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Europe's Rail Freight

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1 Executive Summary

The running safety of freight wagons under longitudinal compressive forces must be assessed to mitigate the risk of derailment. A key value for the assessment is the endurable longitudinal compressive force (eLCF). This is a property of the wagon and its coupler system. The current European rules for the assessment of eLCF are not directly applicable to wagons with DAC.

There has been intensive research in Europe in the past decades. Centre buffer couplers with certain design features enable much higher eLCF than wagons with side buffers. A so-called stabilising joint plays a major role. Wagons with higher eLCF are favourable for railway undertakings to have as they allow for longer and heavier trains in more effective brake positions.

The recommended assessment methodology for the DAC is based on various proven procedures of the past combined with the possibilities of modern multi body simulations. Central component are virtual tests to determine the eLCF of a wagon and coupler combination. These simulations must be validated with real life tests. Automated simulations allow for a large number of virtual tests. All results will be stored in databases and serve as basis for generalised rules. These are assignments of (minimum) eLCF to clusters of wagon parameters. This procedure is very similar to European rules for the assessment of wagons with side buffers.

The simulations of tests to evaluate the eLCF show a good match with real-life tests. Both simulations and real-life tests show higher eLCF for wagons with DAC as for the same wagons with side buffers. There is currently no indication that wagons with DAC have lower eLCF if the DAC has a stabilising joint.

Methods for verification and validation of the virtual derailment tests have been introduced and applied. At the present time, a final validation of the approach is not possible as there have not been any real-life tests with DACs that fully comply with the TRANS4M-R specifications. Therefore, it is currently not possible to derive the final "running safety assessment tool" as simple, practical guidelines, e.g. a set of rules, look-up-tables or diagrams. However, the recommended methodology can be applied to fully specified DAC and the respective test results as soon as they are available.

The proposed methodology is not proprietary. It can be implemented by any stakeholder who has the necessary capacities and expertise. We suggest a coordinated application of the methodology within the sector to ensure that all outcomes of simulations cumulate in simple, practical guidelines ("the tool") that can then be used by the entire sector.

Keywords: DAC, derailment safety, longitudinal compressive forces, multi body simulation, stabilising joint

2 Abbreviations & Acronyms

Abbreviation / Acronym	Description
AAR	Association of American Railroads
DAC	Digital Automatic Coupler
eLCF	Endurable longitudinal compressive forces
ep (brake)	Electro-pneumatic (brake)
ERRI	European Rail Research Institute
GA	Grant agreement
IRS	International Railway Standard
MBS	Multi body simulation
oLCF	Occurring longitudinal compressive forces
ORE	Office of research and engineering
RU	Railway undertaking
UIC	International Union of Railways
V&V	Verification and validation

3 Background

The present document constitutes the Deliverable D4.3 “DAC Running Safety Assessment Tool” in the framework of the Flagship Project FP5- TRANS4M-R as described in the EU-RAIL MAWP.

4 Objective/Aim

This document has been prepared to provide a methodology for the assessment of the running safety of wagons with DAC under longitudinal compressive forces. Existing rules on this topic are currently limited to wagons with side buffers or other types of centre buffer couplers and therefore not applicable to the DAC.

4.1 Task Description

	Task definition from GA (Task X.X)	Output of deliverable
Subtask 4.3.1	Existing rules, like EN 15839:2012 and methodologies for the demonstration of the running safety of freight wagons do not fully apply to the DAC. Individual real-life tests with numerous wagon types are not feasible. Therefore, a generic DAC specific methodology e.g. by means of simulation needs to be developed. Within this work package a build-up of a multi body simulation tool based on the outcomes of propelling and test bench tests should take place. To obtain input values for the simulation models, tests are to be carried out in close coordination with WP13. The derived safety architecture will be assessed by an independent safety assessor respectively assessment body (AsBo).	The deliverable presents a methodology for the assessment of the running safety under longitudinal compressive forces of wagons with DAC. The methodology is based on proven procedures of the past combined with possibilities of modern multi body simulations. The methodology is not proprietary. It can be implemented by any stakeholder who has the necessary capacities and expertise. A simulation environment has been built up as a proof of concept. The simulation results show a good match to real life test results. Additionally, a methodology for verification and validation has been set up. This is aligned with prEN 17833 "Railway applications – Simulation credibility". This is to make sure that the results can be used for the vehicle/coupler authorisation. At the present time, a final validation of the approach is not possible as there have not been any real-life tests with DACs that fully comply with the TRANS4M-R specifications. The recommended methodology can be applied to these DAC and the respective test results as soon as they are available.

5 Fundamentals, Definitions and Rules

5.1 Basics of Longitudinal Dynamics

5.1.1 Definition

Cole defines longitudinal train dynamics as the movements of the rail vehicles in the direction of the track. [1] According to his definition, this includes both the movement of the train as a whole as well as the relative movements of the vehicles with respect to each other.

The investigation of the movement of the train as a whole is an important field in railway operations studies. This involves the determination of journey times for capacity analyses and timetable constructions. However, these considerations are not relevant for the task covered in this report.

The present work deals exclusively with effects caused by the relative movements of the vehicles between each other. Such relative movements are possible because the connections of individual rail vehicles to trains are not rigid. The buff and draw gear enables relative movements by the application of forces. Furthermore, design and/or process-related play in the buff and draw gear also leads to force-free relative movements. Traction and brake forces are the cause of relative movements and the associated forces. This is explained in more detail in the following section.

5.1.2 Occurring Longitudinal Compressive Forces (oLCF)

Traction and brake forces inevitably lead to longitudinal dynamics when operating freight trains. The reason for this is that there is no evenly acceleration/deceleration acting on all vehicles, neither during the acceleration phase nor during brake application.

The acceleration phase of a freight train is a simple example of these relationships: the traction forces are not evenly distributed across the train. They only act at the positions of the locomotives - very often only at the head of the train. Forces therefore arise between the vehicles: tensile forces behind pulling locomotives and compressive forces in front of pushing locomotives. When a freight train accelerates with a locomotive at the head of the train, the highest tensile forces typically occur at the first coupling point behind the locomotive.

The interrelationships during air brake applications are much more complex but are also particularly relevant in the context of the present task. Although the standard air brake used on the railway usually acts on all vehicles in the train, it does not act on all vehicles at the same time, nor does it act with equal decelerations.

The brake is applied by venting the brake pipe (BP) from the front of the train. The air in the BP must flow along the entire length of the train to the venting point. There is a relatively rapid drop in pressure in the brake pipe close to the venting point at the front

of the train. However, as the distance from the venting point increases, the time required for the pressure drop increases.

As the pressure in the BP decreases, the pressure in the vehicle's brake cylinders increases and so does the effective brake force. The front part of the train therefore begins to decelerate earlier than the rear part. As a result, the rear section of the train runs onto the front section due to its inertia. Excessive longitudinal compressive forces can therefore occur approximately in the centre of the train. Figure 5-1 illustrates the above relationships.

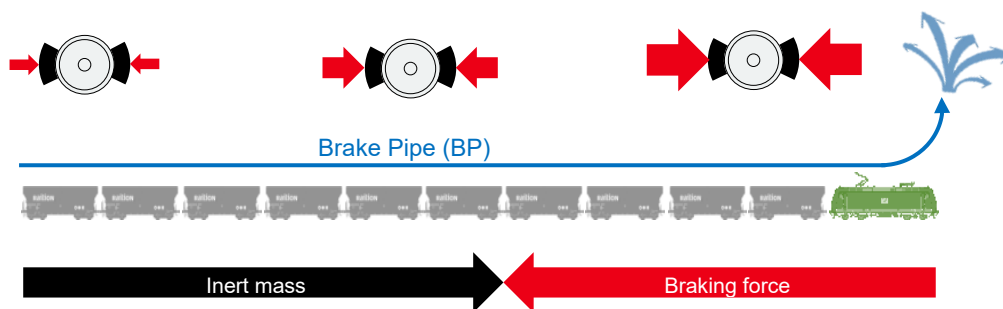


Figure 5-1: Principle of occurring longitudinal compressive forces during brake application

The level of *occurring longitudinal compressive forces (oLCF)* depends on a number of parameters. Some of the most influential ones are:

- Type of brake application (service brake or emergency brake)
- Train mass and length
- Mass distribution
- Brake position
- Characteristics of the buff and draw gear
- Characteristics of the brake's friction elements

The adjustable brake position on the vehicles is a measure for limiting the occurring longitudinal compressive forces. Its effect is to couple the brake cylinder pressure to the pressure drop in the BP with a time delay rather than immediately. This forces the vehicles at the front of the train to have similar pressure build-up characteristics as the vehicles further back of the train. This reduces the differences in braking force and thus also the *oLCF*. Originally, there was the brake position "P" for comparatively short and fast passenger trains and the brake position "G" for longer and slower freight trains (goods trains). In brake position G, the brake cylinder pressure build-up takes at least 18 seconds, as opposed to at least 3 seconds in brake position P. [2]

The brake position G has therefore always been an available measure for reducing *oLCF* in freight trains. However, the delayed build-up of braking force in brake position G is also accompanied by a reduced braking capacity compared to brake position P. For many decades, this had little practical significance, as the maximum speed of freight trains was

rather low anyway due to other boundary conditions. Starting in the 1980s, however, efforts were made to increase the maximum speed of freight trains (to the values known today). The exclusive use of the brake position G for freight trains was no longer sufficient. Extensive investigations were therefore carried out by the European Rail Research Institute (ERRI) into the use of the brake position P for freight trains. [3] [4] [5] [6] [7] [8]

Simulation programmes were also developed to investigate the *oLCF* in this context. Until the mid-2000s, the programmes "TRAIN" and "E-TRAIN" were used by the UIC. [9] [10] [11]. In 2006, the UIC decided to procure and further develop the "TrainDy" software [12]. This software is today state of the art for *oLCF* analyses in a European context and used by several railway undertakings (RU) and industry companies.

The need for simulations lies in the extremely large number of possible freight train configurations. The influencing parameters mentioned above can vary for each individual wagon and with each additional wagon on the train there is an additional possible combination. Assuming that we only consider the three loading states "full", "half-full" and "empty", a train with 30 wagons already has $3^{30} \approx 206$ trillion possible combinations of masses only. It is therefore not expedient to generate a statement on the totality of all trains by means of real tests. Instead, simulations are used to analyse a representative proportion of all possibilities. IRS 40421 contains detailed information on the procedure of performing simulations to investigate *oLCF*. [13]

In the context of this task, *oLCF* of DAC trains are initially assumed to be the same as for trains with screw coupler and side buffers. This applies under two conditions:

1. **freight trains with DACs behave in the same way regarding *oLCF* as freight trains with screw couplers and side buffers.** This is a working hypothesis at the moment. The characteristics of the DAC draw gear are similar to the characteristics of screw coupler draw gears and side buffers. Furthermore, it is not intended to change the longitudinal dynamics properties of freight trains. However, draw gear characteristics have a high influence on *oLCF*. Therefore, this hypothesis should be tested by means of train tests and simulations (e.g. TrainDy) as soon as enough DACs with a finalised design are available.
2. **the same operating rules initially apply to freight trains with *oLCF* as to freight trains with screw couplers and side buffers.** This point is taken up again in section 5.1.4.

When an electro-pneumatic brake (ep-brake) is used, the effect, that all the air in the BP has to flow to the bleeding point at the front of the train, is eliminated. Instead, the BP is vented at each vehicle so that the brakes are applied almost simultaneously throughout the train. In this case, the rear part of the train does not run into the front one. With the UIC braking system, however, not all vehicles decelerate at the same rate, as brake forces are not completely proportional to the wagon load. As different decelerations in the train

lead to forces between the vehicles, this results in *oLCF* despite the ep-brake. [14] However, the *oLCF* values are usually significantly lower than with conventional air brakes.

5.1.3 Endurable Longitudinal Compressive Forces (eLCF)

The previous section shows that the operation of freight trains inevitably leads to *occurring longitudinal compressive forces (oLCF)*. The level of these forces depends on a number of boundary conditions.

Excessive *oLCF* can pose a safety risk for railway operations. At this point, however, it is important to note that this is not about the direct effects of compressive forces on the vehicle structure (strength)¹. Instead, we are talking about potential derailments that can be caused by vertical and lateral forces resulting from the *oLCF* (Figure 5-2). *oLCF* lead to vertical and/or lateral forces if the longitudinal axis of the couplers between two vehicles runs at an angle to the longitudinal axis of the vehicles during the occurrence of the LCF.

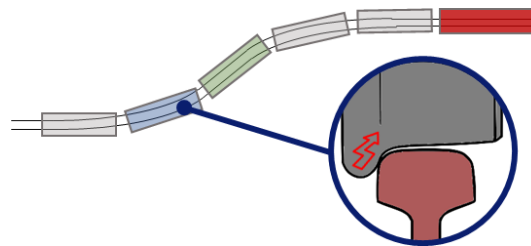


Figure 5-2: Derailment risk due to *oLCF*. Source: DB Systemtechnik

When the train travels through a curve, an angle occurs in the horizontal plane, so that lateral forces arise from *oLCF* (Figure 5-3). Differences in height (e.g. due to load differences) lead to an angled coupler axis in the vertical plane. This results in vertical forces (Figure 5-4).

