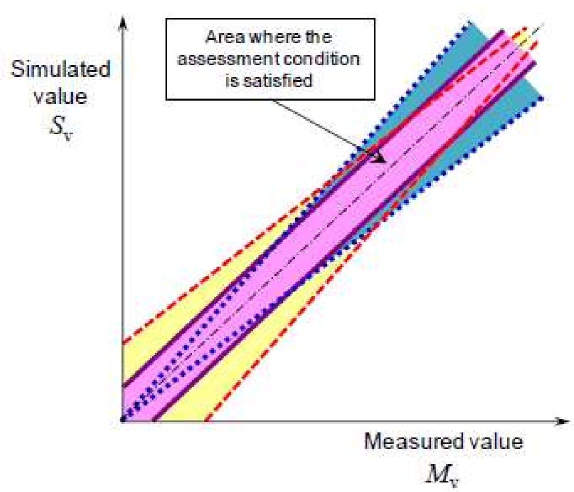

Figure 9: Different zones for limit values [D01]

In the following part, the different validation methods of the reviewed standards and research projects are presented under the former discussed aspects.

Vehicle running characteristics

Model validation in the field of running characteristics is described in EN14363 and has been updated by the results of DynoTRAIN in the year 2016. Concerning model validation most of the proposals of DynoTRAIN were implemented in the latest version of EN14363. The standard describes two different methods: The older one, method 1, needs an independent reviewer for the assessment of conformity of simulation and measurement, while the new integrated method 2 is based on an objective mathematical comparison.
In method 1, the validation process is based on analysing the response of the vehicle model to various inputs. An independent reviewer assesses this analysis based on his subjective assessment. The following parameters can be used to compare simulation and test results:

- Forces: static wheelset/bogie/side force, wheel force/unloading in twist, lateral force in 150 m curve, quasi static wheel force
- Accelerations: vehicle body accelerations, bogie accelerations
- Bogie rotational resistance, Roll coefficient, Eigenfrequencies of the rigid body movements of vehicle body

For some of the listed parameters, maximum and average deviation are defined, but in part these are only given informatively, see [EN14363, table T.1]
Investigations carried out in DynoTRAIN on this method, showed that the method is not objective and that the examiners have come to different conclusions with the same validation principles.
As explained in the introduction, the validation process according to Method 2 is based on a mathematical comparison between the results of on-track tests and the corresponding simulation results.

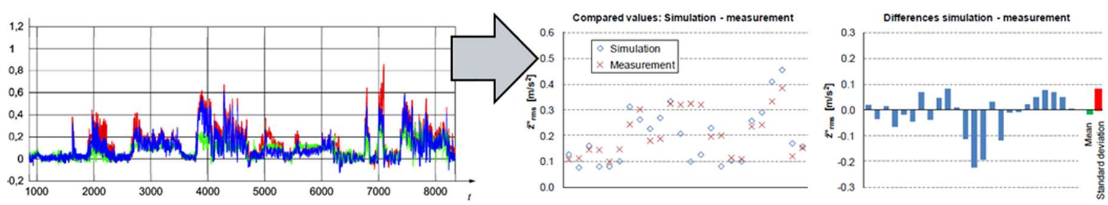

Figure 10: Measurement processing according to validation method 2

The results of a specified quantity of simulation and measurement are to be compared on at least 12 track sections. The sections have to contain 3 sections from all 4 test areas (different curve radii). The other conditions (length of the curve, superelevation, etc) for these sections of the track have to comply with the requirements of the on-track tests. Each output quantity is evaluated for two evaluation points (for example on the 1st and 2nd wheelset). This results in a quantitative comparison of 24 simulated values S_v with the corresponding measured values M_v. All signals are to be filtered according to the normative specifications and the 0.15% and 99.85% percentiles are being calculated. Then the difference D_v between S_v and M_v is calculated, average and standard deviation are then compared to the validation limits defined in [EN14363, table T.2]. To ease the post-processing, normalised values are used; for this purpose, the values of D_v

are divided by the validation limits. Thus, it can be seen at a glance, whether the validation has been successful, corresponding to the situation when D_v is always lower than 1.
The described procedure is carried out for the following quantities and the results are finally clearly presented in a diagram (Figure 11).

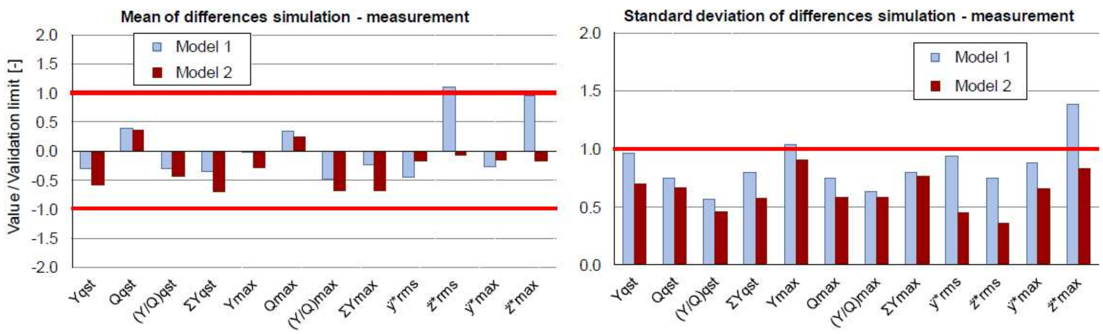

Figure 11: Validation result according to method 2

As it can be seen in the figure, model 1 could not be validated, while model 2 is successfully validated and can be used for the scope of simulation in running characteristics.

__Vehicle Acoustics__

In the field of vehicle acoustics, the proposed validation procedure from the AcouTRAIN project is not implemented in standards. Against this background, the described validation method has to be considered preliminary.
The proposed procedure differentiates between a limited validation, which means the simulation model is only validated for stationary conditions, and a complete validation for stationary and pass-by conditions. Both procedures are based on the comparison of model simulations and the measurement results from the real test.
The stationary test considers the noise during standstill at different positions outside around the vehicle. For model validation, the following 3 acceptance criteria have to be complied:

- Maximum allowed deviation in sound pressure level for each measurement position between real test and virtual test shall be within +/- 2,5 to +/- 3 dB(A).
- Maximum allowed deviation in whole sound pressure level between real test and virtual test shall be within +/- 1,5 dB(A).
- Maximum allowed deviation in sound pressure level for each one-third band shall be within 4 dB in the frequency range between [315; 4000 Hz].

For a complete validation, the simulation model has to pass the additional acceptance criteria, which are based on the comparison between model and real test in the pass-by scenario (vehicle speed: maximum and 80 km/h):

1. Maximum deviation between measured and simulated overall pass by noise less than +/- 1,5 dB(A).

2. Maximum deviation between measured and simulated pass by noise spectra in one-third octave bands less than +/- 3dB(A) in the frequency range between [315; 4000 Hz].

Pantograph/Catenary

In this area, simulations can be used for the preparation of the field-tests. According to EN50318, the validation of a simulation system of pantograph and catenary shall be carried out by comparing simulated results with measured values from a line test of contact forces and displacements in the overhead contact lines. The simulation results have to be filtered for the same frequency range as the measured values and the same type of filter has to be used.
The deviation of the simulated values from the measured values has to lie within the following tolerances:

- Mean value of the contact force: +/- 2,5 N
- Standard deviation of the contact force: +/- 20 %
- Maximum uplift: -10 mm/ + 20 mm
- vertical displacement of the current collector: +/- 20 mm

Optional values, which can be used for the comparison, are the elasticity of the catenary and the maximum and the minimum of the contact force. In the PantoTRAIN project the frequency band analysis, as an advanced comparison method, has been discussed, but was not implemented in the standard.
As a follow-up to Pantotrain, a benchmark of tools and models for the pantograph-catenary interaction modelling was carried out in 2013 across Europe and Asia, involving eleven softwares from ten different laboratories. The results were published in [SC04]. Important similarities in the modelling approaches could be observed. Quite good agreement (a scatter of about 20% on the major indicator) was also observed, allowing to conclude that the basic features of the modeling are now quite solidly established in the sector. But larger dispersion was found for other indicators, in the range of 5-20Hz, showing that further research effort was still needed.

Aerodynamics

In aerodynamics, different methods for the validation of numerical models are proposed for fluid and multi-body dynamic simulations. Fluid dynamic simulations for head pressure pulse loads are validated according to EN 14067-4, for crosswind according to EN 14067-6 and multi-body simulations for crosswind according to EN 14067-6.
In contrast to the other validation methods presented in this chapter, in the field of aerodynamics, model validation is not possible by comparison with measurements in all cases. For example, in crosswind stability, this is because the simulated scenarios would be safety-critical and uncontrollable in a real experiment. For this reason, reference scenarios (also called benchmark tests) are defined, which then form the basis of the comparison, used in the validation of the simulation model. In the standards, these comparisons are called model or process verification, not validation.
For verification of the CFD approach, used for the assessment of train-induced pressure variation in the undisturbed pressure field, simulations shall be made for at least one benchmark vehicle.

This vehicle has to have a similar streamlined or bluff geometry as the vehicle to be assessed. The simulated pressure shall be compared to measurements of the benchmark vehicle which have been obtained from experimental full-scale tests or from reduced-scale tests. The root mean square of the deviation over all heights around the vehicle shall lies

- within - 5 % and + 10 % for a bluff vehicle or
- within - 3 % and + 5 %, in case of a streamlined vehicles.

The same simulation set-up (local mesh size, turbulence model and boundary conditions) can then be used for calculating head pressure variations with the vehicle to be assessed.
The verification of CFD models for crosswind simulations is quite similar. It has to be demonstrated, that the results of the CFD approach for a benchmark vehicle in a wind channel are within a certain range. The results and the input data of the benchmark vehicle are stated in the standard.
In MBS-simulations for crosswind stability, the process as well as the vehicle model has to be verified. The verification of the process can be achieved by calculating the crosswind characteristics (CWC) of two benchmark vehicles, specified in the standard. If the deviation of these results (given in the standard) and those of the benchmark simulation is smaller than 0,5 m/s, the requirements are fulfilled. The verification of the model includes a comparison of measured results of the vehicle to be assessed and results from the simulation model. The following criteria must be met:

- sums of the axle loads of each bogie lie within 1%
- the bumb stop distance is modelled as in the nominal design data
- the flexibility coefficient in the simulation is in the tolerance level of the measurements

If the process and the model is verified, the MBS approach can be used for the assessment of crosswind stability.