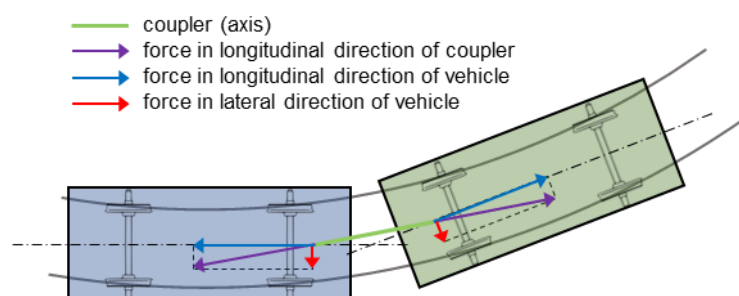


Figure 5-3 Appearance of lateral forces from *oLCF* during curve transition. Source: DB Systemtechnik

¹ *oLCF* in operation (during a train run) are generally in the range of a few hundred kilonewtons. This means that *oLCF* are well below 2000 kilonewtons, which might occur during buffing impacts, and which are taken into account in the strength design of freight wagons [40].

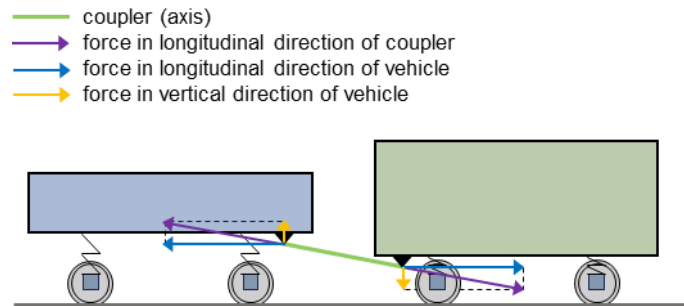


Figure 5-4: Appearance of vertical forces from oLCF due to different (coupler) heights. Source: DB Systemtechnik

It can be deduced from the above explanations that the level of lateral and vertical forces that can arise from oLCF is not only dependent on a vehicle and its coupler system. Instead, the infrastructure and the two neighbouring vehicles also play a significant role. This also means that the risk of derailment of a freight wagon due to oLCF cannot be determined solely by looking at the wagon in question. In principle, there are again a large number of possible combinations.

For this reason, a scenario that includes various unfavourable conditions was defined in the past [7] [8]. This serves as a reference scenario for determining the *endurable longitudinal compressive force (eLCF)*. It is characterised in particular by the simultaneous occurrence of lateral and vertical forces. This is achieved using the following boundary conditions, among others:

- narrow S-shaped curve (150 m) → large coupler angles in the horizontal plane → large lateral forces
- wagons in front of and behind the wagon under test (so-called flanking wagons) with specific dimensions → large coupler angles in the horizontal plane → large lateral forces
- flanking wagons are loaded, wagon under test is empty → large coupler angles in vertical plane → large vertical forces

A constant longitudinal compressive force at which the wagon under test runs over the test track without derailling and without exceeding limit values is referred to as the *endurable longitudinal compressive force (eLCF)* of the wagon under test.

This definition of the eLCF represents a standardised procedure for determining it, as will be explained further in section 5.2. Furthermore, it is possible to compare different vehicles in this way. However, the eLCF determined in this way is not an absolute limit value that must never be exceeded. This is discussed further in the following section.

5.1.4 Relationship between eLCF, oLCF and Railway Operation

For the safe operation of railways, it is necessary for eLCF to reach at least a minimum value and for oLCF not to exceed a maximum value. The lower the eLCF, the more measures to limit oLCF are necessary. Conversely, oLCF may become larger if the eLCF are

high. For example, high *eLCF* and thus higher acceptable *oLCF* enable heavy freight trains to run in more effective braking positions and thus also higher maximum speeds for freight trains. High *eLCF* are therefore desirable from the point of view of railway undertakings.

The description of the above indirect correlations is simple. The derivation of direct quantitative correlations, however, is much more complex. This is because the *eLCF* represents a reference value, but not a generally applicable absolute limit value. If the *oLCF* acting on a wagon is greater than its *eLCF*, then there is only an increased risk of derailment if the same boundary conditions prevail as in the reference scenario. If less critical boundary conditions prevail, for example if the wagon is loaded instead of empty and/or is not in a tight curve, then the *oLCF* may exceed the *eLCF* without this posing a risk.

To quantify the increase in *eLCF* under less critical conditions than in the reference scenario, the ERRI carried out investigations [15] [16] [17] [18]. Generalised rules for *extrapolated eLCF* were derived on this basis. These can be found in the International Railway Standard (IRS) 40421 (formerly UIC Leaflet 421) [13]. These rules include, for example:

- Values for additional *endurable longitudinal compressive force* per additional metre of curve radius
- Values for *endurable longitudinal compressive force* per additional tonne of load

These rules can be used to estimate the *eLCF* in a less critical case than the reference scenario. These approximations are referred to as *extrapolated eLCF*. When applying the rules, some conditions and restrictions must be observed. *Extrapolated eLCF* are more compliant with reality as they also consider (less critical) conditions different from the standard test conditions for the determination of *eLCF*. However, the approximate values are still not absolute limit values in the sense that exceeding them inevitably leads to a derailment.

This is the reason why IRS 40421 describes a method for assessing the level of *oLCF* of freight trains based on the relative comparison of two systems. In this method, an existing freight train operation with long-term operating experience is first defined as a reference system. In the second step, the *oLCF* of this system are determined using simulations. The *oLCF* values are then compared with the *extrapolated eLCF*. The result is the percentage of cases in which the *oLCF* exceeds the *extrapolated eLCF*. The same process is then carried out for a new system with modified parameters. Finally, the percentages of exceedances of both systems are compared with each other. The new system is considered safe if the *oLCF* do not exceed the *extrapolated eLCF* more frequently than the reference system.

This type of assessment of *oLCF* therefore does not require an exact vehicle- and infrastructure-specific determination of (case-specific) *endurable longitudinal compressive forces*. The assessment is based on the following initial conditions:

1. the existing traffic (the reference system) is accepted in terms of *oLCF*.
2. wagons for which sufficient *eLCF* can be verified using the standardised procedures (see section 5.2) can be safely used in the reference system.
3. the positive influences of larger curve radii and additional loading on *endurable longitudinal compressive forces* in real operating situations can be generalised.

The RUs have developed individual operational rules for existing transport operations with wagons with screw couplers and side buffers to ensure that no LCF-related derailments occur during operation. For example, this includes rules regarding:

- the brake position to be set depending on the train mass
- maximum permissible dynamic braking forces of the locomotives
- maximum permissible traction forces when pushing trains

To achieve a benefit with vehicles with larger *eLCF*, the above regulations need to be extended. An example is a special braking rule for trains with UIC couplers that allows the use of brake position P independently of the train's mass and other requirements. This rule is part of German operational regulations. [19]

To make use of higher *eLCF* of DAC-equipped wagons analogue rules have to be defined. This is not part of the present deliverable.

5.2 Existing European Rules and Methods for the Assessment of Running Safety under LCF

5.2.1 Introduction and Applicability of Existing Rules and Methods on the DAC

EN standard 15839 covers the running safety under longitudinal compressive forces in context of the acceptance of running characteristics of railway vehicles. Until December 2024, EN 15839:2016, titled "Railway applications - Testing for the acceptance of running characteristics of railway vehicles - Freight wagons - Testing of running safety under longitudinal compressive forces" [20], was valid. It was replaced by EN 15839:2024, titled "Railway applications - Testing and simulation for the acceptance of running characteristics of railway vehicles - Running safety under longitudinal compressive forces" [21]. As indicated by the title, this new version of the standard also includes simulations as a part of the acceptance procedure.

EN 15839:2016 and former versions are only to be applied for wagons with side buffers. EN 15839:2024 explicitly applies to vehicles with central couplers, too. However, the relevant informative Annex H states "The general assessment of the running safety under longitudinal compressive forces for vehicles with central coupler is not available yet." This is because EN 15839:2024 was elaborated prior to the works in context of the present deliverable.

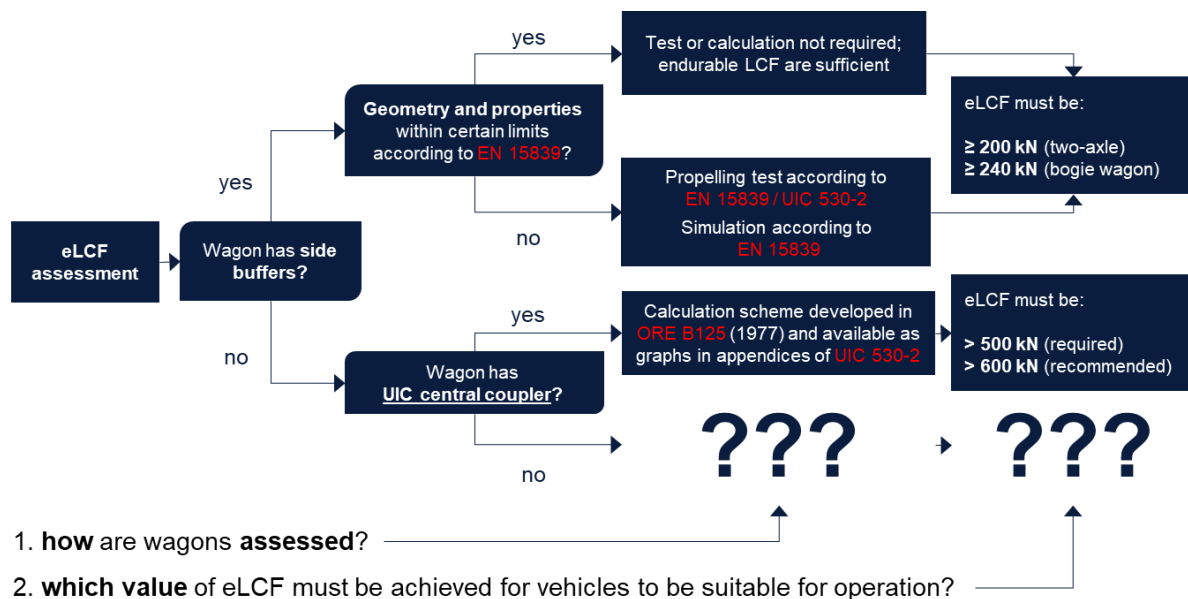


Figure 5-5: Overview of applicable rules regarding eLCF. Source: DB Systemtechnik

EN 15839 originated in large parts from UIC Leaflet 530-2 “Wagons - Running safety”. This document applies to all freight wagons “without exception, regardless of the type of coupler fitted.” [22] This document contains the results of a calculation scheme that was developed by UIC’s office for research and experiments (ORE, the predecessor of ERRI) in the 1970s [23] [24], also see section 5.2.4. However, the section 4.3.3 of UIC Leaflet 530-2 states that this applies to the UIC central coupler only. This means that UIC Leaflet 530-2 is not applicable to the DAC as it differs from the UIC central coupler.

In summary, there is no existing rule that is directly applicable to the DAC. This is the justification why the work outlined in this deliverable is necessary. Figure 5-5 summarises the different rules for the assessment of eLCF, their area of use and the eLCF values to be proven. It also shows that the existing rules consist of two important components:

1. Specifications on how the assessment should be done.
2. The value of eLCF to be proven during assessment.

Both aspects are covered in the present deliverable. However, the focus lies on the first component. Before explaining the methodology for the DAC, the following sections will go into more detail on the existing rules for wagons with side buffers and for wagons with UIC centre couplers. These procedures serve as a basis for the DAC methodology.

5.2.2 Wagons with Side Buffers within Specific Design Parameters

EN 15839 (both the 2016 and 2024 editions) contain ranges of specific design parameters. Wagons that are within these ranges are dispensed from any further assessment. The relevant design parameters are listed in Table 5.1.

Table 5.1: Relevant design parameters

Parameter	2-axle wagon	Bogie wagons	
		2-axle bogies	3-axle bogies
coupler system	x	x	no conditions necessary
torsional coefficient	x		
distance between axles	x		
distance between bogie pivots		x	
length over buffers	x	x	
overhang	x	x	
tare weight	x	x	
wheel diameter	x	x	
type of running gear	x		
buffer radius	x		

Design parameters within these ranges specified in EN 15839 ensure minimum eLCF values of

- 200 kN for two-axle wagons,
- 240 kN for wagons with bogies.

5.2.3 Test Procedure for Wagons with Side Buffers

For wagons whose properties do not lie within the value ranges described in the previous section, EN 15839 defines a test procedure for determining the eLCF. These are referred to as propelling tests.

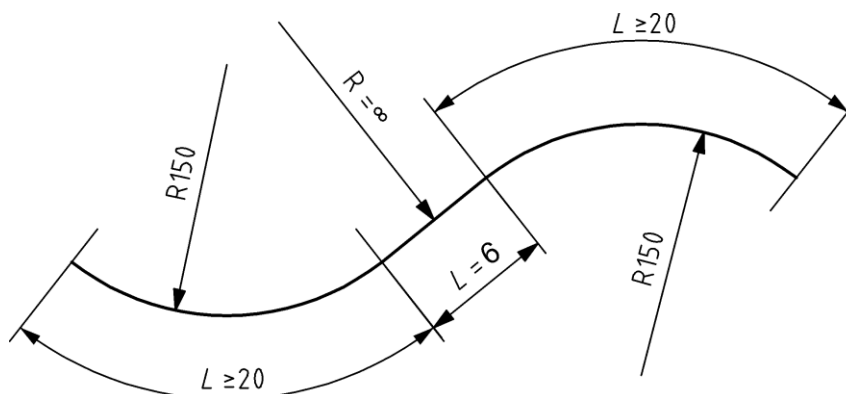


Figure 5-6: Test track according to EN 15839. Source: [20] (modified)

In this test, the wagon to be tested is pushed unloaded through an S-shaped curve with a radius of 150 m and a 6 m straight between the two curves (Figure 5-6) without superelevation. Within the train configuration, the wagon is placed between two exactly specified so-called flanking wagons (see below). The train is pushed by one or more locomotives and there are brake wagons at the opposite end of the train (Figure 5-7). The locomotive(s) push the train at approximately walking pace, with the brake force of the

brake wagons acting against the traction force of the locomotive(s). This results in a longitudinal compressive force that must be kept as constant as possible for each test run.

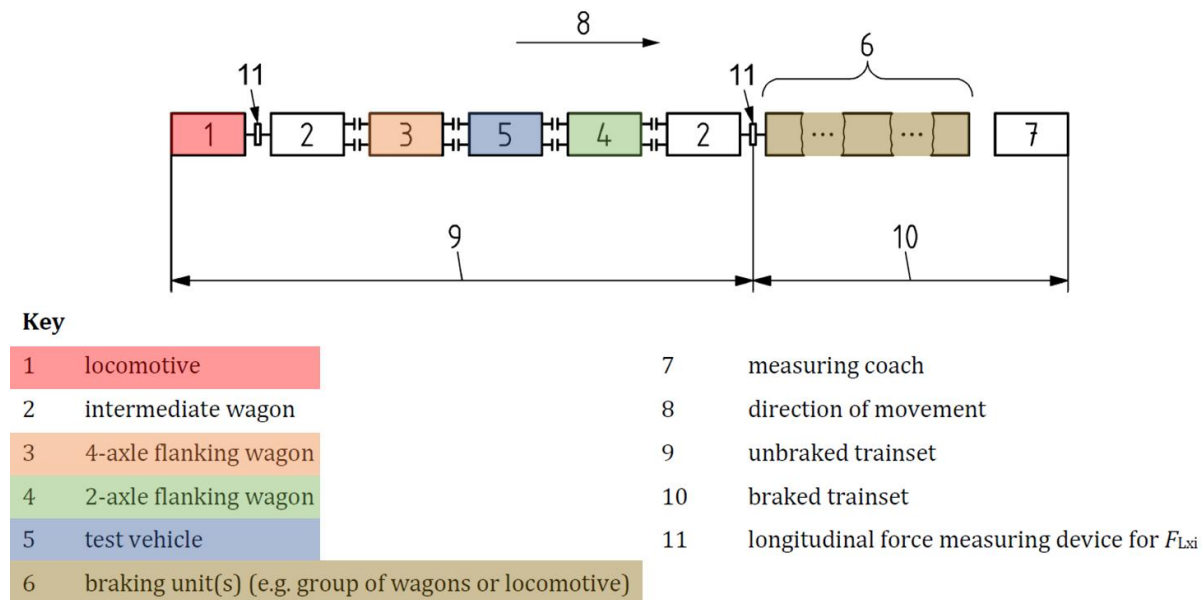


Figure 5-7: Test train configuration according to EN 15839. Source: [20] (modified)

The following variables must be measured on the wagon under test:

- wheel lift
- lateral axle box force
- axle guard deformation (only for two-axle wagons)
- overlap of buffer plates

In addition, the longitudinal compressive force in the consist must be measured. For this purpose, special intermediate wagons with centre buffer couplers are often used in tests with side buffer wagons.

The longitudinal compressive force must be successively increased from test run to test run until a limit value for the measured values is exceeded or a sufficiently high longitudinal compressive force is reached. There is a minimum number of required test runs, some of which must be above the $eLCF$ to be verified. The values to be proven are the same as shown in the previous section: 200 kN for two-axle wagons, 240 kN for wagons with bogies.

The flanking wagon in front of the test wagon is a two-axle wagon with a wheelbase of 6 m and a length over buffers of 9.64 m. Typical types are Fcs and Tds wagons. The flanking wagon behind the test wagon is a bogie wagon with a length over buffers of 19.9 m and a bogie pivot distance of 13 m. A typical wagon with these dimensions is the Rs 680 type. Also see section 5.2.4 for more information on these wagons.

5.2.4 Calculation Scheme for Wagons with UIC Centre Buffer Couplers

ORE working group B 125 developed a calculation scheme for $eLCF$ of freight wagons with UIC centre buffer couplers in the 1970s. [23] This was developed further and has been supplemented by new designs of running gear during the 1980s. These processes are summarised in ORE report B 12 RP 49. [24] The results of the calculation scheme are the appendices of UIC Leaflet 530-2. Appendix A covers two-axle wagons with leaf springs of constant stiffness. [25] Appendix B covers two-axle wagons with leaf springs of progressive stiffness. [26] Appendix C covers wagons with two-axle bogies. [27] Within each appendix, there are different parts of the document for different types of the respective running gear. Each part features several diagrams that contain some design parameters of the wagon on top, the torsional stiffness of the wagon as x-axis of the diagram and the $eLCF$ as y-axis. Furthermore, the diagram contains different lines for different values of the static normal wheel force Q_0 . Figure 5-8 shows this as an example.

It is very important to note that the calculation scheme of ORE B 125 combines two aspects of running safety that are treated separately today:

1. Running safety when running over twisted tracks (without taking longitudinal compressive forces into account)
2. Running safety under influence of longitudinal compressive forces

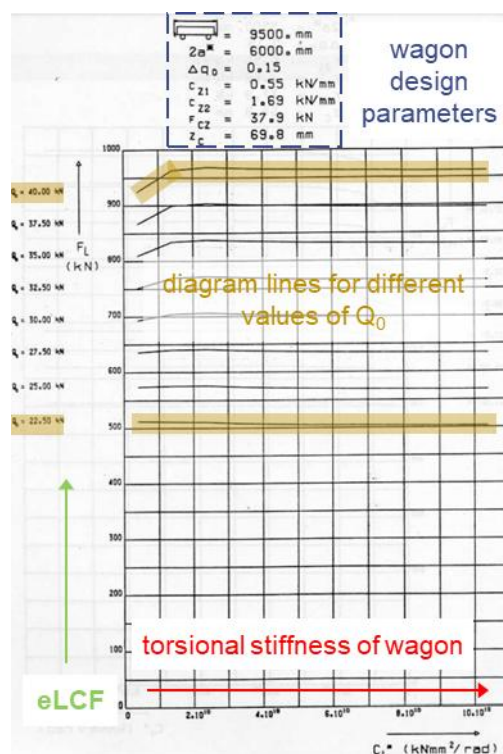


Figure 5-8: Example of diagram in Appendix B of UIC Leaflet 530-2. Source: [26] (modified)

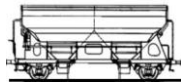
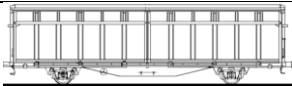
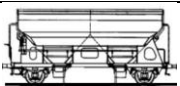
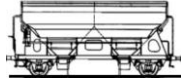
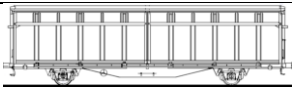
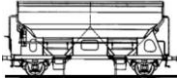
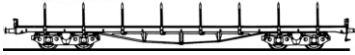
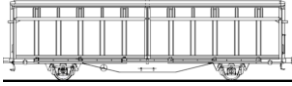
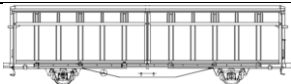
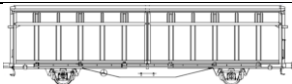
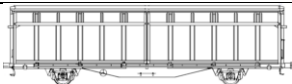
The first aspect is covered today in EN 14363 [28]. The torsional stiffness of the vehicles plays an important role in this context. Therefore, some of the diagrams in the appendices of UIC Leaflet 530-2 show an additional line “A-A”, which is a limit curve for running on twisted track. This is part of EN 14363 and is not discussed further in this deliverable. As mentioned above, the second aspect is today covered in EN 15839.

The basis of ORE B 125 calculation scheme for wagons with UIC central coupler is similar to the EN 15839 propelling test described in section 5.2.3. The scheme calculates the passage of a wagon group through defined types of infrastructures. The wagon group consists of a wagon under test, a flanking wagon in front of it and another flanking wagon in the rear. The types of the flanking wagons can be:

- Rs 680 (same as in EN 15839)
- Tdgs 930 (length over buffers 9.64 m, wheelbase 6 m, same as in EN 15839)
- the same type as the wagon under test

The two specified flanking wagons were chosen because they lead to unfavorable horizontal coupler angles and because they were present in large numbers in the wagon fleet of the UIC railways during the development of the scheme in the 1970s. [24] In contrast to EN 15839, the ORE calculation scheme takes all five possible combinations of flanking wagons into account, see Table 5.2.

Table 5.2: Wagon combinations to be calculated in ORE B 125 scheme

No.	Front flanking wagon	Wagon under test	Rear flanking wagon
1	 Tdgs 930		 Rs 680
2	 Rs 680		 Tdgs 930
3	 Tdgs 930		 Tdgs 930
4	 Rs 680		 Rs 680
5	 Same as wagon under test		 Same as wagon under test

The wagon under test is always considered as empty, the flanking wagons are considered in empty and fully loaded state. Two different positions of the wagon under test on the track are taken into account:

1. Centered position
2. Chord position of the wheelsets (flanges of the outer wheels are in contact with the outer rail)

Finally, two different types of infrastructure are considered:

1. 250 m radius curve, twisted due to cant and track irregularity (represents railway line with narrow curves)
2. 150 m radius curve, twisted due to track irregularity, no cant (represents shunting track in station)

Interestingly, ORE report B 12 RP 49 [24] states that the 150 m full curve was chosen instead of an S-shaped track frequently found in switch connections because of the short time a vehicle is exposed to these conditions during the switch passage. However, the same report states that for vehicles with screw couplers and side buffers, this does not hold, and the conditions may be significantly less favourable in this case.

In total, the aforementioned cases result in 5 (wagon combinations) x 2 (loading state of flanking wagon) x 2 (pos. of wagon under test on track) x 2 (curve radii) = 40 combinations to be calculated for one wagon. The yielded *eLCF* is the minimum value of all 40 calculations. The calculated criteria for a derailment are:

- Climbing of a leading wheel → ratio of lateral wheel forces Y and vertical wheel forces Q ($Y/Q > 1.2$)
- Lifting of a wheel → $Q = 0$ (or $Q > 0$)

The calculation scheme of ORE B 125 takes various parameters of the UIC central coupler as input, i.e. the coupler arm length and the empirically derived behaviour of the stabilising joint (see section 5.3.2). This means that the scheme itself could in principle be applied to the DAC if the required adaptations were made. The diagrams in the appendices of UIC 530-2, however, cannot be applied to the DAC as they are based on these UIC coupler parameters.

The report on the ORE B 125 calculation scheme [24] states that 500 kN was set by ORE as minimum *eLCF* value for wagons with UIC central coupler. UIC Leaflet 530-2 [22] contains 500 kN as minimum value and 600 kN as recommended value for new wagons.

5.3 Further Considerations Regarding oLCF of DAC wagons

5.3.1 General Differences between Centre Buffer Couplers and Side Buffers

There is a general difference between the vehicle reactions caused by oLCF in trains with centre buffer couplers compared to trains with side buffers. This difference also exists on a straight track and is not limited to curves. With centre buffer couplers, a rotation around the vertical axis of the wagon is caused by acting oLCF when there is a horizontal angle between vehicles and the couplers have a spherical joint on the wagon body. The rotation increases the angles occurring between the wagons, resulting in a self-reinforcing (unstable) process. In contrast, in the same situation with side buffers, a rotation occurs that reduces the occurring angles. In this way, the system stabilises in the nominal position. Figure 5-9 shows these relationships.

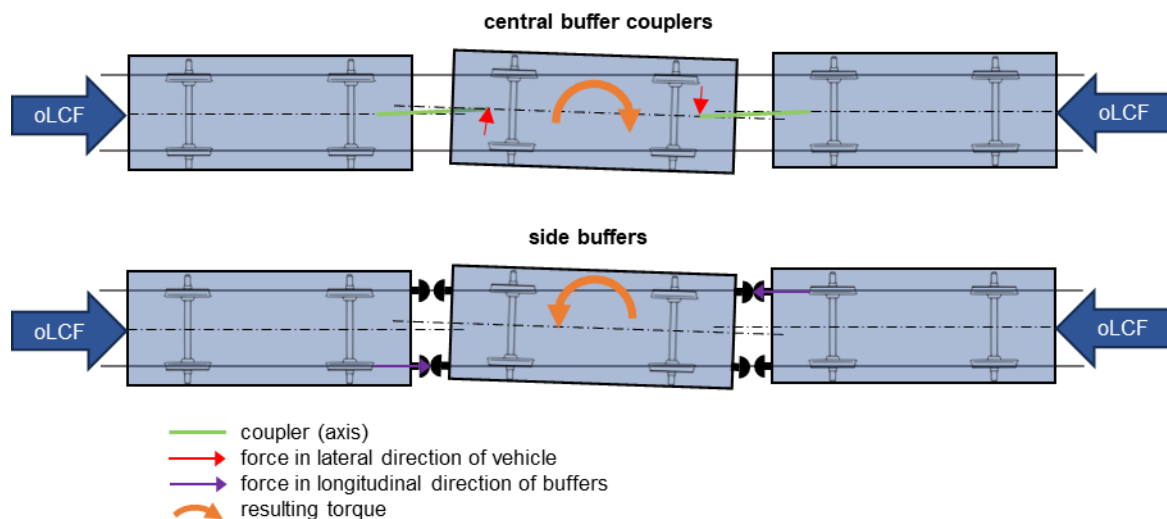


Figure 5-9: General differences between centre buffer couplers and side buffers under oLCF. Source: DB Systemtechnik

As Figure 5-9 indicates, short (often two-axle) vehicles are more prone to take an angled position within the side play between the centre lines of vehicle and track². An article about tests of the UIC centre buffer coupler in the 1960s [29] reports that the Soviet railways conducted experiments where oLCF led to derailments of two-axle wagons. This subsequently led to further experiments conducted by the German railways. Here it was found that light two-axle freight wagons derailed under high values of oLCF on straight tracks, as Figure 5-10 shows. Wagons with side buffers did not derail in the same situation.