Crashworthiness

The requirements for model validation in the field of crashworthiness are regulated in the EN 15227. The requirements of the scenarios in which the simulation results are compared with the measured results, are not specified in detail compared to the other presented fields. The tests used for the comparison shall reflect the energy absorption requirements of the relevant scenarios, but it is not required to reproduce the actual scenario in the test. So, it is permissible to verify the performance of independently acting components by appropriate individual full-size tests. These full-size test specimens shall perform like the crashworthy elements and help to calibrate the simulation model. An acceptable full-size test which can be used for the comparison and validation of the simulation model includes:

- measurement of forces, collision speed, decelerations and deformations
- dimensional measurements before and after the test
- records of the test configuration, general views and detailed drawings using, where necessary, highspeed video for comparison of the kinematics
- definition of tolerances for speed of impact and mass of the test object

The simulation model is validated, if the comparison to the test fulfils the following criteria:

- same sequence of events occurs during the collision
- same observed deformation patterns occur
- dissipated energy by the simulation model is within 10 % of the test value
- global force curve, (with peaks and troughs and levels etc.) shows same general characteristics as measured

In addition, the following criteria for validation have to be fulfilled when the collision energy is absorbed by more than one distinct mechanism:

- overall displacement of the simulation is within 10 % of the test value
- mean force determined from the force-displacement graph shall be within 10 % of the test value

Wheelslide Protection

Standards EN15595 and UIC541 provide clear guidance on the requirements for simulations. The Standard defines requirements for the following models:

- Adhesion Model
- Test and Performance Model
- Vehicle Performance Model
- Vehicle Functional Model

The PINTA project has developed a set of detailed requirements for simulations used in the HiL tools.
Prior to the commencement of the testing programme, the accuracy of the vehicle model simulation shall be validated by comparing the braking performance predicted by the computer model to actual track test data for that particular type of rolling stock. This validation includes the ability of the simulation to detect behaviour that has the potential to occur if WSP units in a train communicate with each other; such functions are then tested in the Vehicle Implementation Test unless the simulator is able to simulate the part of the train which is relevant for WSP control. The simulation validity tests are to be performed on an adhesion profile representing a level of adhesion consistently greater than that which will sustain the vehicle's maximum braking rate (i.e. equivalent to dry rail conditions). If track test figures are unavailable (e.g. for new rolling stock), predicted/calculated dry rail stopping distances provided by the train braking designer/supplier may be used for the validation process.
The test(s) are performed for one of the tare conditions and one of the laden conditions as set out in EN 15663 for each vehicle type, from a braking speed based upon track test measurements or calculation data. This shall be the train's maximum operating speed. The vehicle model simulation shall be deemed acceptable provided the predicted stopping distance(s) concur to within ± 5 % of the dry rail stopping distances achieved by the track tests or by the braking equipment suppliers' calculations. The simulations have to demonstrate that they achieve accuracy and repeatability targets for each test criteria. In order to demonstrate the repeatability target, firstly, the mean value and the standard deviation of the parameters braking distance,

braking time, initial adhesion and mean slide of four valid on-track tests shall be calculated. Secondly, the same test shall be repeated 10 times on the test rig, using the vehicle parameters from the accuracy test. Afterwards the mean value and the standard deviation for the four parameters shall be calculated. Repeatability is characterised with the indicator

$(s/\bar{x}) \cdot 100 - 100$ (s: standard deviation, x: mean value)

and shall lie within the following limits for a successful validation:

- braking distance: 94 %
- braking time: 94 %
- initial adhesion: 90 %
- mean slide: 75 %

EN15595 mandates that an Independent Assessor is appointed. The Assessor is to produce an Assessment report based on the evidence provided. The lab used for any testing is to be operated in accordance with EN ISO/IEC 17025.

Rolling stock gauges

A validation of simulation models is required for the dynamic method according to EN 15273-2. The used simulation model has to be validated with regard to the measured results of the following physical tests:

- Weighbridge test:
  In this test, the static forces of all wheels of a vehicle on a measuring track are determined on the basis of four measurements. The results for the loads on each wheel, on each wheelset and on each side are compared with the results of the simulation model. The simulation model is considered sufficiently representative when the maximum deviation and the averaged deviation is within the following limits:
  - Wheel loads: maximum deviation 15 %, averaged deviation 7 %
  - Wheelset loads: maximum deviation 6 %, averaged deviation 3 %
  - Side loads: maximum deviation 15 %, averaged deviation 7 %
- Bogie rotation test:
  In this test, the bogie yaw resistance relative to the carbody (x-factor) is determined for 2 different rotation velocities. The following limits for the x-factor apply for validation:
  - Maximum error: 15%, averaged error 7 %
- Sway test:
  In the sway test, the vertical and horizontal movements as well as the rolling movements of the vehicle are measured on a test bench. The results of the primary roll angle, the secondary roll angle, the solebar sway and the solebar drop are compared with the results of the simulation model. The following limit values are defined for validation:
  - Primary roll angle: averaged error 4 mrad, maximum error 2 mrad
  - Secondary roll angle: averaged error 4 mrad, maximum error 2 mrad
  - Solebar sway: averaged error 10 mm, maximum error 15 mm
  - Solebar drop: averaged error 10 mrad, maximum error 10 mrad

- Dynamic ride test:
  Here, the acceleration of the car body in vertical and horizontal directions, measured during on-track tests, are considered. The specifications are not defined in detail but the comparison between the measurement and the simulation model should be based on time written results and power spectral densities (PSD) of the acceleration data. The model is validated for this test if a skilled person evaluates a sufficient match of all signals.

A distinction is made between four cases, which limit the application possibilities for the simulation model:

- Full validation: the simulation model is validated for all of the four tests and could be used for gauging analysis and as basis for design variations.
- Partial validation: the simulation model could not be validated for all the tests. Then, the simulation model could be used for gauging analysis but not as basis for design variations.
- Static validation: the simulation model could only be validated for the weighbridge test and the bogie rotation test. Then the model is suitable for static gauging analysis.
- Rejection of validation in all other cases and the simulation model is not allowed to use in any context.

Traction Power Supply Systems:

EN50388 recommends the use of simulations during the design development and demonstration of compatibility. Simulation results can be used to reduce the infrastructure tests to critical cases for the demonstration of quality index of the power supply. All other technical areas require type tests to be executed.
PrEN 50641:2017 is in development to validate the simulation used to demonstrate compliance to the requirements in this standard. The standard provides the minimum required functionalities and ensures that the output data of different simulation tools are consistent when using the same input data. The Standard only applies to simulations of traction power supply systems at their nominal frequency for AC and DC systems. It does not apply to harmonic, electrical safety or EMC studies over a wide frequency spectrum.
Assessment of the simulation is in two parts:

1. Validation process shall be undertaken which compares specific characteristics of the key simulation output graphs;
2. The quantitative verification of the simulation is assessed by comparing key calculated values with those given in the standard.

The verification process is based on a defined benchmark example of a traction power supply system with common input data for the infrastructure, types of trains and timetable.
The Standard defines the following in detail:

- A set of common parameters regardless of power supply system which include:
  - Timetable
  - Station positions

- Route topology
- Train sets

- Detailed characteristics (mass, tractive effort, Davis coefficients, max speed, deceleration etc.) are provided for three types of train set
  - High speed – loco and coaches
  - Suburban EMU
  - Freight train – loco and wagons
- Infrastructure electrical characteristics are defined for various types of traction supply system – this is variable depending on supply system

Validation of the tool is through the assessment of outputs using the following steps:

- Plausibility of expected outputs – a set of output graphs are to be generated and this step involves reviewing these against the expected results to ensure that certain features are present in the output. This step involves reviewing the shape of the output rather than the actual recorded values. These graphs assess:
  - Train graphs for the timetable
  - Time functions of voltage, current, speed and tractive effort for a train
  - Time function of substation current and voltage
- Verification of expected output – the results of the simulation are documented in tables defined in the EN to record the data for each trainset and for the substation
- Validation with simulated values – The output of the simulation is compared to minimum and maximum values specified in the EN. It is expected that the results are within the bounds set by the EN. It is accepted that up to 10 results may be out of tolerance as long as the shape of the output curves are correct with the exception of the parameters travelling time, the useful voltage and consumed power where only two out of tolerance values are acceptable.

The simulation tool developer is to produce a report defining the details of the software used for the simulation tool and the output of the analysis against the EN. A third party assessor is required to certify that the simulation tool is compliant and specify the types of traction system(s) validated.

<u>Train Control Systems</u>

The general strategy for TCMS system is a declaration of conformity on basis of a tool validation according to the standard EN 50128.
It is necessary to differentiate between the usages of the simulation for testing of technical standard conformity, safety and non-safety functionality of the tested TCMS system. According to homologation regulations in the European Union, technical standard conformance (e.g. TSI) and safety functionality need to be validated. If the functionality is not required by homologation processes, an explicit validation of the test system and the related simulation is not necessary.

The general procedure of qualification or validation of the test system consists of three main functions, which meet the demands of an attestation of conformance regarding the defined requirements of the test system and the corresponding simulation.

- Selection: The selection and definition of the required tests and conformance declarations of the test system and the corresponding simulation, as well as the basis of the detailed test procedure need to be specified within a validation plan.
- Investigation: The Investigation activities will be executed to get the complete information about the conformance regarding the specified requirements.
- Assessment and confirmation: The decision if the requirements are fulfilled and the object of the assessment is ready for use can only be done after the analysis of the results of the assessment. The confirmation and conformance declaration is a statement of proved fulfilment of specified requirements. Specified pass or fail criteria for test or samples are used. Certificates could be used as well.

Each of these aspects must be documented is an appropriate way. Any deviations are also to be recorded in the documentation. The conformance declaration could lose its validity if there are changes or adaptions of the test system of the simulation.

AcouTRAIN:

The general approach for verification of the tool in the AcouTRAIN project is to define common inputs and to use reference test cases. A Tool Certification Report is required to be produced which covers the following:

- The set-up for the simulation tool
- Information about the simulation tool: ground model, source model…
- The computed results for the reference cases, to be compared to the corresponding reference corridors

The method for verification of simulation tools has been defined by simulation experts in the AcouTRAIN consortium. This method is named Deltamax and is based on two parameters:

- Delta-max: Difference in each third octave band, between the reference and simulation-tool spectra, which is limited to an acceptable maximum.
- Delta in global dB: the previously calculated delta-max is added to the pass-by or stand-still-comparison spectrum. The parameter of interest is the difference between the overall value (dB) of the comparison spectrum, and that of the comparison spectrum plus delta-max, and is a measure of the influence of differences on the total level in the whole-frequency range

7.3.4 Consideration of variability and uncertainties

One of the most frequent arguments when defending that simulations cannot replace physical tests is that modelling is always an “idealisation” of the real life and that it cannot take into account all the diversity of potential situations and model all the numerous parameters that can affect the behaviour of a system. This statement is true, but it can also be made for physical tests. Actually, because of the effect of many parameters that cannot be totally handled, it is often required that physical tests are performed for several configurations (various load conditions, various environment conditions) and for each configuration, it is sometimes mandatory to

repeat the tests several times.
So variability - in materials, geometries, loads, usages, temperature, friction coefficient, etc. - is most of the time already taken into account in mandatory field tests: many configurations are prescribed, and sometimes, many runs are prescribed as well.
For example, for the pantograph/catenary homologation, in EN50367, five speed ranges are required (with a tolerance of ±2.5km/h) and for each one of them, at least 3 out of 5 runs must be successful.
Another illustration of variability is given in Figure 12 from DynoTRAIN project [D02]: the ratio Y/Q (transversal load divided by vertical load at the wheel/rail contact) determined from load measurements made the same day on the same track with the same vehicle and the same velocity instructions is plotted. The values in blue and in green represent the mean value and the 99.85 % percentile of the filtered signal of the two runs in 6 track sections which had the same quality as defined as according to EN14363. It clearly showed the variability of the dynamical behaviour of the train-track interaction (in this example, the variation is less than 13% for 5 sections, and about 30% in the last section!).

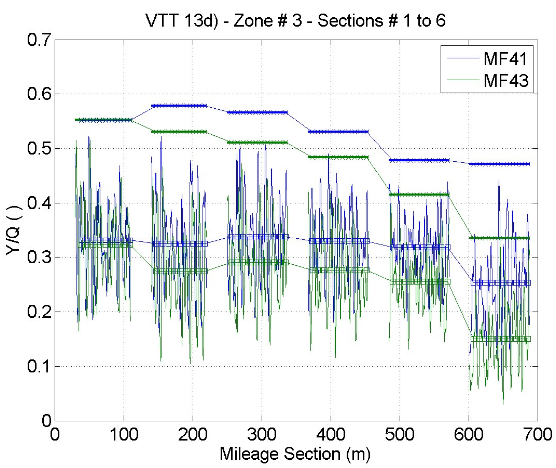

Figure 12: Time history of filtered loads (derailment ratio Y/Q): mean value and percentile 99.85 % for 6 different track sections measured the same day on the same vehicle [D02]

When replacing physical tests by simulations, it is therefore necessary to adopt methods that can handle this variability. Moreover, simulations introduce additional uncertainties, due to the idealisation inherent to modelling (the model is an imperfect representation of reality) and due to the numerical approximations. In PINTA, for example, it was also quoted that simulations are performed only with ideal electronic components, without any parasite. In the TrioTRAIN projects, the variability in the influence quantities was defined as the uncertainty (e.g. for pantograph/catenary issues, the uplift at supports, or the derailment ratio Y/Q for running dynamics) [P01] [D02]. It is this assessment uncertainty that could change between accepted regulatory methodologies and innovative virtual ones and needs to be quantified.
One must point out here that physical tests also induce uncertainties and errors related to the measurement procedures and equipment capabilities, but they are generally reputed to be

smaller or at least, better known.

The simplest way to handle this variability is to introduce safety factors. These safety factors can be added to the loads and/or the accepted limits (see Figure 16). They generally come from past experimental studies during which information on the in-service variability is caught, consolidated by operational feed-back and finally normalised in leaflets or standards, after that a consensus has been reached among the main stakeholders.
An example for this is EN12663 on structural railway body design and validation. A safety factor *S* is defined and the design is validated when: $R_d*S < R_L$, where R_d is the quantity of interest (for example, stresses) and R_L is the permissible limit value. Different values of *S* are defined in EN12663, depending on which method is used to determine R_d. *S* is higher when only simulations are used (for example for the ultimate failure verification, *S=1,5* if exclusively simulations are used and *S=1,3* if an experimental or a mixture of simulations and physical tests is used). It should be highlighted here that there are additional prescriptions on R_L: the method to establish its value is defined in another standard to take into account the scatter inherent to material properties.
In DVS1612/1608, the same approach is proposed: the stress limits are based on a survival probability of 97,5% and for higher requirements, an additional safety margin is considered, as given in the following table.

<table>
<tr><th rowspan="2">Utilisation of strength</th><th colspan="3">Need for security</th></tr>
<tr><td>great</td><td>mid</td><td>low</td></tr>
<tr><td>≥ 90%</td><td>CP A - CT 1 (100% NDT-V)
with S_s = 1,0
CP B - CT 2 (10% NDT-V)
with S_s = 1,15</td><td>CP B - CT 2 (10% NDT-V
or
100% NDT-O)</td><td rowspan="2">CP C2 - CT 3</td></tr>
<tr><td>< 90%</td><td>CP C1 - CT 2 (10% NDT-V
oder
100% NDT-O)
with S_s=1,15</td><td>CP C2 - CT 3</td></tr>
</table>

S_s: Safetyfactor
CT1, CT2, CT3: Weld inspection class according to DIN EN 15085

Figure 13: Safety margin in DVS 1608/1612

In AeroTRAIN project [E02], uncertainties were also considered with the introduction of a safety factor *X*, which will vary depending on the expected confidence in the modelling (for unsteady simulations, *X* will be equal to 3%, for steady simulations – less representative - , *X* will be equal to 3% if the train has streamlined shape, and equal to 5% if the train has bluff shapes).

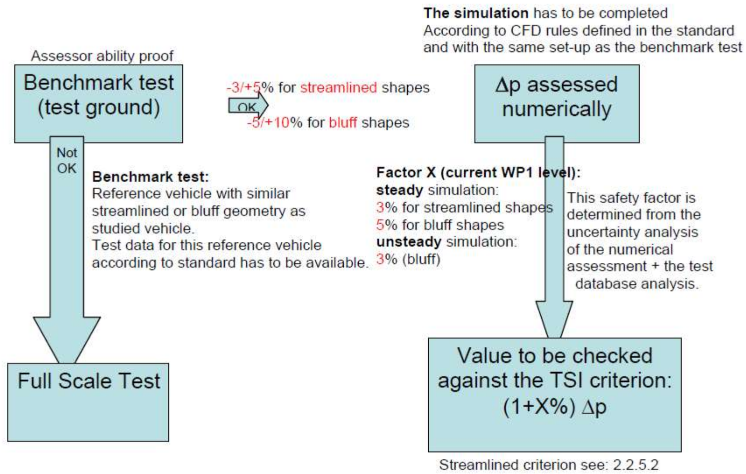

Figure 14: Full CFD assessment scheme [E02]

This approach has the great advantage to be simple to apply and, if the safety factors are correctly defined, safety is guaranteed. But the first difficulty one can encounter is that the values of these safety margins are set in standards and frozen for years while technologies or operational conditions can evolve. Secondly, the real margins induced by these factors are unknown, so it is very difficult to make them evolve. This approach does not facilitate the introduction of disruptive innovations.

In order to adopt a more flexible method and go towards a more optimal design, a "just necessary" approach, using reliability methods, has been developed in different areas, for example in the nuclear and the automotive industries. Instead of defining simple constant safety factors, the reliability approach consists in identifying the most effective parameters, characterizing their scatter, propagating their variability in the deterministic model of the system to be validated and finally, calculating the distribution of the quantity of interest. Then, the acceptance criterion is not a limit on the quantity of interest but a limit on the probability of exceeding the limit.

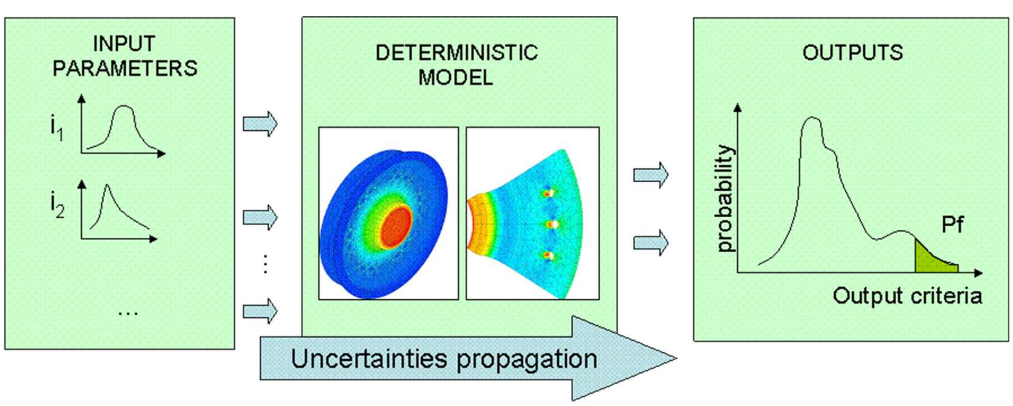

Figure 15: Scheme of a reliability approach, courtesy of SNCF/Euraxles [EX01]

The methods to solve this kind of reliability problem vary from quite simple linear approach to complex multi-input non-linear solving approaches.
The simple approach is called the Stress-Strength Analysis, which is largely used in the electronic industry or in the automotive industry [SC09][SC10], but has also been analysed for railway applications in FP7 European projects, such as in Euraxles [EX01][SC11] for the fatigue analysis of axles or in Aerotrain for the risk analysis of ballast projections [SC05]. The principle of the method is to determine the distribution of the loads – referred to as STRESS - and compare it to the distribution of acceptable limits – referred to as STRENGTH. The Stress and the Strength need to be characterised by a single scalar in which all the sources of variability must be taken into account. For example, for a mechanical component submitted to fatigue, the Stress represents the mechanical loads – which vary with the transported mass, the velocity, the track characteristics - and the environmental conditions (temperature, hygrometry). The Strength represents the fatigue limit of the component, which varies because of the scatter relative to materials, manufacturing conditions, geometry, etc. Once the distributions of the Stress and the Strength are identified, a probability of failure can be easily calculated (it is the probability that a Stress is higher than a component Strength).

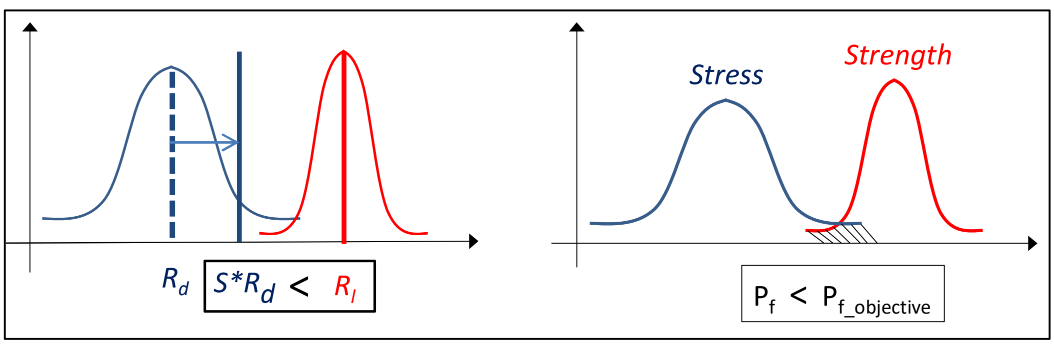

Figure 16: methods to take into account variability (left: safety factor approach / right: reliability approach)

When the system to be studied is very complex with many parameters affecting its behaviour, with non-linear relationships between these parameters, a more elaborated method is needed. First, it is necessary to identify very carefully the most impacting parameters and to characterize their ranges and statistical distributions – they can be modelled with a Gaussian, a log-normal or more complex distributions - with respect to available data. Particular attention is to be paid on the statistical dependencies between parameters. Then many simulations need to be run in order to scan the whole design space. A random draw or more sophisticated drawing strategies, depending on the nature of the distributions and values to be post-processed (mean value, rare event probability…) can be used. The final result may depend on the number of simulations that are performed and their representativeness. If simulations globally cover the same level of variability as the physical tests, the acceptance limit defined in the standards for an experimental approach can be used; if not, the acceptance limit should be adapted. The scheme below shows the two design spaces (experimental vs simulated) confronted to the “real life space”.

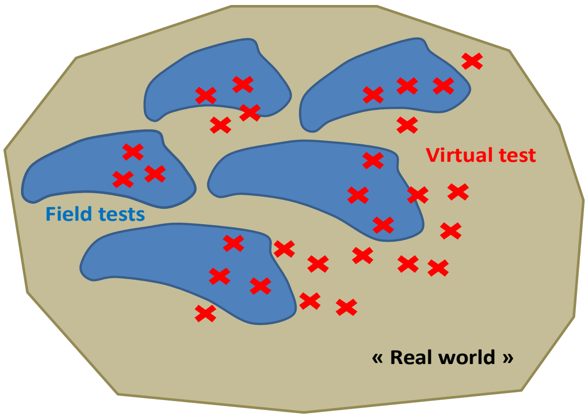

Figure 17: Design spaces when using field tests (in blue), virtual tests (in red) compared to "real world space"

In the following example, from PantoTRAIN project, the necessity of performing many simulations before concluding on a new pantograph design is highlighted. A French pantograph, already validated in France using field-tests, is to be homologated to circulate on a German line. First of all, one single simulation of the pantograph on the German infrastructure was performed. The results (6 parameters were analysed) are shown in Figure 18. The pantograph was validated based on the results from the simulation. When physical tests are performed, one single pantograph is tested but the physical catenary exhibit variability along the line and the wind conditions vary along the day. So, in order to make the simulations more realistic and representative of the field tests, the variability of, on one hand, the aerodynamic force applied to the pantograph and, on the other hand, the contact wire height needs to be taken into account. Many other simulations, with other wind conditions and other catenary geometry characteristics, were run for that purpose. The results are shown in Figure 18. The pantograph/catenary couple was still accepted, but the values of the criteria (second line of Figure 18) Figure 18: Consideration of uncertainties from PantoTRAIN [P01were slightly different.

		EN50318 requirements			Optional value	
	F_m	σ /F_m	SA_{uplift}	Contact point displ.	F_{max}	F_{min}
Without uncertainty	**146.5N**	**0.18**	**7.0cm**	**2.9cm**	**222N**	**78N**
With uncertainty	**146.4N**	**0.23**	**7.2cm**	**3.4cm**	**249N**	**45N**
Standards	**TSI curve**	**< 0.3**	**< 10cm**	**< 4cm**	**< 350N**	**> 0N**
Decision	☑	☑	☑	☑	☑	☑

Figure 18: Consideration of uncertainties from PantoTRAIN [P01]

It can be expansive to characterise all the input parameters distributions (it is sometimes just impossible to experimentally measure them all) and perform all the simulations induced by the tremendous number of possible parameters sets (it could require thousands of simulations). One possibility to consider the variability of the input parameters with as few attempts as possible is provided by Design of Experiments (DoE) but will not be discussed here.
One solution consists in performing a sensitivity analysis to identify the most effective parameters and then focus on them. The other parameters can then be assumed to be constant. This step is moreover encouraged that it can be useful even in the design phase for optimisation of the product, as well as in the virtual model development for robustness. Many methods such as Sobol indices [D02] are proposed to lead this sensitivity analysis.

In DynoTRAIN project, a sensitivity analysis was performed. The effects of different input parameters on different outputs were quantified and evaluated as Low, Medium or High. They are given in Figure 19.