² This side play has two main sources:

1. difference of wheel gauge and track gauge
2. side play in axle guidance, lateral suspension etc.



Figure 5-10: Derailment on a straight track during tests in the 1960s. Source: [29]

This mechanism of derailment is referred to as “buckling” and “jackknifing” by North American railways. Also see section 5.3.3 for more information on North American procedures regarding *eLCF*. [30]

The derailments in the 1960s led to ORE’s further work in this area that ultimately resulted in the ORE calculation scheme presented in section 5.2.4. It should be noted that the work was carried out over a period of more than ten years. As already mentioned above, the ORE scheme considers the 150 m and 250 m full curves for the calculation of *eLCF* for wagons with centre buffer couplers. However, the report on the calculation scheme also highlights the relevance of 150 m S-shaped curves with 6 m intermediate straights for wagons with side buffers. This is explained with the high friction forces between the buffer plates that influence the kinematic movements of the wagons.

There is no such pronounced influence of frictional forces with the centre buffer coupler. This means that the position of the wagons in curves and thus also the coupler angles responsible for the generation of lateral forces can be determined from geometric considerations. Analytic formulas for this can be found both in the report on the ORE calculation scheme [23] and in UIC Leaflet 530-1 [31]. It is important to cover both the angular positions because of curving and the angular positions because of side plays between the centre lines of vehicle and track, as shown in the beginning of this section.

5.3.2 Role of a Stabilising Joint

The results of the tests carried out in the 1960s led to extensive work on the development of special joints to connect the coupler arm to the draft gear and thus to the vehicle body. The aim of these developments was to create a joint that does not have an unstable effect as described in Figure 5-9 in section 5.3.1, but has a stabilising effect similar to the side buffers. The basic principle is visualised in Figure 5-11.

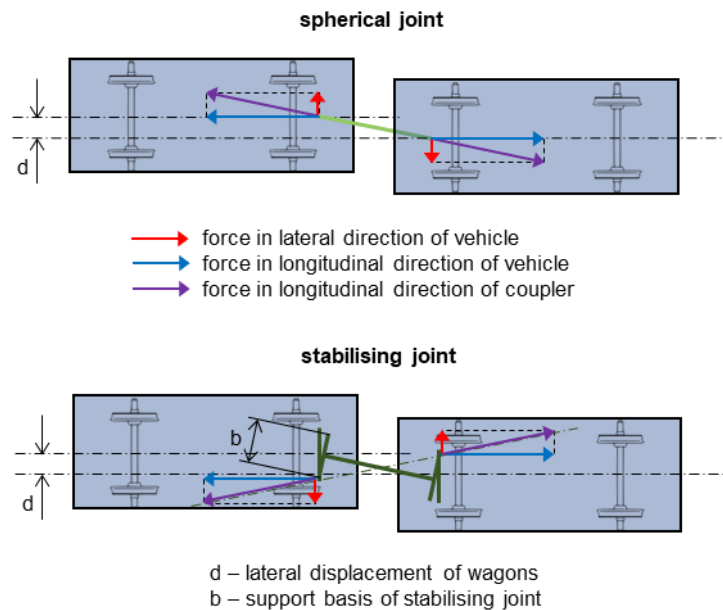


Figure 5-11: Principle of a stabilising joint

A parallel displacement of the longitudinal axes of the wagons leads to an unstable situation in an unstable joint as already shown in section 5.3.1. The resulting lateral forces lead to an increase in the lateral displacement. With stabilising joints, a lateral displacement of the wagon axes leads to a displacement of the contact points in the joint. This creates a line of acting force that is inclined in the opposite direction to the coupler arms. The resulting forces at the contact points therefore aim to reduce the lateral displacement, i.e. have a stabilising effect. This effect is present as long as the lateral displacement is smaller than the so-called support base. Depending on the design of the joint, this stabilising effect can act horizontally only or both horizontally and vertically. The latter joints are referred to as complete stabilising joints (stabilising on all sides). Figure 5-12 shows an overview of different types of stabilising joints. The bottom line shows typical diagrams for characterising the properties of the joints. Here, the ratio of lateral/vertical forces to longitudinal compressive force is plotted against the coupler angle.

Various tests were carried out to evaluate different designs of stabilising joints, which are documented in test reports [32] [33]. These tests included tests in which empty wagons were pushed between loaded wagons under constant longitudinal compressive force. The track used for this test was a passage from a straight into a 150 m full curve. The result of these tests was the finding that a complete stabilising joint is clearly superior to other designs. Furthermore, the need for such joints on two-axle wagons has been proven beyond doubt. Additionally, the tests showed that the stabilising effect of the joints is less efficient in reality than in a (simplified) theory. For this reason, efficiency levels for the stabilising effect were introduced on the basis of the test results.

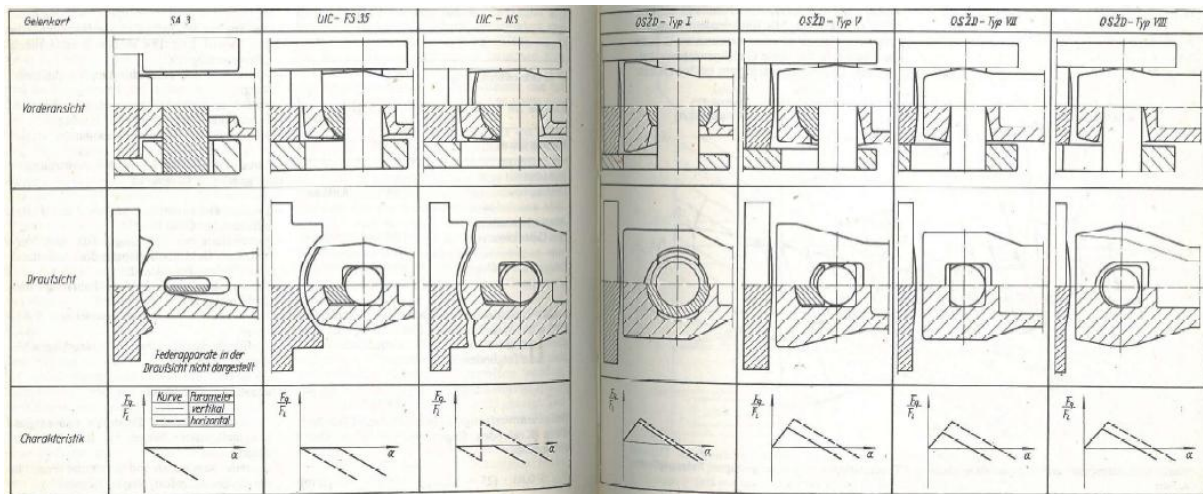


Figure 5-12: Different types of stabilising joints. Source: [34]

During the development and testing of the stabilising joints, requirements and component tests were also defined for the joints. These requirements and tests ensure that different versions of the complete stabilising joints offer the required functionality. Details on this can be found in UIC Leaflet 524 [35]. A detailed procedure for tests of positional deviations of the thrust plate under load are an example.

In the TRANS4M-R context, the stabilisation joint is commonly referred to as “interface A”.

5.3.3 Procedure for AAR couplers

On railways that use the Association of American Railroads (AAR) standard, the Janney coupler is used as a centre buffer coupler. The topics of *oLCF* and *eLCF* are also relevant here and have been addressed. For the past decades, there was and is a continuing trend towards longer and heavier trains on several AAR railways. In 1989, there were 2146 derailments in the USA alone, of which around 200 were due to longitudinal dynamics. For this reason, the AAR developed a new evaluation procedure for the curving behaviour under tensile and compressive forces. The development was based on tests with special test wagons as well as analyses and computer simulations and is described in a publication [36].

With the special test wagon, lateral forces could be introduced into the wagon under test independently of *oLCF* and coupler angles. The test unit was pulled through a 175 m full curve with a constant lateral force. This test was repeated several times with successively increased lateral force values. Vertical and lateral forces in the wheel-rail contact were recorded via instrumented wheel sets. The wagons under test were in the critical empty state. The limit values in these tests were:

- wheel unloading of 90 % or more (wheel normal force less than 10 % of the static value)
- ratio of individual lateral wheel forces Y and individual vertical wheel forces $Q > 1$ ($Y/Q > 1$)

To be able to determine lateral forces arising from *oLCF* in real situations, the coupler angles must be known. A simulation programme was developed for this purpose and validated using real tests.

The AAR Manual of Standards and Recommended Practices Part C-II [37] (section 2.1.6) defines a test to verify the safety of light wagons against derailment under longitudinal forces. The wagon under test is pulled through a 175 m curve under a force of 890 kN (200,000 pounds of force), whereby it is connected on both sides to wagons that have a length of approx. 12.8 m between the coupler arm supports (strikers). This test aims at the effect of wagons overturning under longitudinal forces. This can happen in both buff and draw direction. A tensile force leads to overturning towards the inside of the curve, a compressive force towards the outside of the curve. This latter case is illustrated in Figure 5-13.

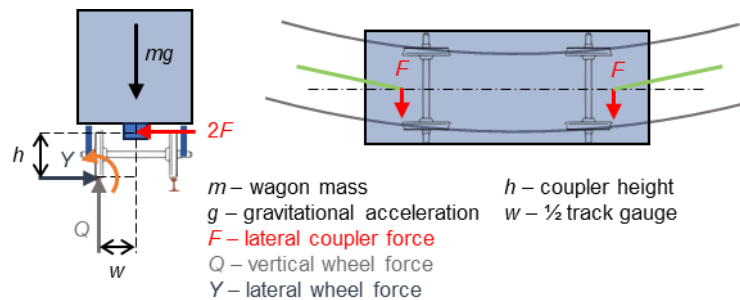


Figure 5-13: Static equilibrium at 100 % wheel unloading of one wagon side. Source: DB Systemtechnik

The limiting case (complete wheel unloading on one wagon side) can be determined statically. [36] [38] There is no torque in this situation if the following equation holds:

$$Y/Q = w/h$$

For the AAR railways, h equals to 876,3 mm (34.5 in) and w equals to $\frac{1}{2} \times 1435$ mm, resulting in $Y/Q = 0.82$. Both Y and Q refer to the sum in the bogie in this case. [37] This is consequently defined as the limit value for this test.

Despite having this test defined, there was again an increase in derailments that were related to longitudinal dynamics in Northern America in the 2000s. [30] [39] Investigations found that further increasing train lengths and masses had an influence on these derailments. Furthermore, it was found that jackknifing of the wagons in curves leads to larger coupler angles which leads to increased lateral forces and that this effect was not covered by the test mentioned above. [38] The AAR identified additional Y/Q limit values, one of them being $Y/Q > 0.75$ where the risk of wheel climbing on worn rails arises. [39]

A report on *oLCF*-related derailments in Canada [39] lists some interesting statistics:

- All of the derailed trains were mixed goods trains. No empty or loaded unit trains were involved.

- Most of the first derailed wagons were empty except for two yard locomotives (without alignment control, see below).
- 64 % of the derailed trains were longer than 2.4 km (8,000 feet)
- The lightest of the derailed trains had a weight of 4,500 t, the heaviest 17,200 t.

A report of the US Federal Railroad Administration [30] identified “difficult” wagons. These are:

- Wagons with Jacob’s bogies; not because of these articulated bogies but because of the vehicle’s light tare weight
- Wagons without bogies because of their very low tare weight
- Long wagon-short wagon combinations on turnout combinations in sidings

The findings of the investigations led to further improvement of operational rules, especially rules regarding the make-up of trains.

Couplers for AAR wagons do not have stabilising joints. In contrast to that, modern AAR mainline locomotives are required to have couplers with so-called alignment control. This feature limits the coupler angles during curve negotiation. AAR locomotives without alignment control couplers might derail under high *oLCF* values [38]. The reasoning for locomotives needing this feature while the wagons do not is given in an alignment control coupler patent [40]. Here it says that the different geometry of locomotives compared to freight wagons in connection with short coupler shanks can lead to misalignments of the couplers.

5.3.4 Existing Test Experience for Wagons with DACs

In 2020/21, the DAC4EU project carried out the first propelling tests with DAC wagons. In this phase of the project, the aim was to compare different basic types of DACs to create the basis for the selection of the future DAC type. The behaviour under longitudinal compressive forces was only one aspect of many. The various basic types of DACs were each tested in standardised three-wagon groups. The propelling tests are described in a published test report [41].

The tests were based on the procedure described in EN 15839 but deviated from it in some details. One major difference was the configuration of the test train. The same wagon types were used for this purpose as for all other DAC4EU tests in this phase. This resulted in the following DAC4EU test configuration:

- Eanos-x 059 (leading flanking wagon)
- Hbbins 306 (test wagon)
- Zags 119 (trailing flanking wagon)

In all cases, the test wagon was a two-axle wagon of type Hbbins 306. The results of these DAC4EU tests are shown in Figure 5-14. Except in the case of Wabtec, the forces shown

are the nominal LCF at which derailment occurred. In the case of Wabtec, it was the largest nominal force with critical vehicle reaction.