		Relates to				track loading				running safety				running behaviour		
Code	Parameters	Vehicle	Track	Interface	Running conditions	Qqst	Qmax	Yqst	Ymax	ΣYmax	Y/Q	ΣYrms	ÿ+max	ÿ*rms	ÿ*max	z''*max
V1	Carbody mass and inertias	x				H	H	M	M	M	H	M	M	L	L	H
V2	Bogie spacing and wheelbase	x				M	L	M	M	M	M	M	L	M	M	L
V3	Secondary suspension yaw, lateral (K, C)	x				L	L	M	M	M	M	H	H	H	H	L
V4	Secondary suspension vertical (K, C)	x				M	H	L	L	L	M	L	L	L	L	H
V5	Primary suspension yaw, lateral (K, C)	x				L	L	H	H	H	H	H	H	L	M	M
V6	Primary suspension vertical (K, C)	x				M	H	L	L	L	M	L	L	L	L	L
V7	Primary sprung mass and inertias	x				M	H	L	L	L	L	L	M	L	L	L
V8	Unsprung mass	x				M	H	L	M	M	M	M	M	L	L	L
In1	Wheel and rail profiles (conicity)			x		L	M	H	H	H	H	H	H	L	M	M
In2	Wheel and rail coefficient of friction			x		L	M	H	H	H	H	H	H	M	M	M
R1	Cant deficiency distribution and max				x	H	H	H	H	H	H	H	M	H	H	H
T1	Curve radius distribution		x			H	M	H	M	H	H	H	M	M	M	L
T2	Track stiffness		x			L	M	L	M	M	M	M	M	L	L	L
T3	Track Quality (vertical)		x			L	H	L	L	L	H	L	L	L	L	H
T4	Track Quality (lateral)		x			L	L	L	H	H	H	M	H	L	H	L

Figure 19: Sensitivity analysis in DynoTRAIN [D02]

Another solution to handle the input variability is to use other simulations. It's the idea of Virtual Test tracks: a big effort is made in the automotive industry to develop such kind of tools. In DynoTRAIN, a similar tool, EU VTT [D03], was proposed, allowing the generation of synthetic test tracks made out of real measurements, which have the same characteristics as the original input track data but are simplified and shortened in order to reduce the computational time. In EN12663, the use of train-track simulations to determine the loads imposed to the vehicle carbody is also mentioned. But there is no practical example that has been ever published.

To conclude, the aim of this sub-section is to emphasise the necessity of taking into account the variability in the design and validation process. Of course, for safety critical cases, it is important to deal very properly with variability (define large safety factors or develop quite extensive sensitivity analyses). For less critical cases, the approach and the derived acceptance criteria (for example to validate a virtual model) could be less demanding. Many recent and on-going research projects (ex. NURESAFE, IMVITER, …) in this area show that most of the industrial sectors agree on this statement and are working on establishing applicable reliability approaches. The NAFEMS (International Association for the Engineering Modelling, Analysis and Simulation Community) highlights the importance of conducting sensitivity and tolerance analyses for simulations and extend these methods to experimental testing since probes and measurement acquisition systems have their own tolerances and induce uncertainties as well. One proposal is to add the probes behaviour in the simulation tool to ease the comparison simulations/tests.

7.4. Methods to evaluate credibility of simulations

In the PINTA project three methods are discussed to evaluate the credibility and representativeness of simulations, technologies and processes. These methods go beyond verification and validation of models and consider further influencing parameters, like the quality of input data or the qualification of the people working in the process. The three methods are:

- TRL (for technologies): Technology Readiness Level
- PCMM: Predictive Capability Maturity Model
- CAS: Credibility Assessment Scale

The Technology Readiness Level (TRL) is used to assess the state of development when introducing new technologies. The assessment is based on a systematic analysis and was initially introduced by NASA for risk management in the late 1980s. PINTA comes to the conclusion that it is not as easy to apply for software development or for evaluating simulation processes.

The Predictive Capability Maturity Model (PCMM) is a new method to evaluate the level of maturity of modelling and simulation approaches. Six categories are used for the assessment:

1. Representation and Geometric Fidelity
2. Physics and Material Model Fidelity
3. Code Verification
4. Solution Verification
5. Model Validation
6. Uncertainty Quantification and Sensitivity Analysis

The system to be assessed is evaluated with a level from 0 to 3 in each category against the background of accuracy of data, level of comparison, level of impact of simulation results on the study and decisions. In the end, a final score is calculated and stated in the following way:
PCMM = [min, mean, max]
A disadvantage of the method is that the quality of the inputs and the competence management is not considered in this approach.

The Credibility Assessment Scale (CAS) was developed and defined by NASA [NA03], [NA04] and then further refined and applied in various projects [NA05] [NA02]. It describes the credibility justification of simulation results. It contains 8 criteria to quantify factors influencing simulation credibility. The criteria and the questions to be evaluated are:

- Verification: Were the models implemented correctly, and what was the numerical error/uncertainty?
- Validation: How well did the modelling and simulation results and the reference data compare?
- Input Pedigree: How confident are we of the current input data?
- Results Uncertainty: What is the uncertainty in the current M&S results?
- Results Robustness: What are the sensitivities of the parameters?
- Use History: Have the current M&S been used successfully before?
- M&S Management: How well managed were the M&S processes?
- People Qualifications: How qualified were the personnel?

The result of the CAS analysis is a diagram that clearly shows strengths and weaknesses of the simulation and modelling approach.

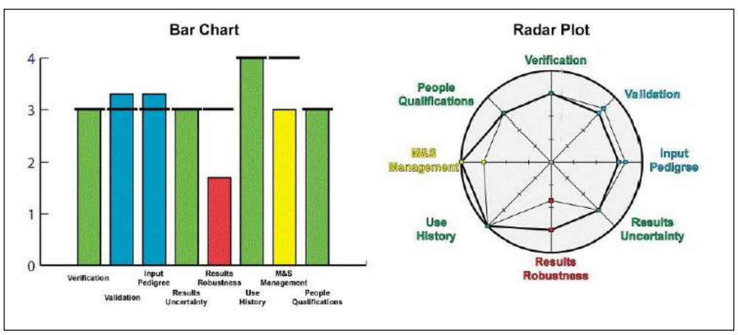

Figure 20: Result of a CAS analysis from PINTA project [PN01]

8. Approval process with virtual testing

The EC (European Commission) type approval is the acknowledgement of the regulatory conformance of a vehicle type to legislative and safety requirements.
It is granted without time limits and can be revoked under special circumstances or can terminate because of modifications of the vehicle.

In order to obtain approval for a vehicle type, its conformance to the European Technical Specifications for Interoperability and National Notified Technical Rules (remaining national requirements) are assessed by a NoBo and a DeBo. The results of these assessments are documented in a Technical File. This Technical File together with the Declaration of Verification is forwarded to the ERA or the responsible National Safety Authority. The ERA / NSA then issues the type-approval. For each individual vehicle, an Authorisation for Placing on the Market (APoM) is issued to the entity holding the type approval after it declares Conformity to Type (C2T).

The process of national and international homologation raises requirements on construction and development, the technology used in solutions and operation. These requirements could originate in legacy restrictions, regulations of national authorities, standards or homologation processes themselves. The compliance to these requirements needs to be demonstrated through the production of appropriate evidence of conformance.
Modelling and simulation have been recognised as a method for teaching in terms of learning exercises as well as risk mitigation for functional aspects. The use of evidence-based tools for validation of real-world scenarios in the homologation process is relatively new to the rail industry with a lack of standardisation. The reason originates in the natural purpose of the homologation. It requires evidence that the as built product satisfies the design requirements. To generate part, or all, of the conformance evidence using simulations of the system or environment appears in conflict with this objective. A natural uncertainty is therefore applied to the simulation approach however the use of modelling and simulation in the homologation process. The formal demonstration of the robustness and representativeness of the model/simulation results to the relevant stakeholders is therefore essential for this change in approach to enable virtual certification methods to be used in the homologation process. Agreement of the criteria for authorisation and the allowable variation/uncertainty is required to be agreed with the relevant bodies as an enabler to this approach. The use of standards to formalise these ensures consistency across the industry and aids the acceptance of the approach for homologation. Development of a framework which can be applied to any proposed implementation of virtual testing will support in enabling the process to be used more extensively when appropriate.

This section describes the following three scenarios for the implementation of virtual testing in the homologation process and provides examples of current applications:

- Full virtual testing – either the use of numerical simulations, SiL or HiL to demonstrate conformance to the requirements for approval. In this scenario, field tests are not used for conformance evidence but may be used for validation of the virtual testing model;

- Partial virtual testing - a blend of virtual testing and field tests are used to demonstrate conformance to the requirements for approval;
- Extension of Approval – using models for already homologated systems/products to validate changes in terms of design change of system/product or change in operational environment.

8.1. Full virtual testing

Full virtual testing is characterised by the final results of the test not being attained through a full-size field test. Instead, they are achieved through either a complete simulation or a HiL/SiL test.

A fully virtual test does not imply the unnecessity of validation and/or calibration tests. Instead, the focus for this categorisation is on the means by which the final results – that are usually compared to reference values given in the respective standards or the regulatory framework – are attained, in order to validate the product. Field tests or full-size component tests can be conducted when testing fully virtually, as long as they are only used for model calibration and validation purposes and the final results only consist of Output data of a simulation or HiL/SiL test. In the following, examples from the respective projects and standards considered in this document are given:

Crashworthiness (EN 15227)

The methodology proposed in EN 15227 (see section 6.1.1) can be considered full virtual testing. The results of validation and calibration tests of the full vehicle or the interacting sub-systems (extent depending on applicability of reduced validation programme) are fed into the simulation model. Finally, compliance with the measures that provide protection of occupants in case of a collision is determined only through simulation of the applicable crash scenarios.

AcouTRAIN

In the AcouTRAIN project, it is proposed to assess requirements only based on simulation predictions. The Notified Body would grant or reject the type approval after evaluating the outcomes of a virtual vehicle developed with a certified simulation tool. It is not intended that there are no testing activities. On the contrary, during the validation phase prior to the assessment of technical requirements, specific validation tests shall be defined and implemented. These tests will mainly concern the reliability of equivalent noise sources definition.

Aerodynamics (EN 14067-6)

Various methods are available to determine the wheel unloading on passenger or freight vehicles due to cross wind. Time-dependent multi-body simulation and an advanced quasi-static approach often serve as the full proof that the vehicle fulfils a given aspect of the specifications.

IMVITER

The IMVITER project proposes a process for full virtual testing that consists of three phases. It is visualised in Figure 21.

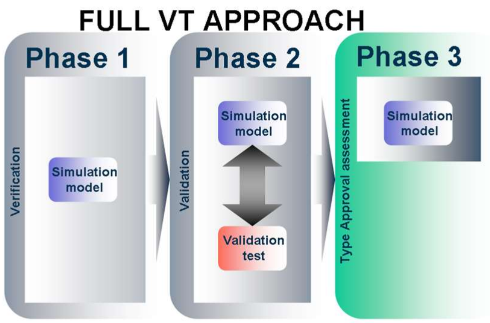

Figure 21: Full virtual testing process in the IMVITER project [I01]

After its verification in phase 1, the simulation model is validated against test results in phase 2. This is the only phase where field tests are considered. Finally, in phase 3, only simulation results are used for the assessment of type approval technical requirements. In the project, the pilot case 3 (Towing devices strength case) was identified to be suitable for this approach.

8.2. Partial virtual testing (Combination of field test/virtual testing)

Partial virtual testing is the use of a blend of virtual testing and field testing to demonstrate conformance to the product requirements. This approach relies on the correlation of results from field tests and virtual testing before the virtual environment is used to obtain results for more extensive scenarios or specific scenarios. Partial virtual testing can be used, for example, to avoid field testing in fault modes, to complement field testing when some configurations were not encountered, or when the virtual models are only partially validated.
The following are examples of this approach.

AcouTRAIN

The hybrid approach is a combination of measurements and computations. It is to be used if there is no reference vehicle for which a validated virtual model has been developed. For this approach, the simulation model (the virtual vehicle) has to comply with the requirements of a limited validation and then it can be used for simulations of the pass-by scenario.

Running characteristics (EN 14363)

The four cases when virtual simulations are accepted according to the standards are the following:

- Slightly modified vehicle/system
- Extension of the operational conditions
- approval of new vehicles by comparison with an already approved reference vehicle
- investigation of additional cases and fault modes

The second and fourth cases clearly follow a partial virtual approach.