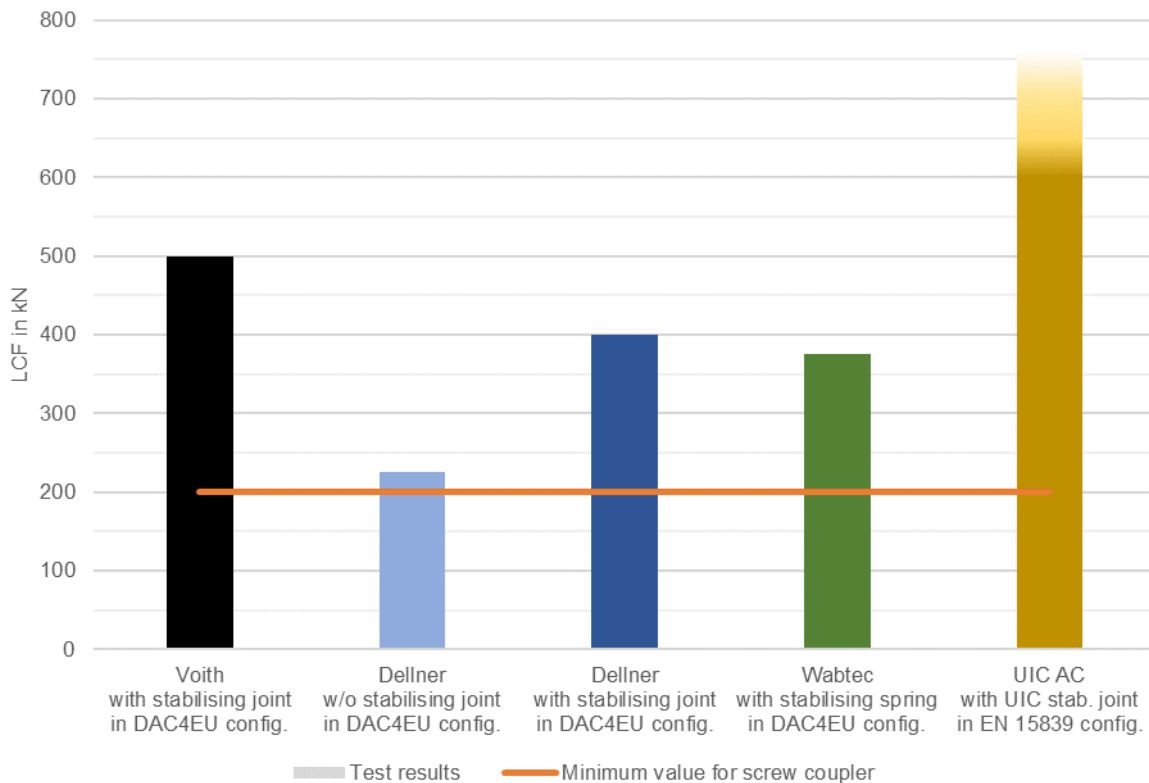


Figure 5-14: Results of propelling tests with (D)AC wagons

With a wagon of the Hbbins 306 type, propelling tests with an UIC centre buffer coupler and the EN 15839 wagon configuration were carried out in the 1990s. Here, eLCF of over 600 kN were determined. The locomotives used were unable to apply greater forces. In two publications, the authors state that based on the measured values, the eLCF could be extrapolated to at least 700 kN without exceeding the limit value. [42] [43] This case is also included in Figure 5-14 as a comparative value.

Overall, the tests conducted provide two key findings:

1. DACs with stabilising joints achieve significantly higher values in the propelling test than the minimum value required for wagons with screw couplers and side buffers.
2. There are differences both between different types of DACs and between DAC and the UIC centre buffer coupler.

The latter point was investigated further by Deutsche Bahn and the DAC4EU project. It turned out that the tested DACs (before TRANS4M-R specification) deviated significantly from the maximum values of the UIC and from the real measured values of the UIC centre buffer coupler in the tests on behaviour under load mentioned in section 5.3.2.

Simulations (see section 7.3.2) show that a DAC with small positional deviations of the thrust plate under load leads to significantly higher eLCF than one with larger positional deviations. However, verification in real propelling tests is still pending.

5.3.5 Mixed Use of Centre Buffer Coupler and Side Buffers

From investigations regarding the use of draw bars to connect wagons to permanently coupled units it is known that the mixed introduction of LCF into the wagon frame (side buffers on one wagon end, centre coupler on the other) forms a special case. Two-axle vehicles are especially critical in this regard. Further details can be found in an UIC report [44] and in EN 15839 [21].

5.4 Interim Conclusion

The above explanations show that there is currently no methodology that can be used without restriction to assess the running safety of wagons with DAC under longitudinal compressive forces. The reasons for this lie both in system-related differences between side buffers and centre buffer couplers and in different system parameters within the group of centre buffer couplers. However, it is also clear that a lot of work has already been carried out in this area in the past and that there is a large knowledge base. The critical case to be assessed is the same for all the methods presented:

- Wagon to be assessed in an empty state,
- in a curved situation, resulting in coupler angles,
- with flanking wagons that lead to particularly large coupler angles.

The assumed critical curve situation differs between the various sets of rules. Overall, empirical evidence (tests as well as dispensation based on experience), analytical calculation methods and numerical simulation methods are used for the assessment. Table 5.3 summarises this.

Table 5.3: Summary of methodologies for eLCF assessment. E = empirical, A = analytical, N = numerical

Methodology	Area of Application	Context	Type of Infra.	Type of Methodology		
				E	A	N
Dispensation from further consideration if design criteria are met	wagons w. side buffers	EN 15839	-	x		
Propelling tests	wagons w. side buffers	EN 15839	150 m S curve	x		
Simulation of propelling tests if validated simulation model available	wagons w. side buffers	EN 15839	150 m S curve			x
Calculation scheme and result diagrams	wagons w. UIC AC	UIC 530-2	150 m, 250 m full curves	x	x	
Lateral force test	AAR Wagons	AAR	175 m full curve	x	x	x

6 Virtual Test Procedure for Wagons with DACs

6.1 General Concept

The proposed methodology for evaluating the running safety of freight wagons with DAC under longitudinal compressive forces consists of three parts:

1. Execution of a high number of virtual propelling tests
2. Some real propelling tests to validate the required simulation models
3. Derivation of rules based on the results of real and virtual tests

This approach can be seen as a consistent continuation of the existing procedures and methods of evaluation. It combines various approaches mentioned in the previous section and adds the possibilities of modern multibody simulations (MBS).

To carry out virtual propelling tests, simulation models of wagons, their running gears, the couplers, and the infrastructure are needed. Figure 6-1 shows an example for a virtual propelling test train configuration.



Figure 6-1: Example for a virtual propelling test train configuration

The virtual test train configuration can then be pushed through the curve while opposite longitudinal compressive forces act on the outer wagons. These forces substitute the locomotives and braking wagons. We propose to define a 150 m S-shaped curve as the reference curve. This curve is also defined in EN 15839 and it contains a 150 m full curve which was defined in the ORE calculation scheme described in section 5.2.4.³ Figure 6-2 shows the virtual test train configuration in this infrastructure.

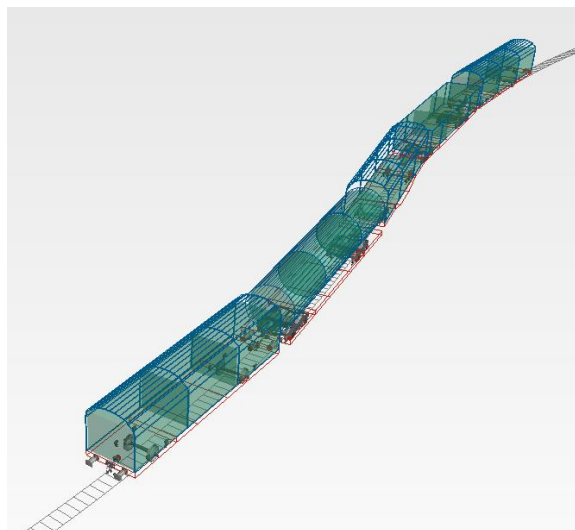


Figure 6-2: Virtual propelling test on S-shaped curve

³ The effects of twisted tracks are covered in EN 14363 and therefore not considered here.

The procedure described above enables the virtual determination of the eLCF in the modelled wagon configuration. Changing this configuration or an individual model parameter would require the creation of a new model. For the efficient realisation of virtual propelling tests with

- numerous wagons under test,
- different train configurations and
- parameter variations

the modelling is automated. For this purpose, parameterised generic base models for wagons, running gear, couplers and tracks are created and stored in databases. When creating a virtual test configuration, the parameters of the components to be simulated are loaded into the generic base models. In this way, specific models are created from the generic models. The specific models are then automatically compiled into the virtual test configuration. The procedure is described in detail in section 6.3.

The results of the virtual propelling tests will be stored in databases. The central result of the simulations is the eLCF for each wagon under test and the respective test configuration. However, detailed results of the virtual propelling test shall also be stored in the databases, for example the relevant criterion that led to the determination of the eLCF (derailment or exceeding of a limit value). The databases will be the basis for deriving generalised rules. This is described in more detail in the following section. For information on ownership and government of the result database(s) see section 8.2.

Verification and validation are essential to ensure that the virtual propelling tests deliver reliable results. This is dealt with in detail in section 6.4.

6.2 eLCF Target Values and Generalised Rules

The specific freight wagon models for carrying out virtual propelling tests can serve two different purposes. Firstly, they can represent real freight wagon types. In this case, the model parameters correspond to the parameters of the real wagons. Secondly, the specific freight wagon models can be part of a parameter variation. In this case, for example, the length of the vehicle body is varied within certain limits and in defined increments. In this case, there is not a real-life equivalent for every parameter combination.

Both cases ensure that eLCF are available for more and more parameter combinations as the number of virtual propelling tests carried out increases. The parameter combinations and the corresponding eLCF are stored in results databases. Over time, these results will make it possible to derive generalised rules. These are assignments of (minimum) eLCF to clusters of wagon parameters. This corresponds to the methodology used today in EN 15839 for wagons with side buffers. A simple example of such a generalised rule would be:

“Every two-axle wagon with a tare mass of at least 12 t and a length over couplers between 9 m and 18 m that is equipped with a DAC with stabilising joint achieves an eLCF of at least 200 kN.”

We propose a two-stage procedure for establishing such generalised rules on the basis of the virtual propelling tests. The first stage consists of proving that freight wagons with DAC achieve at least the minimum values for wagons with screw couplers in all relevant cases. With this proof, the use of wagons with DAC would be possible under the same operating conditions (same oLCF hypothesis, see sections 5.1.2 and 8.3.3) as today. Based on the test and simulation results to date, there is no indication that this proof cannot be provided. On the contrary, the test results to date (real and virtual) show eLCF of wagons with DAC (with stabilising joint) that are approx. twice as high as the minimum values for wagons with side buffers.

To extend the operating conditions of DAC trains in the future (which means increased oLCF, see sections 5.1.2 and 5.1.4), generalised rules for eLCF at a higher level are to be derived in the second stage. In this case, a greater differentiation of cases than in the first stage will probably be required. For example, there could be a case differentiation between two-axle wagons and wagons with bogies. At the present time, however, no test results are yet available from propelling tests in which DACs of the current specification were used (see section 8). For this reason, no reliable statements can yet be made on the second stage of the generalised rules. Also see section 8 for further information on this topic.

6.3 Simulation Environment

6.3.1 Overall Structure of Generic Simulation Environment

The overall structure of the generic simulation environment is shown in Figure 6-3. A data and model library is built up with input data, for example from wagon keepers and coupler manufacturers. The information and models from this library and the test configuration, specified in a control script, are used to create a specific simulation model for the eLCF calculation. With this specific model for eLCF calculation and the configured calculation algorithm, the eLCF is calculated for the defined test configuration. The results are then imported into a results database.

The simulations and the build-up of the generic models take place in a commercial multi body simulation software. The used software should be broadly available and well proven for railway applications. We use SIMPACK as it is commonly used in the European railway sector. However, any other commercially available MBS software could also be used.

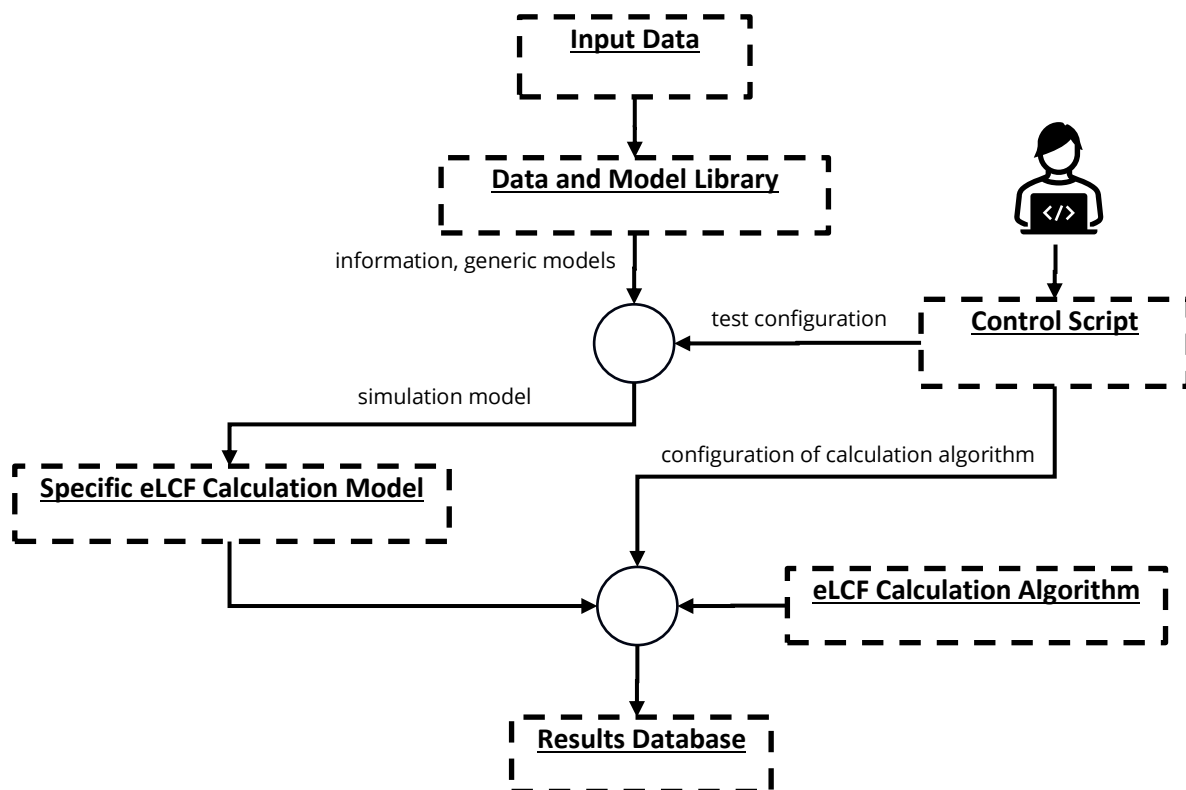


Figure 6-3: Process of eLCF calculation

6.3.2 Input Data

The input data serves as a foundation for the data and model library. It includes wagon information, coupler information and infrastructure information. The information required for wagons and couplers is provided by the wagon keepers, wagon manufacturers and coupler manufacturers. The wagon information also includes the descriptions of the running gear installed. Test infrastructure information can be provided by infrastructure managers, by track geometry measurements or on the basis of synthetically defined track configurations. Unknown input data can be supplemented by assumptions. Figure 6-4 shows an overview of input data.

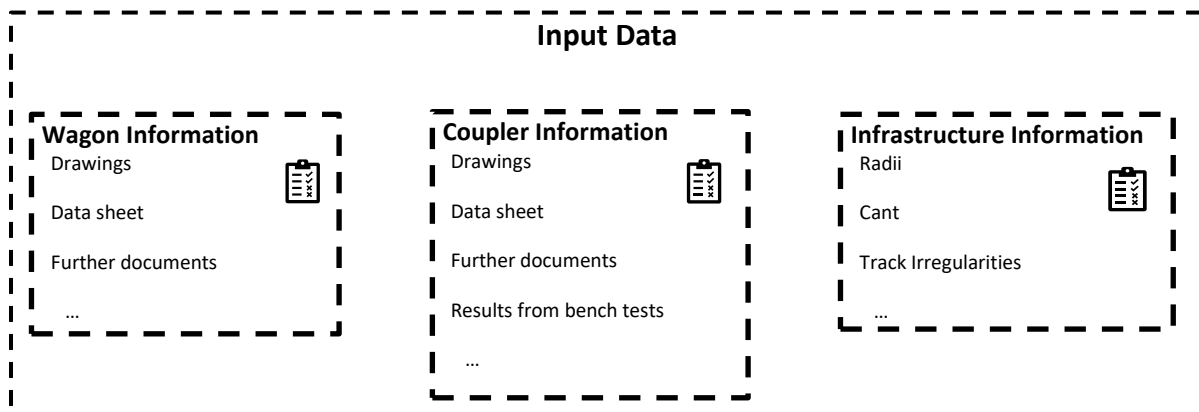


Figure 6-4: Overview of input data

6.3.3 Control Script

The test configuration and calculation algorithm are configured in the control script. The test configuration includes the topology of the train set to be tested. For example, the number of wagons in the train set and whether wagons with semi-permanent couplers, Jacob's bogies or three-axle bogies are present. In addition to the topology, the front and rear flanking wagon types, test wagon type and couplers must be defined. The control script accesses the data and model library and uses the test configuration to create the specific model for the eLCF calculation. The configuration of the calculation algorithm is also carried out in the control script. This includes, among other things, the criterion for determining the eLCF. This can for example be the exceedance of limit values according to EN 15839 or an actual (virtual) derailment. Furthermore, the configuration of the calculation algorithm includes calculation procedure (e.g. interval halving procedure) and the corresponding input parameters (start value, limit values, accuracy).

6.3.4 Data and Model Library

Figure 6-5 shows the structure of the data and model library. It contains all the information required for modelling as well as generic MBS models. The data library comprises the following databases:

- Wagon information database
- Running gear information database
- Coupler information database
- Infrastructure information database

The corresponding information is derived from the input data and is transferred to the databases in a defined form to ensure compatibility with the control script. The model library includes generic MBS models for:

- Wagon body substructures
- Running gear substructures
- Coupler substructures

- Track substructures

The control script links the required information with the corresponding generic substructures to form a specific MBS model for the eLCF calculation.

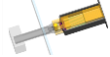
Wagon Information DB Wagon: Eanos-x 059 Mass: 21 t Running Gear: Y25 	Running Gear Information DB Running Gear: Y25Lsi-C_BA689_0 Weight: 4.258 t Wheel Diameter 0.92 m ... 	Coupler Information DB Coupler Type: XYZ Weight: 400 kg Coupler Length: 1.06 m ... 	Infrastructure Information DB Route: s_curve1 R1: 150 m R2: 150 m Straight: 6 m ... 
Generic Wagon Body Substructures 	Generic Running Gear Substructures 	Generic Coupler Substructures 	Generic Track Substructures 

Figure 6-5: Data and Model Library

6.3.5 Specific Model for eLCF Calculation

The specific model for calculating the eLCF is created from the test configuration, which is defined in the control script, and the data and model library. It is ultimately used to calculate the eLCF. The model is an MBS model consisting of various substructures, see Figure 6-6. The specific model consists of two substructures. One substructure contains the model of the entire train set, the other substructure contains the specific infrastructure model. The specific train set model comprises the substructures of the specific wagon models, which are connected by the substructures of the couplers. The wagon models are made up of substructures of the running gear and vehicle MBS-models.

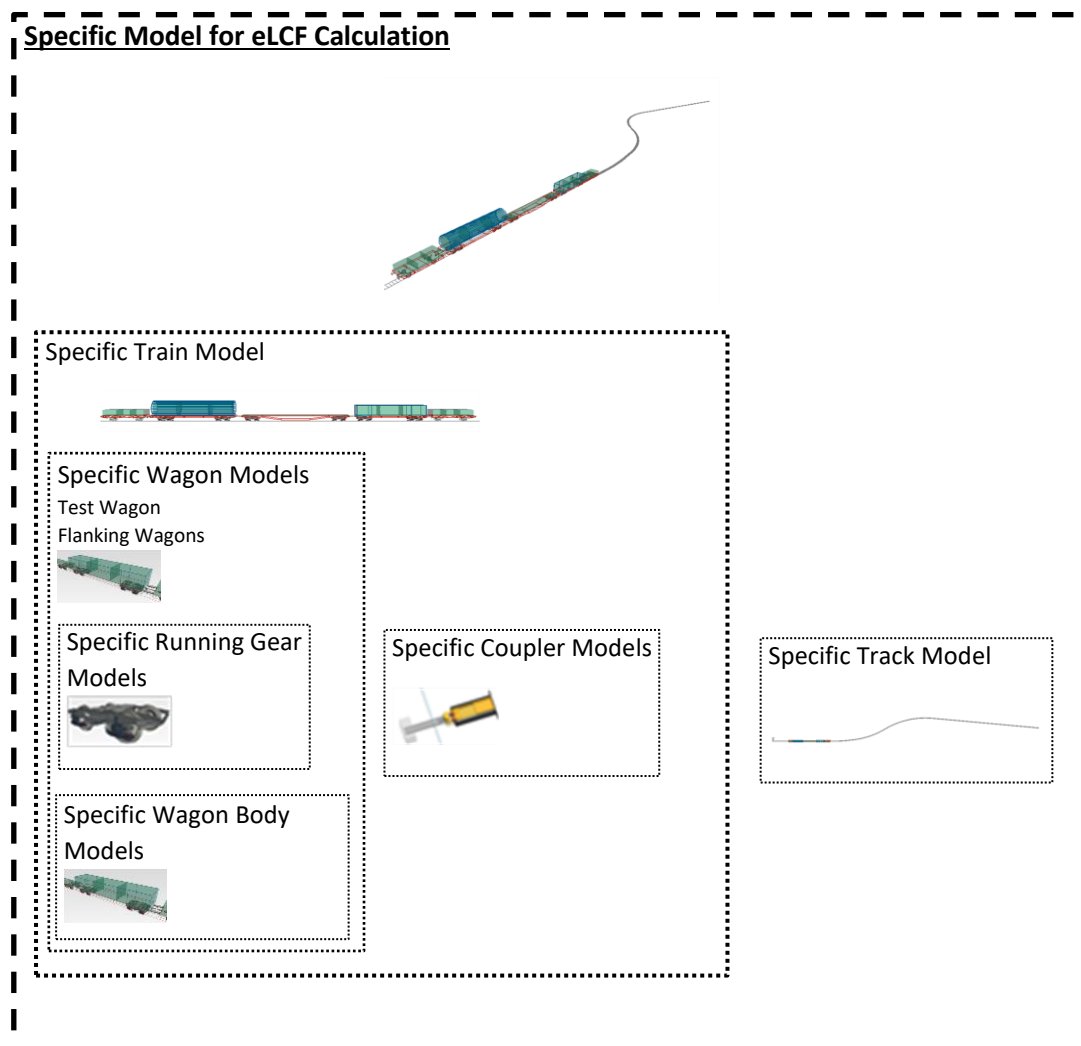


Figure 6-6: Specific model for eLCF calculation

6.3.6 eLCF Calculation Algorithm

The calculation algorithm for determining the eLCF starts the time integration of the complete model (section 6.3.5), considering the parameters from the control script. Furthermore, it processes evaluation variables, e.g. limit values from EN 15839.

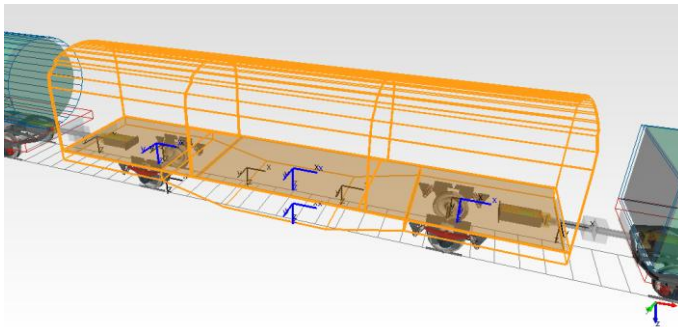
In addition to the determination of the eLCF based on the exceedance of the limit values, the eLCF can also be determined based on a derailment event in the simulation. Boundary conditions for the detection of the derailment must be given in the control script.

6.3.7 Results Database

The obtained eLCF values of simulated test configurations will be stored in the results database. Further evaluation variables will be stored as well to enable parameters studies on the entirety of results. For information on ownership and government of the result database(s) see section 8.2.

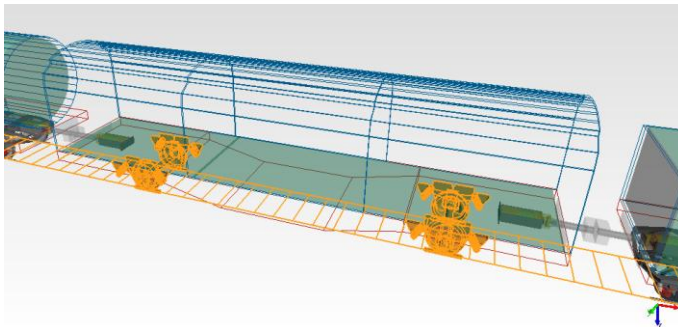
6.3.8 Generic Multi Body Simulation Models

The specific models, which are used for eLCF evaluation, are built from generic MBS-models with information from input database. For every topology that shall be investigated, a generic model must be created. These generic models are variable by a defined degree of parametrisation. At present time there are generic models for car body, running gears, couplers and tracks. In Figure 6-7 examples of different generic models are shown orange highlighted.



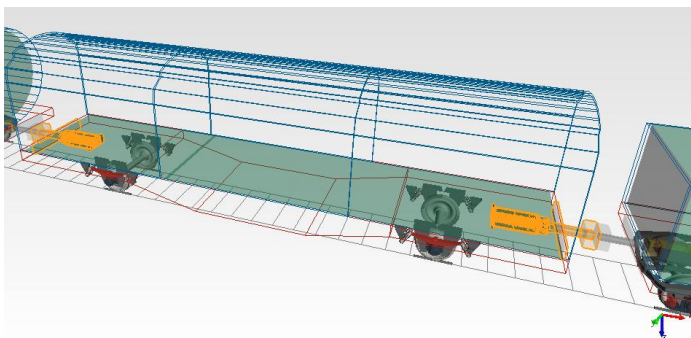
Generic Car Body

Topology: Single Wagon



Generic Running Gear

Topology: Double Link Suspension



Generic Coupler

Topology: DAC

Figure 6-7: Generic Model Topologies

As an example of parametrization the generic model of the DAC is shown in detail. The model consists of five bodies shown blue highlighted in Figure 6-8. The defining parameters to build the specific coupler model from generic coupler model are read from "Coupler Information DB". This database contains all necessary information for the specific model. On the one hand the database contains "geometry" parameters, which are defining the size of bodies or masses. On the other hand there are "force" parameters, which are defining the implemented force elements, like springs, dampers or contacts (Figure 6-9). The parameters from database are assigned to models with use of scripts.