IMVITER

In phase 3 of the hybrid approach proposed in IMVITER, mainly simulation results are used for the assessment of type approval technical requirements, although they are complemented by test results. In phase 3, simulation and test results are not compared because the simulation model was previously validated against test results in phase 2. Pilot case 1 (Pedestrian head impact protection case) and 4 (Pedestrian lower leg impact case) are identified as candidates for this approach.This approach is suitable for regulatory acts in which repetitive testing is involved.

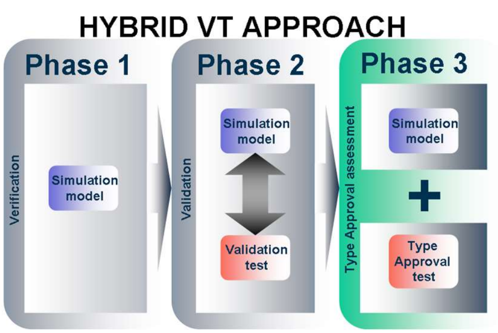

Figure 22: Three phases of the hybrid VT approach in IMVITER [I01]

8.3. Extension of Approval

Extension of Approval uses models of already homologated systems/products to validate changes in terms of design change of system/product or change in operational environment. Extension of approval can consist in 3 cases:

- Slightly modified vehicle/system
- Extension of the operational conditions
- Approval of new vehicles (sufficiently similar types within the fleet) by comparison with an already approved reference vehicle of the fleet

Extension of approval can follow a full or partial approach.

The pre-requisite for this approach is that there is a reference vehicle that can be used on which to define the virtual testing model/simulation environment or that a validated virtual testing model/simulation environment already exists. The level of change to be assessed as to be bound appropriately to ensure that the integrity of the model/simulation does not have the potential to be compromised during the changes. This approach is the most readily accepted means of virtual certification due to the sound base on which the further virtual testing is built on.

Examples of the extension of approval approach are:

PantoTRAIN

The PantoTRAIN project considers the approach to validate extension of approval for pantograph systems. The approach is based on the use of validated models previously used for a pantograph and catenary system. The example below, Figure 23, shows how validated models for a German pantograph and French catenary systems can be used to demonstrate the interaction between the two and demonstrate conformance to relevant requirements.

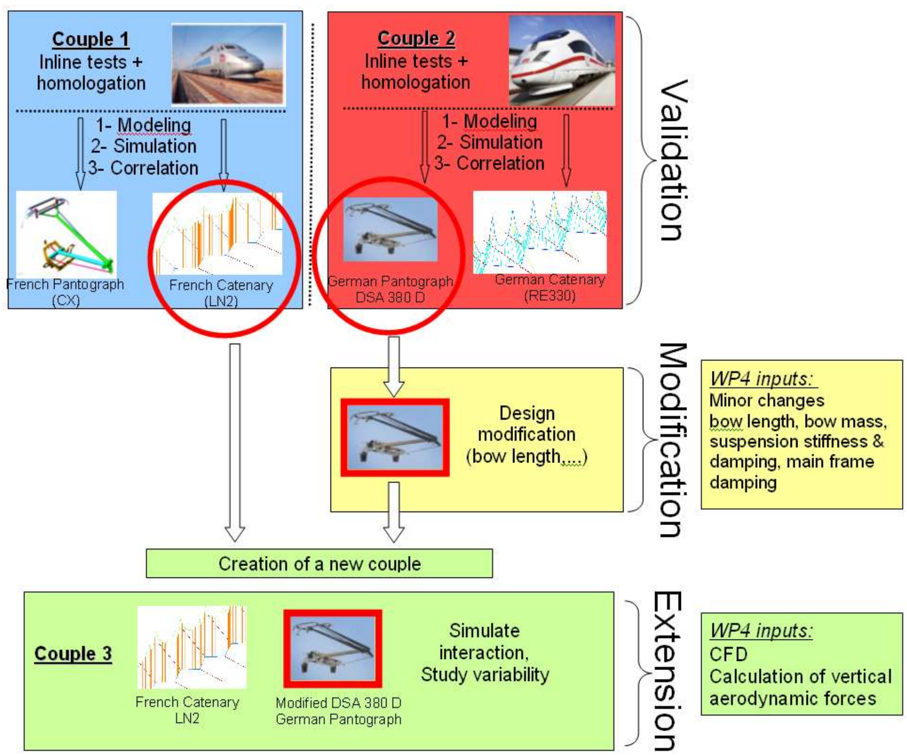

Figure 23: Proposed process for the extension authorisation process for pantograph/Catenary, courtesy of SNCF/PantoTRAIN [P01]

IMVITER

A previously validated simulation model is the base for the introduction of small modifications. As a consequence the new simulation model is validated, starting from the assessment of the influence of introduced modifications. A reduced number of validation tests would be used in phase 2, taking advantage of the validation work already done. The second pilot case is used as showcase in which the assessment of seat belt anchorages strength is performed. An already certified model is necessary as an input as reference model. A derivative model is compared to the original one in order to assess whether its predictability can be considered acceptable after introducing modifications from the reference model. If this phase is met, the simulation model would be used in the assessment of technical requirements in a similar fashion as in the Full VT approach. This approach is suitable in several regulatory acts, especially in those cases in which a product is developed as a derivative of an existing product.

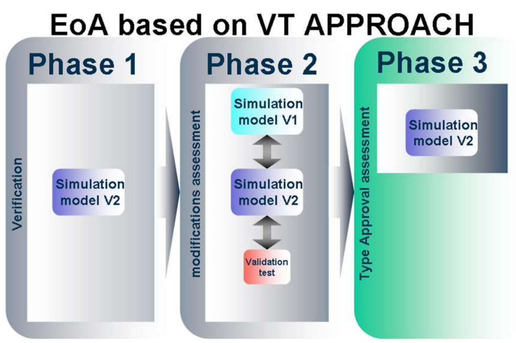

Figure 24: Three phases of the Extension of Approval based on VT approach in IMVITER [I01]

Running gear and bogies (EN 15827 and EN14363)

In the standard on running gear and bogies, numerical analysis is permitted as the only final means of demonstrating compliance to requirements if the following conditions are fulfilled:

- Analysis software has pedigree – all software used for theoretical analysis, simulation or analysis of test data should have established pedigree in its field of application or be supported by specific corroboration of its suitability and accuracy
- Models are validated – the vehicle model and track input models are validated against real test data and conform to the stated requirements
    - Allowable variation between the test and simulation defined for critical criteria
- Criteria for change defined in the standard are satisfied
    - Base Design has been defined and accepted
    - Simulation cannot be applied if the suspension concept or interface to the body has changed
- Independent assessment process has been implemented and fully documented – mandatory

AcouTRAIN

AcouTRAIN was concerned with the question of how to define a slightly modified vehicle which can be used as a reference vehicle for extension of approval. For this purpose, a similarity test has been developed to ease the decision whether two vehicles are similar enough. This test was a proposal for the assessment of standstill noise-sources and could be adapted for similar approaches for pass-by.
The first step is to list all the modified noise sources of the new vehicle compared to the reference vehicle, to rank them and to attribute weighting factors. Second step is the assessment of the modification's uncertainty. Further factors as removal of sources, shieldings and modifications without noise emission are considered, but do not contribute to the increase of points in the decision model. At the end, the points in the decision model are accumulated and the total score decides whether similarity exists or not. The proposal for a preliminary limit for similarity was a total <= 15 points.

STATIONARY NOISE	*	POINTS**
Ranking of the source(s) modified (the ranking takes into account the number of occurrences of this source on the train)	rank	
	1 – 3	8
	4 - 6	5
	> 6	1
Assessment of modification's uncertainty***	uncertainty	
	> 2.5 dB	7
	2.5 dB > > 2 dB	3
	2 dB > > 1.5dB	2
	1.5 dB > > 1 dB	1
Removal of source		0
Addition of shielding		0
Modification without effect on noise emission		0

Figure 25: Decision model for similarity test in AcouTRAIN [A03]

Practical case of extension of approval

The double deck TGV high speed train built by Alstom and operated by SNCF has been certified TSI Noise in 2011 following the acoustic standard EN ISO 3095. In order to improve the drag resistance in the area of the cavity of the pantograph, additional fairings were designed and included in a new version of the train. This design evolution clearly brought modifications in the acoustic sources in this specific area. It was therefore necessary to prove that the new train was still compliant with the requirements.

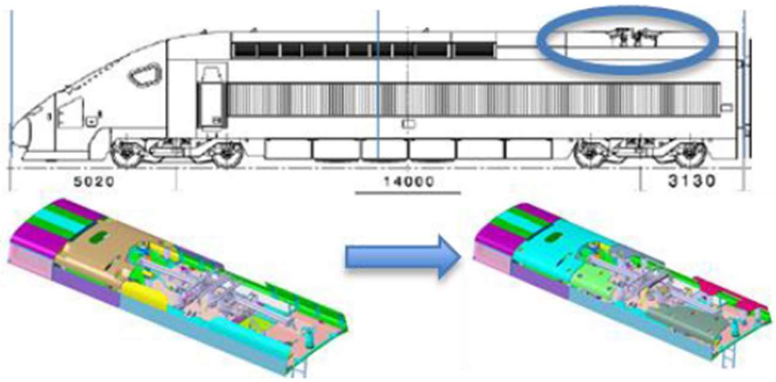

Figure 26: SNCF TGV High speed train modifications in the pantograph area, [SC08]

For that purpose, a virtual certification process has been applied by SNCF to verify the §7.1.5.2 of TSI noise criteria.
The first step was to build the model of the reference train which has already been certified by acoustic testing. The comparison with field tests results, using tolerance factors defined in Acoutrain, enabled to validate the model. In Figure 27, the noise global indicator LpAeq,Tp values obtained with the simulations of the reference train are compared to the field tests results for three operating train speeds: 80 km/h, 190 km/h and 320 km/h. In the second step, a new model was built for the modified vehicle and simulations were carried out to evaluate the maximum impact of the modifications on the noise sources level and finally, to verify that the slightly modified train was compliant with the acoustic requirements. Detailed information can be found in the paper published by SNCF in EuroNoise 2018 [SC08].

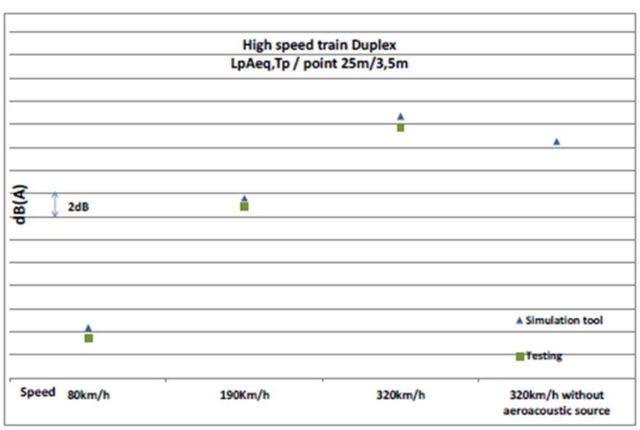

Figure 27: Comparison between field tests and simulation performed for a TGV high speed train, from [SC08]

9. Barriers

There are several barriers to the introduction of simulations in the European railway sector. This chapter provides an overview of the potential barriers and those that have been previously identified in the various projects and fields when trying to introduce simulation.

9.1. Technical

Simulation maturity/representativeness

In order to be used for certification and homologation purposes, tools and models must have a certain degree of maturity and representativeness. In certain cases, this necessary level cannot yet be attained.

For instance, in pantograph/catenary simulation, the maturity of CFD modelling is not yet sufficient. Therefore, tethered tests to measure the aerodynamic uplift force versus train speed are still mandatory and recommended in the near future.

Another example is given in the AcouTRAIN project: The correlation between measurement and simulation results is currently not good enough for virtual certification purposes, particularly for stand-still VT. Hence, the proposed procedures cannot be fully demonstrated yet.

Wide Area Networks limitations

Some types of simulations still cannot be conducted because of a lack of computational power or network speeds and latencies. For example, the simulation framework designed in CONNECTA includes remote testing, where physically separated HiL are connected by Internet network. This framework finally could only be applied for functional testing but not for performance testing because the synchronisation requirements from EN 61375 could not be ensured over non-deterministic Wide Area Networks (WAN) such as Internet.

Availability and quality of input data

In many cases, no adequate input data is available, or its quality cannot be sufficiently assured. For manufacturers and railway operators, it can be difficult to obtain reliable network data (e.g. height profile, rail profiles and geometrical defects of the tracks) for certain networks. Sometimes other data can be missing such as mechanical characteristics of train components. Without such data, representative simulations cannot be demonstrably developed.

An example is the wind forces the pantograph is subjected to: measurements can be carried out, but the results vary daily. The outcome is a spectrum. It is then necessary to derive representative forces from these measured spectra. Technically, the whole process is still a challenge.

Comparability of field tests and simulations

Because of their different nature, field tests and simulations often cannot be compared using the same principles. This means that in many cases, the requirements for field testing cannot simply be extended to simulations.

For example, uncertainties and variability in boundary conditions must be treated differently in both approaches. As explained in section 7.3.4, variability and uncertainties must be taken into account in the model validation and at the end of the approval process. It raises two questions: how to compare physical tests to simulations, when variability and uncertainties may be different (for example probes uncertainties vs simulations approximations)? How to define relevant requirements for simulations so that variability is taken into account with the same manner than in field tests; and if this is not possible, how to adapt the limit criteria? Different approaches can be proposed, from safety factors to multi-input reliability method. The initial effort to settle these approaches for each technical field can be significant: sensitivity analyses, characterisation of the variability of the most effective inputs, definition of a drawing strategy to launch the minimum number of representative simulations to capture variability, development of tools to automate the process and the analysis of the results.

9.2. Non-technical

Simulation cost

When first introducing a new type of simulation, significant initial development costs can occur for setting up the processes, tools and models. Even when a simulation is already well established, there are cost drivers such as maintenance and adaptation of the simulation, licenses, computational power and documentation that must be considered.

Know-how protection

Simulation models can contain confidential know-how that shall not be disclosed. Without this data, it may be difficult for third parties to assess a simulation and its quality, or for a user to perform the simulations.

Compatibility of simulation tools

When different stakeholders involved in the development and validation of different parts of the product want to share models, it is sometimes difficult to re-use them because the different software tools, require different formats of input data.

Lack of harmonisation and standardisation

Currently, there is no harmonised approach for simulation in the European railway sector. Where use of simulation is allowed, requirements are provided in the respective standards. When trying to introduce simulation where not explicitly permitted, manufacturers face problems in proving that their simulations are acceptable because no generic rules on simulations exist. The goal of PLASA2/VC is to help close this gap and improve harmonisation by proposing a generic framework for simulations in the sector.

The analysis of validation and verification methods for models and tools has shown, that the reviewed standards are not harmonised in the definition of terms. The terms validation and verification are interpreted differently, sometimes merge, and there is no clear separation of model and tool. The definitions need to be precise when introducing a generic approach.

An example standardisation problem that was dealt with in the AcouTRAIN project was the objective definition of a slightly modified system for which a validated simulation model is allowed to be used as a reference model.

In the DynoTRAIN project, it was observed that in cases without specific methods for simulations, assessors might encounter difficulties in making objective judgements. In such cases, significant variations in visual comparisons of measurements and simulations (for the purpose of validation) by different assessors were observed, that could only be restricted by introducing quantitative methods.

Trust in simulation

Because of the novelty of the approach in the sector, the experience with simulations is limited especially for certification purposes, which evokes justified concerns that must be addressed accordingly. Additionally, some stakeholders may have subjective reservations to accept simulation in principle

10. Benefits

Virtual Certification is an important key in achieving the Shift2Rail overall high level objectives:

- 50 % reduction of the life-cycle cost of the railway transport system, through a reduction of the costs of developing, maintaining, operating and renewing infrastructure and rolling stock, as well as through increased energy efficiency;
- 100 % increase in the capacity of the railway transport system, to meet increased demand for passenger and freight railway services;
- 50 % increase in the reliability and punctuality of rail services (measured as a 50 % decrease in delay minutes);
- Removal of remaining technical obstacles holding back the rail sector in terms of interoperability, product implementation and efficiency, in particular by endeavouring to close points which remain open in Technical Specifications for Interoperability (TSIs) due to lack of technological solutions and by ensuring that all relevant systems and solutions developed by the S2R JU are fully interoperable and fitted, where appropriate, for upgrading;
- Reduction of negative externalities linked to railway transport, in particular noise, vibrations, emissions and other environmental impacts.

The potential benefits to the rail industry from the applications of virtual certification are documented in the following sections. The benefits as evaluated in all individual S2R and previous FP7 projects are collated to enable a holistic picture to be presented. The data generated from this activity can then be used in support of any subsequent business case to develop processes, tools, etc., required to remove any barriers to the approach.

10.1. Life-cycle costs

One of the parameters considered in the life-cycle cost is the Fleet Capital Cost and the Command, Control and Signalling (CCS) Capital Cost. Both include not only the cost of engineering and manufacturing but also the cost of the validation, customer acceptance and certification of all the trains for each System Platform Demonstrator (SPD).

In the field of Virtual Certification, a reduction of the duration and cost of the process for an appropriate authorisation to put a new train into service is needed. Today, the authorisation process for putting new rolling stock into service is largely based on full-scale field and line tests, which is expensive, time and capacity consuming. A breakthrough in performance can only be made if numerical simulations are progressively introduced in a mixed virtual/experimental authorisation process, resulting in less field tests.

Virtual Validation and Certification will play an important role in the near future in order to ease vehicle certification and reduce the associated cost and time expenses by means of simulation without penalising the real vehicles performances and safety. Thus, current simulation tools and models require further research and validation in order to ensure that the procedures and methodologies applied, and the results obtained represent the performance that the real train will

have.
The benefits are even higher in case of an approval of new vehicles following minor modifications by extension of approval through comparison with an already approved reference vehicle and with a reduced test program to cover the modified aspects.

Integration of simulation models into the complete railway vehicle development process is beneficial, even if it is not accepted for the certification purposes, for three additional reasons:

- Reduce also the number of invalid certification tests (first time right) and therefore reduce cost
- Achieve trust by Authorisation Entities into the simulation models. This trust is the basis for the acceptance of the virtual simulation as an alternative to the full-scale field and line tests.
- Faults and design errors are detected early in the development process when using simulations.

10.2. Railway capacity

Today, the authorisation process for putting new rolling stock into service is largely based on full-scale field and line tests, which is expensive, time and also track capacity consuming as it involves track access.

Currently, the track capacity [trains in service/day] takes into account that there is some time, typically in the night and not close to the peak hours, where maintenance takes place, it does not generally consider that time the track is occupied for rolling stock field tests. Introducing this new factor in the calculation of the track capacity will involve an increase in the track capacity when using virtual testing comparing with line testing.

10.3. Reliability and punctuality

The S2R aim regarding reliability and punctuality is interpreted as 50% reduction of the sum of delay minutes.

Virtual Validation and Certification will play an important role in order to enhance the quality of the products and increase reliability therefore reducing the number of delay minutes due to 4 major reasons:

- Possibility of achieving virtual tests on a wider range of running conditions, especially around critical situations that are difficult to meet experimentally.
- Increased number of foreseeable conditions encountered by the vehicle during its lifetime that are assessed during the certification process, and therefore increase the confidence level on the results.
- Fault modes are reduced due to the possibility to test more operational scenarios during the design and development process. Root causes of in-service faults can be identified

sooner due to the use of virtual testing methods and therefore rectified in a shorter time period. This has a positive impact on the reliability of the railway.

10.4. Other Benefits

Virtual Simulation can also provide following benefits:

- Extension of the range of test conditions where the full on-track test program has not been completed or is not feasible in the test location. Simulators also increase the possibility to perform tests in degraded conditions offering the possibility to avoid carrying out potentially dangerous field-tests.
- The “heavy” current full on-track certification processes without virtual testing could hamper the development of innovative solutions and the consequence could be that no improvements are implemented, so the real vehicles performances are penalised (per example noise reductions).
- The use of Virtual Testing enables a distinction of different physical phenomena, for example in acoustics it is possible to separate different noise sources on pass-by noise tests. The improvement of separation techniques shall finally lead to more flexibility, better comparability and hence a better vehicle characterisation in current homologation procedures.
- The maintenance of the infrastructure and of the vehicles could be optimised thanks to numerical predictive tools.
- Virtual Certification can help improving interoperability across EU Nations, since virtual homologation techniques can be applied to extend vehicle/sub-systems homologation across different National railway networks. As an example, the pantograph-catenary (OCL Overhead Contact Line) system represents one of the major barriers to rolling stock interoperability: traditionally each country in Europe has developed its own overhead line equipment leading to different catenary and pantograph designs. Hence, cross-acceptance requests many tests, to be repeated for each new type of line that is circulated. It is therefore very important to have an efficient and unified approval method, able to consider the diversity of existing designs in Europe, for a competitive railway system.
- Virtual Testing is an assessment tool to comply with increasing safety requirements, see Figure 28. Since the appearance of the European type approval system on the automotive market in 1970, the European authorities are working on the improvement of safety levels across the market. Virtual Testing provides the opportunity to efficiently meet the increasing number of safety requirements.

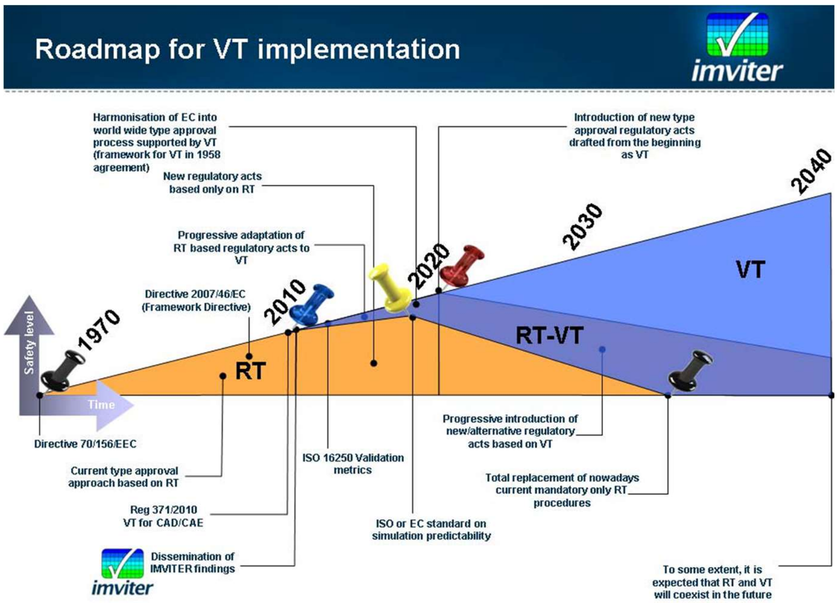

Figure 28: Roadmap for VT implementation in the project IMVITER [I01]

10.5. Benefits of the Virtual Certification declared in the projects

The benefits of Virtual Certification have been analysed in many S2R projects and also in previous FP7 projects. In most cases, the evaluation is only conceptual, but some projects have also quantified it.

PINTA

As described in section 6.1.3 the expected benefits of PINTA WP5 are:

- To significantly reduce the physical validation tests done at vehicle level for the Traction system.
- To detect early in the design/validation process failures and/or non-compliances
- To optimise the design in order to reach a “right first time” validation

Important savings in terms of costs and time-to-market are targeted:

- Short term savings: 10% cost reduction
- Long-term target (2025): 30% cost reduction
- Adhesion/wheel slide protection (WP8 and 9): Expected saving of 50%

Based on the state of the art analysis described in PINTA [PN02][PN05], a list of 74 tests has been proposed related to rolling stock standards such as EN50215 (Testing of rolling stock on completion of construction and before entry into service), EN15595 (Braking - Wheel slide protection), IEC61373 (Rolling stock equipment – Shock and vibration testing).

As illustrated in the following figure, virtual testing could replace 27% of these tests. In addition, by transferring tests done at vehicle level into power lab facilities, the figure shows that 42% of tests can be significantly reduced thank to simulation and dedicated test benches.
Currently, the remaining 58% of tests can't be replaced by virtual proof mainly for safety issues or application of standards requiring a physical test. However, it is interesting to highlight that simulation can be used to optimise the system even if a test has to be done to complete the validation process.