The structure of the generic models of car bodies, running gears and tracks is basically the same as for the coupler model.

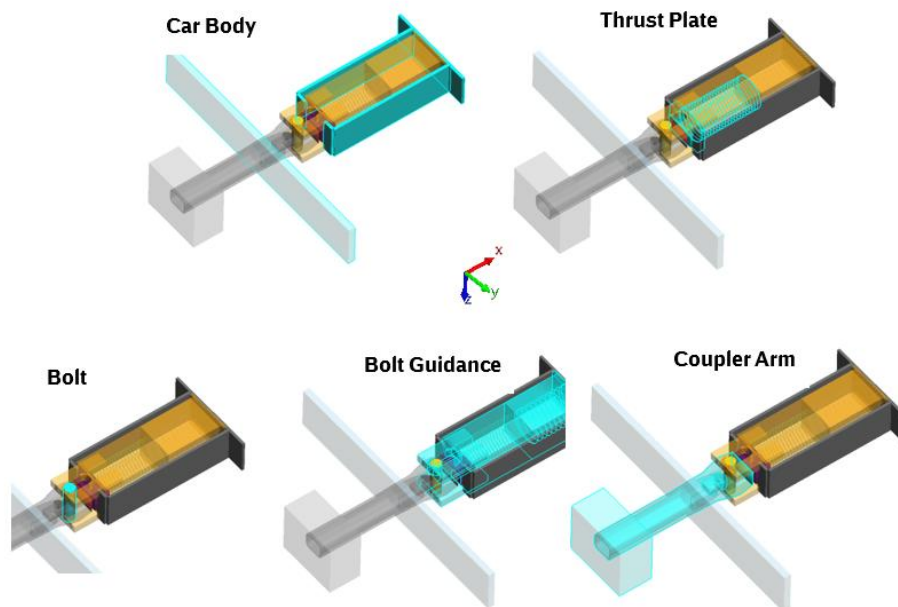


Figure 6-8: Generic DAC Model

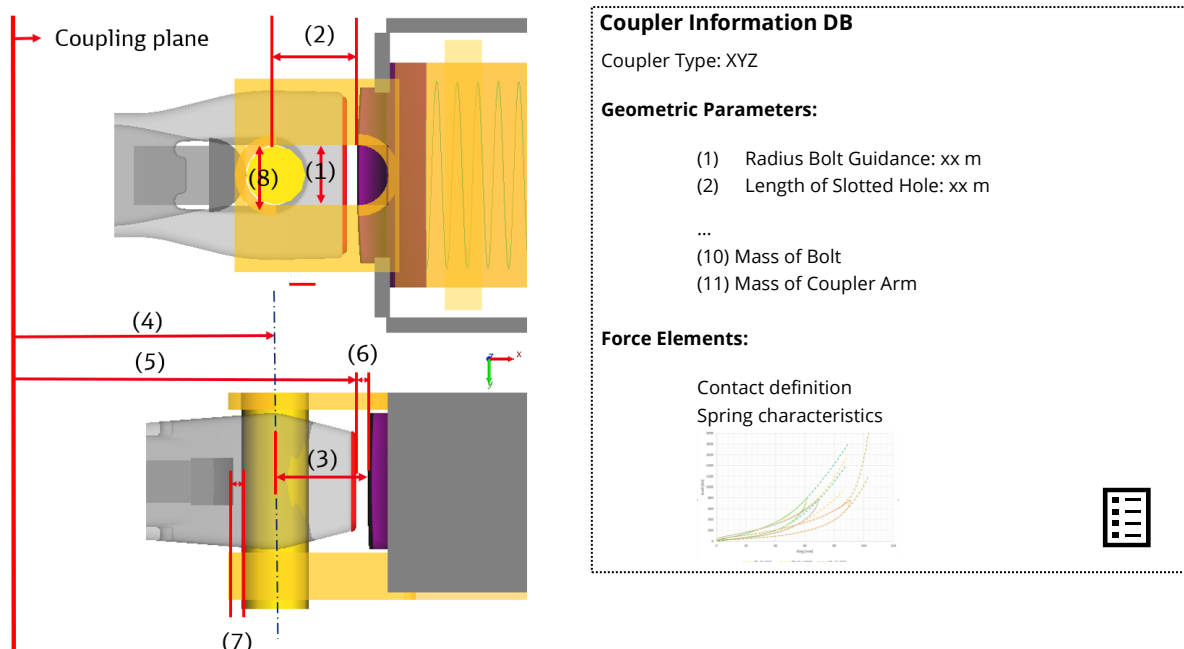


Figure 6-9: Generic Model Parameters

6.4 Verification and Validation

6.4.1 Introduction

To use simulation results in approval procedures, it must be proven that the simulations achieve the same level of confidence as would be achieved by corresponding tests. Proof is provided by defining the simulation process and by validating the simulation models by comparing simulation results with measurement data from real tests. The process definition describes, for example, which input parameters must be considered. The definition of the validation process also describes the processing of the measurement data, the evaluation variables to be compared and the permissible deviations between simulation and measurement.

The verification and validation process can be seen as a part of a risk management procedure. The European Commission Implementing Regulation No 402/2013 explains the application of the common safety method for risk evaluation and assessment. The basic process of risk management is always the same, regardless of the underlying standard, see Figure 6-10.

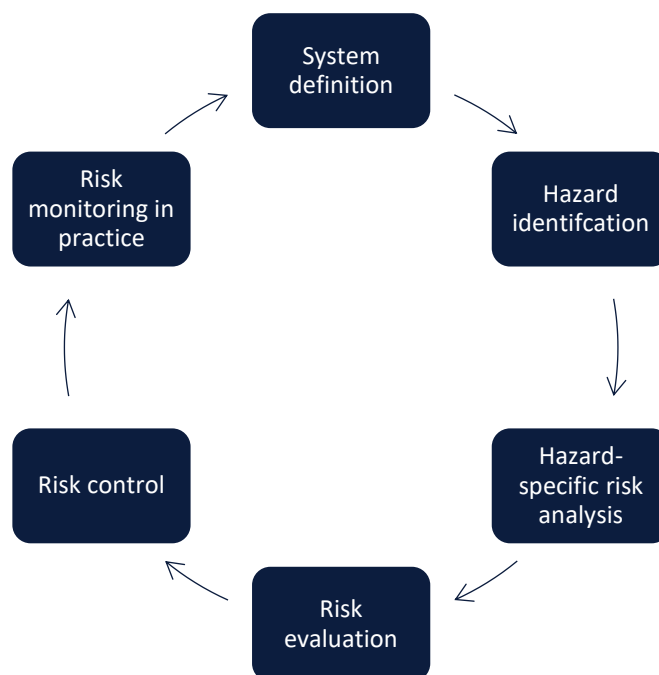


Figure 6-10: Basic process of risk management

Figure 6-11 gives a guideline for the connection between the general risk management process and the verification and validation activities to be applied on the eLCF simulation environment.

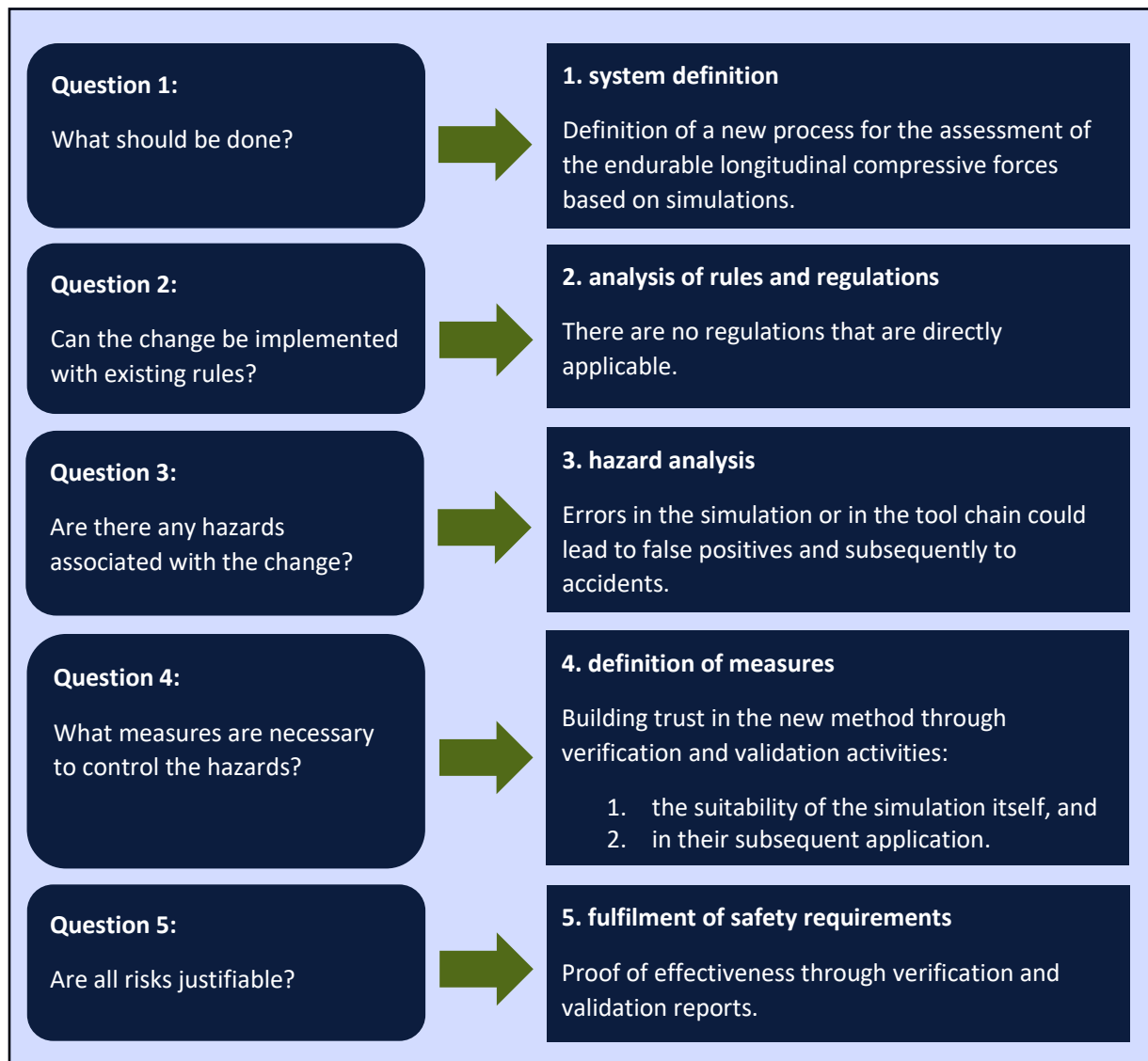


Figure 6-11: Risk management process - 5 steps to accepted risk for introduction of eLCF simulation

6.4.2 Examples for the Use of Simulations in Railway Authorisation Procedures

In the rail vehicle sector, multi-body simulations (MBS) at the current state of the art are used in the development and approval of vehicles. These simulations are a cost-effective option to expand system knowledge or, for example, to detect any design errors at an early stage in the development process. Areas of application for MBS in the rail vehicle sector include:

- Investigation of eigenvalues and their influence on vehicle dynamics
- Evaluation of stability
- Ride comfort analyses
- Running behaviour in curves
- Running behaviour under crosswind conditions
- Running behaviour under longitudinal compressive forces [45]

The use of MBS in the approval process can reduce the scope of physical tests and increase the probability of a successful test. Existing areas of application for MBS in the approval process include, for example, the verification of the running characteristics of rail vehicles (EN 14363 [28]) and the dynamic verification of compliance with railway gauge profiles (EN 15273 [46]).

The existing processes for model validation in these standards are only applicable to the topics covered in the respective standards. Therefore, they cannot directly be applied to the present task of eLCF simulations. However, standard prEN 17833 "Railway applications – Simulation Credibility" [47] is currently under development. The requirements of this standard are explained in the following chapter as they are considered for the validation process of the eLCF simulation environment.

6.4.3 Requirements of prEN17833 for Verification and Validation

This section presents the requirements of prEN 17833 [47] for verification and validation, which are considered in the present task. According to this standard, a system assessment must be carried out, which depends on the expected safety risk and the design complexity. The system assessment defines a "target credibility level" based on these two factors. The resulting target credibility level is decisive for the requirements of verification and validation. In addition to the requirements for verification and validation, the system assessment is also decisive for the requirements for the process, the organisation and the assessment of uncertainties.

Table 6.1 shows the four different levels of safety risk that are defined by prEN 17833. Table 6.2 shows the four design levels.

Table 6.1: Safety risk levels according to prEN 17833. Source [47]

Safety Risk Level	Consequences to persons or environment
1	possible minor injury
2	- no possibility of fatality, severe or minor injuries only and/or - minor damage to the environment
3	- affecting a very small number of people and resulting in at least one fatality, and/or - large damage to the environment
4	- affecting a large number of people and resulting in multiple fatalities, and/or - extreme damage to the environment

Table 6.2: Design levels according to prEN 17833. Source [47]

Design Level	Criteria
1	both system novelty and system complexity rated low
2	either system novelty or system complexity, or both, rated medium
3	either system novelty or system complexity rated high
4	both system novelty and system complexity rated high

A dedicated assessment for the eLCF simulation environment [48] yielded a risk level of 3 and a design level of 2. According to the prEN 17833 procedure, this results in a target credibility level of 3. This is visualised in Table 6.3. The requirements for verification and validation resulting from this categorisation are described below.