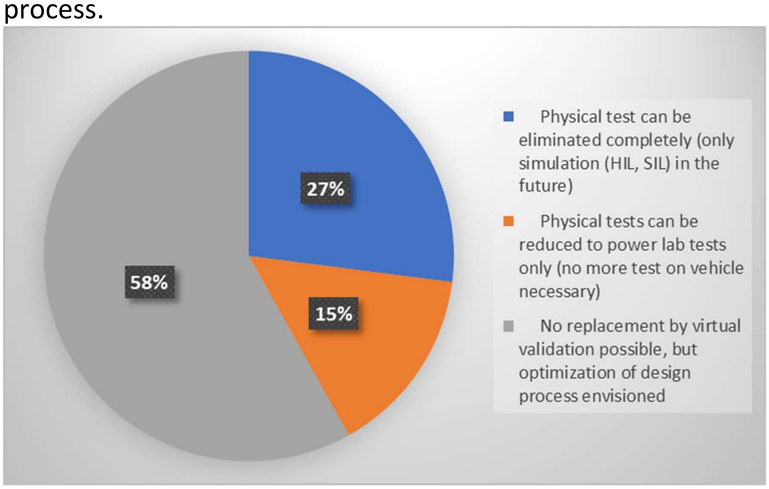

Figure 29: Status on simulation application for the Traction tests list identified in PINTA [PN02]

CONNECTA

The TCMS is an essential subsystem of a rolling stock but currently it is not subject to any certification as the functionality that is currently performing the TCMS is not safety relevant and there is not any applicable regulation for this functionality.
Even if virtual certification is not required, CONNECTA has positively valuated the virtual simulation to validate the design. Increasing the amount of virtual testing vs field testing of the TCMS will facilitate the authorisation of rolling stock and reduce its cost and duration. Moreover, simulation has been recognised as a method for risk mitigation for functional aspects. [C01]

PIVOT

PIVOT has considered the benefits of the virtual testing and virtual certification for the brake system. Virtual Testing and Certification will facilitate the authorisation of rolling stock and reduce its cost and duration.
The objective of TD1.4 is that more efficient authorisation will give a reduction of up to 50% in cost, time and effort. A part of this will be achieved by improving the validation process and by replacing on-track tests with simulations. For example, a simulation process will be proposed replacing over-speed testing, which is becoming increasingly difficult to execute. Another objective is to influence the standard EN14363 to extend the application of simulation.
This work will be done in WP4.5 of PIVOT and WP7.3 and 8.3 of PIVOT2. The work will be completed by the end of 2021.

Assessments have been produced to provide the split of brake testing on the network but no detailed analysis of the time or the cost that could be saved. A detailed analysis of the benefits of virtual validation is in progress within the PIVOT project. The results of this analysis are planned to be published in December 2019 and therefore are unable to be summarised in this report.

Within the project Roll2Rail, a Universal Cost Model (UCM) has been developed and will be further developed in PIVOT2. The main objective of the UCM is to quantify the economic benefits of innovations of the running gear on infrastructure and vehicles. Costs that are included in the UCM are: LCC for infrastructure and vehicles, energy costs and noise costs. Virtual simulation has to be used to generate input for the UCM.

X2Rail

The zero on-site project has done a survey to suppliers, infrastructure managers and research institutes within the railway sector in order to get an overview about the reasons to make the tests in a laboratory instead of on-site tests. In this context, we consider laboratory tests as virtual tests. The result of the survey can be shown in Figure 30.

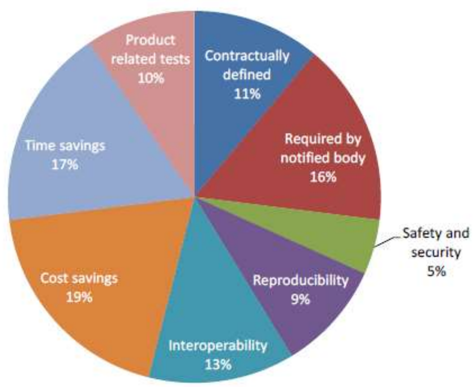

Figure 30: Distribution of the reasons for performing laboratory tests [X01]

All these reasons have been classified into three main groups.

- Time and Cost savings: 36 % of the answers.
- Contractual definition or required by the authorities: 27 % of the answers.
- Functional reasons such as interoperability, reproducibility, safety, security and product related tests: 37% of the answers.

From all these reasons only 27% corresponds with contractual or legal obligations. The remaining 73% corresponds with benefits that are more detailed next:

- Time and Cost:
    - Tests can be performed in early stages of the product lifecycle. Thus, failures are identified very early and this involves saving costs and time.

- Tests can be corrected and modified easily. Thus, various scenarios can be performed within a short time. This is involving also shorter testing time and consequently lower cost.
- The higher availability of laboratories compared with on-site testing areas involves also a reduction in the overall testing time.

- Functional reasons:
    - Safety: Laboratory testing it is safer not only for human, but also for material and environment
    - Reproducibility: The repeatability of the test is guaranteed.
    - Security: As the laboratory is a controlled environment it is possible to test worst-case scenarios and stress-test scenarios.

<u>AcouTRAIN</u>

AcouTRAIN proposes to use virtual testing to the stationary and pass-by tests. TSI Noise tests are costly and time consuming:

- 4 to 6 months of duration, 4 weeks of effective work
- Around 70k€ for an EMU/DMU certification (classic speed), from 65k€ to 90k€ for high speed train certification, depending on the network where the measurements take place
- For 1 manufacturer, 2 to 4 TSI certifications are required per year

More detailed cost figures, based on estimates provided by the ATSA, BT and SNCF measurement teams, is displayed in Figure 31 below:

	Costs categories	Detailed costs	Total
Stationary noise	Man-days	From 12 to 20 man-days	From 13k€ to 19k€
	logistics	From 1k€ to 3k€	
Pass-by noise regular speed	Man-days	From 24 to 30 man-days	From 27k€ to 50k€
	Logistics	From 3k€ to 5k€	
	Track access charge	From 5k€ to 25k€*	
Pass-by noise high speed	Man-days	From 24 to 30 man-days	From 27k€ to 67k€
	Logistics	From 3k€ to 5k€	
	Track access charge	From 5k€ to 40k€*	
Starting noise	Man-days	From 12 to 20 man-days	From 10k€ to 19k€
	logistics	From 1k€ to 3k€	

Figure 31: Costs associated with TSI Noise certification testing [A01]

AcouTRAIN has estimated that for example, for a case in which virtual testing can avoid carrying out pass-by measurement, with only a few additional measurements at standstill (for noise source characterisation for example), the cost of testing within a noise certification procedure could be reduced by a factor of 2.

AeroTRAIN

Regarding Virtual Testing AeroTRAIN project has proposed amongst other things the use of numerical simulation to determine the open air pressure pulse and to assess aerodynamic coefficients in place of wind tunnel tests. A key benefit of simulations determined in AeroTRAIN was that they provide the opportunity to have better controlled environmental testing conditions.

AeroTRAIN has also estimated the potential annual savings thanks to virtual testing approaches to 5% of Grand Total costs for Test & Approval.

DynoTRAIN

The DynoTRAIN project has proposed a procedure for validation of multi-body vehicle models, which makes it possible to replace on-track tests for running safety by simulations as part of the vehicle certification. This will have an economic impact on new vehicle certification costs. Cost savings for new designs will be limited but larger savings are possible for repeat builds and the management of changes to existing vehicles.

Other advantages explicitly mentioned are:

- reduction of Measurement campaign
- Recommendations for inclusion in the issue of EN 14363:2016
- Increased competitiveness of the railway mode
- Increased interoperability;
- Reduction in the cost of train ownership;
- Improved availability and reliability of rolling stock.

PantoTRAIN

The PantoTRAIN approach related to virtual certification is to partly replace the track by simulations as part of the vehicle certification. This will have an economic impact on new vehicle. Cost savings for new designs will be limited but larger savings are possible for extension to other lines or slightly modified pantographs.

Other advantages are:

- reduction of measurement campaign
- Increased competitiveness of the railway mode
- Increased interoperability
- Reduction in the cost of train ownership

10.6. Method for quantification of benefits on the certification process

The quantification of the benefits of Virtual Certification should consider:

- the reduction in train testing due to Virtual Testing and the associated cost benefits and
- the reduction in the homologation schedule and therefore time to market due to the application of Virtual Certification.

The benefit of Virtual Certification has to calculated on a case by case basis, however, this section outlines the how it may be quantified and also provides an indication of the potential benefits of Virtual Certification for new rolling stock.

Virtual testing enables the duration of train testing, either on the network or at a test facility, to be reduced. The cost of executing tests on the railway network or at a test facility can be split into generic costs and test specific costs. The generic costs are those associated with the logistics and operational aspects of the test. Generic costs associated with testing include:

- Track Access Charges
- Costs for train drivers during the testing
- Test engineers on board the train
- Management and operational support required to successfully execute the test programme

The cost to cover these generic aspects may be in excess of €20k per day of the test programme.

Specific costs are in addition to the generic costs and associated with the specific aspects of the test. Specific costs would include:

- Instrumentation costs such as hire, purchase, depreciation, installation, removal, etc.
- Costs associated with specific operational controls to be implemented to execute the tests such as signal protection zones for EMC and brake testing
- Specialist technical support for the test
- Data analysis and report writing costs

These costs may vary considerably depending on the type of test being executed but can be significant.

The total benefit of Virtual Testing can be calculated by the total cost of the test, which includes generic and specific costs, associated with the reduced duration of testing. Reducing the test programme duration can soon realise significant cost benefits to the manufacturer and the customer.

Determining the reduction in the homologation schedule and therefore time to market due to the application of Virtual Certification is relatively straightforward. This can be derived by assessing the difference between the date of Authorisation of a product with and without the application of Virtual Certification. Quantifying the financial advantage of this change to the manufacturer is more difficult, however, as it should consider many factors specific to the manufacturer and their contract terms with their suppliers and customers. An example of this is the financial benefit of reduced time between material procurement and selling the trains earlier i.e. financial profile of the business.

The tables below provide an indication of the time and cost for certification of new rolling stock and the potential reduction that could be achieved through Virtual Testing. Each table considers the test programmes for a typical Commuter Train and a High Speed Train. The case for the High Speed Train assumes that the certification is required to be performed for three regions. The two scenarios aim to present the possible range of costs and durations of test activities based on the differing complexity and scope of products.
The first table (Figure 32) assesses the potential reduction in the time for certification for the core performance test areas.

Time for certification	Certification of new rollig stock			Extension of existing approval
Main tests	Commuter Train [test day]	High Speed Train [test day]	Potential reduction with VT	Potential reduction with VT
Running performance, stability and comfort	27	72	30%	50%
Fatigue Wheelset & Bogie	29	77	30%	50%
Aerodynamics	22	58	15%	50%
Brake performance	32	86	10%	15%
Traction performance	22	58	30%	40%
Climate	22	58	5%	25%
Pantograph	18	48	30%	50%
Acoustics	9	24	30%	50%
Potential total time reduction [test day] for certification of new rollig stock	39	104	**21,60%**	
Potential total time reduction [test day] for Extension of Approval with VT				**39,50%**

Figure 32: Potential time reduction for certification with VT

The reduction in certification time could be reduced by approximately 20% through the application of Virtual Testing. This could be equivalent to between 39 - 104 test days.

The analysis related to the ‘extension of existing approval’ is an assumption of the potential reduction that may be achieved if the design is based on an already approved product. In reality this value can vary significantly and is dependent on the specific scope of change of the product to be validated. The key point is that the level of reduction that may be achieved in this type of scenario is greater than that of a new product. It is estimated that the reduction could be increased to approaching 40% in cases for extension of existing approvals.

The next table (Figure 33) evaluated the cost reductions for the same two test programmes.

Costs for certification	Certification of new rollig stock			Extension of existing approval
Main tests	Total Certification Costs Commuter Train [EUR]	Total Certification Costs High Speed Train [EUR]	Potential reduction with VT	Potential reduction with VT
Running performance, stability and comfort	525.000	1.500.000	30%	50%
Fatigue Wheelset & Bogie	560.000	1.600.000	30%	50%
Aerodynamics	420.000	1.200.000	15%	50%
Brake performance	630.000	1.800.000	10%	15%
Traction performance	420.000	1.200.000	30%	40%
Climate	420.000	1.200.000	5%	25%
Pantograph	350.000	1.000.000	30%	50%
Acoustics	175.000	500.000	30%	50%
Potential total cost reduction [EUR] for certification of new rollig stock	756.000	2.160.000	**21,60%**	
Potential total cost reduction [EUR] for Extension of Approval with VT				**39,50%**

Figure 33: Potential cost reduction for certification with VT

The certification cost reduction could be reduced in excess of €750k through the application of Virtual Testing. For the more complex High Speed Train scenario it is estimated that savings in excess of €2M could be realised.

The certification durations, costs and potential reductions for each main technical field are approximate figures that the project has agreed on. They do not come from detailed analysis but were chosen by the experts as realistic values. The potential reduction in certification time and cost derived in this section are indicative but provide an order of magnitude of the benefit of Virtual Testing. The results show that the benefits associated with the application of Virtual Certification are significant.

In principle, the presented method is also suitable for quantification of benefits of Virtual Certification for other components, e.g. signalling systems. More detailed data for this could be developed in IP2 projects, but at this stage of the project it is not available.

11. Conclusion

Virtual testing has a dominant role in past and present research activities and is implemented in many standards today. The progress of implementation of virtual testing in the homologation process, however, is still at different levels in the various fields in the railway sector. Crashworthiness and aerodynamics, for example, can be considered pioneering fields that exploit the technical possibilities of numerical simulations. The verification and validation approaches used in these fields are accepted and proven. The basic concept of these approaches can be adapted, modified and then used in other fields.

The barriers which hinder the dissemination of virtual approaches in the European railway sector can be categorised into technical and non-technical issues. While the technical barriers can be overcome by increased research, this is not possible for the other aspects because of the identified lack of harmonisation in the standards. Here, a harmonised approach is necessary in order to support the acceptance of simulations and bring them to the same level of reliability that field testing has.

The discussed benefits of virtual testing range from time and cost savings in the design phase and in the homologation process to an increase of safety. Based on the quantification method and potential benefits presented in section 10.6, the reduction in the test programme of a new product through the application of Virtual Testing can lead to cost and time benefits in the order of 20% for the certification process. These benefits will increase further in cases of extension of an existing product approval. The benefits, however, can be realised through the whole value chain of the railway, from component to integrated railway system design. Most of these benefits are already observed in the technical field where virtual testing is already accepted for approval. Extending virtual testing to other fields would contribute to the objectives of the Shift2Rail program and increase the competitiveness of the railway sector.

12. References

DynoTRAIN:

[D01] DynoTRAIN, D5.5 - Final report on model validation process, 2013
[D02] DynoTRAIN, D6.1 - Certification of a modified vehicle, 2013
[D03] DynoTRAIN, D6.2 - Certification for other running conditions, 2013
[D04] DynoTRAIN, D6.3 - Final report on the virtual certification, 2013
[D05] DynoTRAIN, D7.3 - Proposals for integrations to existing standards and homologation processes and their assessment for safety, quality and practical feasibility, 2013
[D06] DynoTRAIN, D7.1 - Report on uncertainty analysis, 2013
[D07] DynoTRAIN, Final Report Summary – DYNOTRAIN, https://cordis.europa.eu/project/rcn/92249/reporting/en, 18.11.2019

AcouTRAIN:

[A01] AcouTRAIN, D1.2 - Recommendations for a future certification process, 2013
[A02] AcouTRAIN, D1.7 - Global functional requirements of a virtual certification for the next revision of the TSI, 2012
[A03] AcouTRAIN, D1.8 - A virtual certification process (validated), 2015
[A04] AcouTRAIN, D4.6 - Report with a validation guideline to certify tools, 2014
[A05] AcouTRAIN, D5.4 - Report on Validation Methodology, 2015
[A06] AcouTRAIN, D6.3 - Technical Recommendations, 2015
[A07] AcouTRAIN, Final Report Summary – ACOUTRAIN, https://cordis.europa.eu/project/rcn/100582/reporting/en?rcn=168013, 18.11.2019

AeroTRAIN:

[E01] AeroTRAIN, D0.5 - Final Report, 2012
[E02] AeroTRAIN, WP1 - T1.2 Output Document, 2012
[E03] AeroTRAIN, D6.3 - Proposals for integrations to existing standards and homologation processes and their assessment for safety, quality and practical feasibility, 2012
[E04] AeroTRAIN, D6.1 - Report on uncertainty analysis, 2012

PantoTRAIN:

[P01] PantoTRAIN, D3.2 - Procedure to extend pantograph homologation to different catenary systems by numerical simulation, 2012
[P02] PantoTRAIN, D3.3 - Procedure to extend pantograph homologation to different catenary systems by HIL testing, 2012
[P03] PantoTRAIN, D6.1 - Report on uncertainty analysis, 2012

CONNECTA:

[C01] CONNECTA, D6.1 - Specification of Virtual Homologation Principles, 2018, Vol. 8
[C02] CONNECTA, D6.2 - Specification of the Simulation Framework and Train Virtualization, 2019, Vol. 12

PINTA:

[PN01] PINTA, D5.1 - State of the art of numerical and system validations and gap analysis description, Revision 2, 2017
[PN02] PINTA, D5.3 - New methodologies for validation, 2018
[PN03] PINTA, D8.1 - Adhesion modeling specification, Third Edition, 2017
[PN04] PINTA, D8.3 - Wheel Slide Protection Test Rig Specification, Second Revision, 2017
[PN05] PINTA, final conference, Rabat, 2018
[PN06] https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA, 18.11.2019

PIVOT:

[PV01] PIVOT, TSK 5.5 - Virtual Validation & Certification Status Quo, Version 5, 2018

X2Rail:

[X01] X2Rail, D6.1 - Current test condition and Benchmarking report, R2_Updated version, 2018

EURAXLES:

[EX01] Euraxles, D2.2 - Report on the Fatigue-Equivalent-Load methodology and the load severity distribution, 2013

IMVITER:

[I01] IMVITER, Final Report Summary – IMVITER, https://cordis.europa.eu/project/rcn/91055/reporting/en, 18.11.2019
[I02] A. Eggers, H. Schwedhelm, O. Zander, R. Cordero Izquierdo, J. Polanco, J. Paralikas, K. Georgoulias, G. Chryssolouris, D. Seibert, C. Jacob: Virtual Testing based Type Approval Procedures for the Assessment of Pedestrian Protection developed within the EU-Project IMVITER, Paper Number 13-0344

Nuresafe:

[N01] NURESAFE, Project Final Report, https://cordis.europa.eu/docs/results/323/323263/final1-nuresafe-final-report-publishable-summary-june-29-2016.pdf, 22.11.2019

Standards:

[S01] ISO 3095:2013, Acoustics - Railway applications - Measurement of noise emitted by railbound vehicles
[S02] EN 13979-1:2003, Railway applications - Wheelsets and bogies - Monobloc wheels - Technical approval procedure - Part 1: Forged and rolled wheels
[S03] DVS 1608:2011-08, Design and strength evaluation of welded constructions of aluminum alloys in rail vehicle construction
[S04] DVS 1612:2014-08, Design and fatigue evaluation of welded joints with
[S05] EN 13103-1:2017, Steels in rail vehicle construction, Railway applications - Wheelsets and bogies - Part 1: Design method for axles with external journals
[S06] EN 15273-2:2013+A1:2016, Railway applications - Gauges - Part 2: Rolling stock gauge
[S07] EN 13979-1:2003+A2:2011, Railway applications - Wheelsets and bogies - Monobloc wheels - Technical approval procedure - Part 1: Forged and rolled wheels

[S08] EN 14067-4:2013, Railway applications - Aerodynamics - Part 4: Requirements and test procedures for aerodynamics on open track
[S09] EN 14067-6:2018, Railway applications - Aerodynamics - Part 6: Requirements and test procedures for cross wind assessment
[S10] EN 14363:2016+A1:2018, Railway applications - Testing and simulation for the acceptance of running characteristics of railway vehicles - Running behaviour and stationary tests
[S11] EN 15595:2019-03, Railway applications - Braking - Wheel slide protection
[S12] UIC 541-05: 2016, Brakes - Manufacturing specifications for various brake parts - Wheel Slide Protection device (WSP)
[S13] EN 15827:2011, Railway applications — Requirements for bogies and running gears
[S14] EN 50388:2012, Railway Applications - Power supply and rolling stock - Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability
[S15] prEN 50641:2017, Railway applications — Fixed Installations - Requirements for the validation of simulation tools used for the design of traction power supply system
[S16] EN 15227:2008+A1, Railway applications - Crashworthiness requirements for railway vehicle bodies
[S17] EN 152732:2013+A1:2016, Railway applications – Gauges – Part 2: Rolling stock gauge
[S18] prEN 50367:2017, Railway applications - 3 Fixed installations and rolling stock - Criteria to achieve technical compatibility between 4 pantographs and overhead contact line
[S19] prEN 17149: Railway applications — Strength assessment of railway vehicle structures

Other:
[O01] EPSF, Recommendations regarding the use of numerical simulations to demonstrate compliance with technical and regulatory requirements on the rail network, https://securite-ferroviaire.fr/reglementations/recommandations-relatives-lusage-de-la-simulation-numerique-dans-les-demonstrations, 2019
[O02] CEN TC256 / CLC TC9X, SG Simulation, Guide on the use of simulation (draft, title might still change)

NASA:
[NA01] NASA-STD-7009, Revision A, 2016, NASA Technical Standard for Models and Simulations
[NA02] NASA-HDBK-7009, 2013, NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009
[NA03] Towards a Credibility Assessment of Models and Simulations, 2008; NASA Langley Research Center
[NA04] NASA Standard for Models and Simulations: Credibility Assessment Scale, 2009; Babula et. al.
[NA05] A Credibility Assessment Scoring (CAS) Process for Mission Risk Management, 2011; S. P. Colombano, NASA Ames Research Center

AFCEN (French Association for the design and construction rules of the electronuclear materials):
[AF01] AFCEN guidelines, https://afcen.com/fr/qui-sommes-nous/nos-codes, 18.11.2019

Scientific Publications:

[SC01] C. Funfschilling, G. Perrin, S. Kraft, Propagation of variability in railway dynamic simulations: Application to virtual cdertification, *VSD,* 2012

[SC02] C. Funfschilling, G. Perrin, M. Sebes, Y. Bezin, L. Mazzola, M.L. Nguyen, Probabilistic simulation for the certification of railway vehicles, Proc. Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit, 229(6), 2015

[SC03] J.P.Massat, C.Laurent, T.M.L. Nguyen, A. Facchinetti, S. Bruni, Simulation tools for virtual homologation of pantograph, Railways, 2012

[SC04] S.Bruni, J.Ambrosio, A.Carnicero Lopez, Y.Hyeon Cho, L.Finner, M. Ikeda, S.A.Kwon, J.P.Massat, S.Stichel, M.Tur, W.Zhang, The pantograph-catenary interaction benchmark, IAVSD, 2013

[SC05] G. Saussine, C. Voivret, N. Paradot, E. Allain, A risk assessment method for ballast flight; managing the rolling stock/infrastructure interaction, Proc. Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit, 229(6)(6):581-593, 2015

[SC06] Licciardello R, Grappein E, Rueter A. On the accuracy of the assessment of open-air pressure loads due to passing trains: Part 2: Assessment by simulation. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2015 Aug;229(6):657-67.

[SC07] Licciardello R, Funfschilling C, Malavasi G. Accuracy of the experimental assessment of running dynamics characteristics quantified through an uncertainty framework. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2017 Sep;231(8):945-60.

[SC08] F. Poisson, F. Aubin, C. Chaufour, Virtual certification of acoustical performances of a railway vehicle, EuroNoise, 2018

[SC09] Bignonnet A.: Fatigue Design in the automotive industry. In CISM courses n°392 - High Cycle Metal Fatigue, from theory to applications- Papadopoulos I.V. and Dang Van K. Eds Springer Verlag 1999, pp. 145-167, 1999

[SC10] Bignonnet A. Lieurade J.P. Application in the industry of the reliability approach in fatigue design: a CETIM multipartners project, Fatigue Design 2007, Cetim, Senlis, France, 2007

[SC11] T.M.L. Nguyen-Tajan, X. Lorang, Euraxles - A global approach for design, production and maintenance of railway axles: WP1-Advances in fatigue load analysis and reliability assessment of railway axles, Materialwissenschaft und Werkstofftechnik, 2017