Table 6.3: Target credibility level of the eLCF simulation according to prEN 17833

		Design Level			
		1	2	3	4
Risk Level	1	1	1	2	3
	2	2	2	3	4
	3	3	3	4	4
	4	4	4	4	4

The term “**verification**” is defined in prEN17833 as:

“The process of determining that a simulation in its tool environment produces expected results according to the underlying model.”

The central requirement for verification at target credibility level 3 is:

“Verification shall be based on defined techniques. All key parameters shall be verified to identify and quantify errors.”

A key parameter is defined as follows:

“A key parameter is a parameter which has high relevance for an analysis. The parameter has direct significant impact on the analysis. It can be distinguished to a parameter that is only slightly connected with the context it is used in. Key parameters can be identified with a sensitivity analysis.”

Furthermore, the verification process according to prEN 17833 divided into two steps:

1. verification of the tool used → each component of the tool must be verified individually and in combination.
2. verification of the implemented model → verification of individual sub models of the system, verification of the complete model including input and output parameters.

According to prEN 17833, the aim of **validation** is:

“The aim of validation is to ensure that the reference system and simulation have the appropriate level of similarity for the functionality or the physical phenomenon to be

The requirements for validation at target credibility level 3 are:

1. the validation must be based on defined techniques.
2. the measurement data of the reference object must originate from a real system operating in a representative environment.
3. the validation points must mainly cover the application area of the reference object
4. the limit values must be determined on the basis of expert experience
5. the validation results must show agreement with the limits for the most important results.

One method for verifying the requirements for level 3 is the use of an independent expert who is familiar with the specific area of application and assesses the validation activities [48] Appendix A section 9.4.3.

In addition to the direct requirements for verification and validation, there are indirect requirements prEN 17833 regarding organisation, process, and assessment of uncertainties.

The following is specified for the **organisation**:

1. application of a competence management process with documented evidence of the competences of individuals / assigned roles within the organisation.
2. audit report with a note on the application of the competence management process.
3. independence of the persons responsible for verification and validation.

The following applies to the **process**:

1. the traceability of simulation objectives to the verification and validation results must be ensured.
2. an independent review of the simulation process must be carried out and documented.
3. defined criteria for evaluating the simulation results must be established before the simulation (quantitative values with tolerances and deviations).

The requirements for the evaluation of **uncertainties** are:

1. assessments must be made to determine the input parameters with the greatest impact on the results.
2. the variability of the system response must be determined.

6.4.4 Concept for eLCF Simulation Environment

6.4.4.1 Introduction

The verification and validation concept (V&V concept) refers to the eLCF simulation environment described in section 6.3. As mentioned in the previous section, prEN 17833 requires the assessments of:

- Verification
- Validation
- Organisation
- Process
- Uncertainties

The present deliverable focuses on verification and validation. As requirements for organisation, process and uncertainties also have an influence on verification and validation, these are also taken into account in the presented concept.

The V&V concept uses the fault tree analysis approach, which is a type of system analysis. The fault tree is used to determine the logical links between subsystem failures on all critical paths that lead to an overall system failure. A total system failure is defined here as the determination of an insufficiently accurate eLCF value. With the help of the fault tree for the eLCF simulation environment, all possible errors that lead to the calculation of insufficiently accurate eLCF values are to be detected. When the error sources are known, they shall be avoided, or their influence shall be reduced by appropriate countermeasures. These countermeasures are referred to below as verification tasks. Deviations between the calculated eLCF and the eLCF determined by real tests are nevertheless unavoidable. Measures are therefore also carried out to quantify and evaluate these differences for defined reference configurations of wagons and couplers. These measures are referred to below as validation tasks. The aim of this procedure is to establish sufficient confidence in the model.

6.4.4.2 Fault Tree Analysis

A fault tree is intended to help identify possible sources of error. It is determined from the structure of the eLCF calculation process that is described in section 6.3. Figure 6-12 shows a section of a corresponding fault tree. The identification and derivation of countermeasures (verification and validation tasks) will be explained on the basis of this section. The top-level event of this fault tree is that an incorrect result for the eLCF is taken from the results database. The cause of an incorrect result in the results database can be subsystem 2.1 “Output of eLCF calculation incorrect” or 2.2 “Corruption in results database”. The reason for a “Corruption in results database” can be the basic events “Assignment of result to test configuration incorrect” or “Data corrupt”.

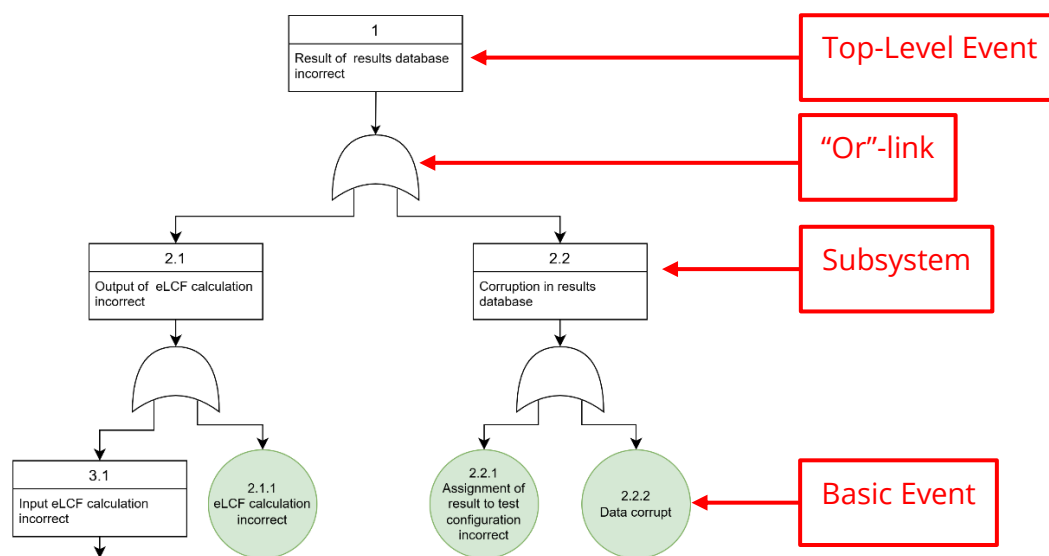


Figure 6-12: Fault Tree

Verification tasks can be derived from the basic events. For example, an incorrect assignment between the result and the test configuration in the results database is caused by an error in the interface between the result database and the output of the eLCF calculation. A verification task can be derived from this, which, once completed, proves a correctly functioning interface. Similarly, verification tasks for all the other basic events can be defined.

In addition to verification tasks, validation tasks can also be identified using the fault tree and programme structure. This applies, for example, to assumptions made during modelling or model simplifications. In order to quantify their influences, validation tasks are defined where corresponding data is available.

In cases where no measurement data is available and cannot be easily generated, simulation results can be compared with results from theoretical/analytical considerations. This is then again a verification task.

6.4.4.3 Verification Tasks

To fulfil the requirements of prEN 17833, verification must be based on defined techniques. However, prEN 17833 does not name or describe any accepted verification techniques. Various verification, validation and testing techniques are described in the “Handbook of Simulation” [49]. The techniques are categorised as informal, static, dynamic and formal. They originate primarily from the field of software engineering and, according to handbook, are also suitable for verifying simulation models. The solutions to the verification tasks should be based on these techniques. “Interface testing”, for example, is suitable for verifying interfaces. The descriptions of the verification techniques to tackle the verification tasks are documented in dedicated verification reports.

A further requirement is that all key parameters must be verified to identify and quantify errors (target credibility level 3 requirement). Key parameters can be identified with a sensitivity analysis. Parameter studies and sensitivity analyses can be carried out in the eLCF simulation environment. However, a multitude of key parameters can also be determined through existing experience and literature research. Many input parameters and their influence on eLCF are already known (also see section 5).

To fulfil the indirect requirements of prEN 17833 for verification, the independence of the verifiers must be ensured by the organisation. In addition, traceability of the verification results must be ensured via the documentation.

6.4.4.4 Validation Tasks

The validation tasks are generated from the fault tree and selected depending on the available measurement data. Individual components (springs/dampers, etc.), substructures (e.g. running gear, couplers) or complete models (simulation of a propelling test) can be validated. A validation process is defined for each type of validation. In addition to the validation process, the permissible differences between simulation and measurement must be determined. The following validation tasks have been identified:

1. validation of specific complete models
2. validation of running gear
3. validation of couplers
4. validation of individual components

The model validation process consists of the following components:

1. preparation of the measurement data for comparison
2. setting up the simulation model using the generic simulation environment
3. preparation of the simulation data for comparison
4. comparison of simulation and measurement results

Examples for validation can be found in section 7.2.

6.5 Acceptance of the Methodology

The methodology outlined in the previous chapters has been presented to officials of the European Agency for Railways (ERA) in early 2026. They signalled that the results of simulations according to the methodology can be used for vehicle authorisation if the required target credibility level according to prEN 17833 can be met.

7 Results of Virtual Tests with DACs

7.1 Introduction

This section shows exemplary results of the eLCF simulation environment. The procedure of validation is presented using all available real-life propelling test data. Large parts are explained using test data from the DAC4EU project from 2020 and 2023 as this data was available early in the process. Additionally, exemplary results for the FP5DACtiVate test campaign in 2025 are presented.

7.2 Validation

This chapter deals with the comparison of measurement results from propelling tests with simulation results generated from models built by using the eLCF simulation environment. The following sections contain a brief description of the tests carried out, modelling details, exemplary comparisons of individual evaluation values from measurement and simulation and a discussion of the results.

7.2.1 DAC4EU Tests 2020

In 2020, propelling tests were carried out with an empty two-axle sliding wall freight wagon (Hbbins306) as test wagon and four different kind of couplers. In front of the test wagon was a loaded flanking wagon of type Eanos-x059 and in the rear of the test wagon was a loaded flanking wagon of type Zags119 (Figure 7-1). This configuration (not according to EN 15839, see section 5.3.4) was pushed through an S-curve shaped track with a nominal radius of 150 m and a 6 m straight in between these curves. The LCF was induced by braking units in front of the Eanos-x059 in combination with two pushing locomotives type BR232 which were directly coupled to the rear flanking wagon Zags119. The train was equipped with measuring devices to record data for selected evaluation values. A detailed description of these tests can be found in the associated report [41]. Table 7.1 shows the test runs and simulations, for which the comparison between measurement and simulation is done. The runs mainly differ in LCF. The simulations with Dellner coupler were done with 250 kN and 350 kN LCF, the simulations with Voith coupler were done with two different modelling approaches of stabilising joint. The simulation model is shown in Figure 7-2.

Table 7.1: Compared Tests and Simulations 2020

Test	Simulation	Coupler	Test Wagon	Comment
486 - 493	D250kN_compl D350kN_compl	Dellner	Hbbins306	No stabilising joint
539 - 551	V500kN_compl V500kN_DoF	Voith	Hbbins306	With stabilising joint

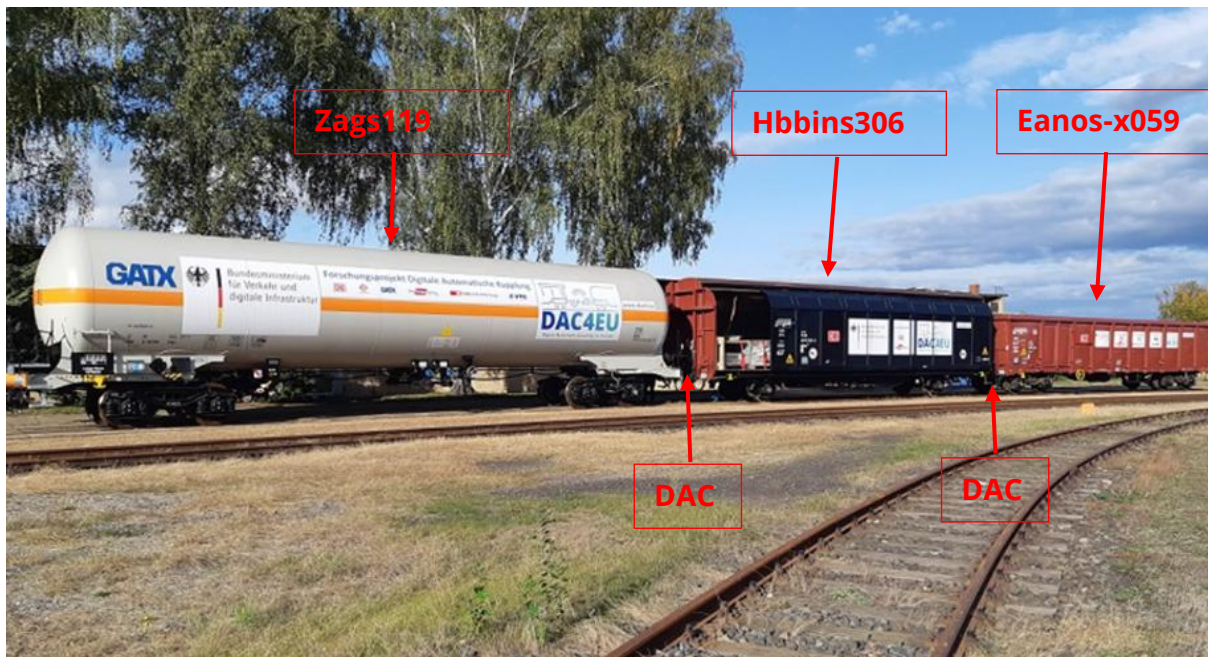


Figure 7-1: Test Setup 2020

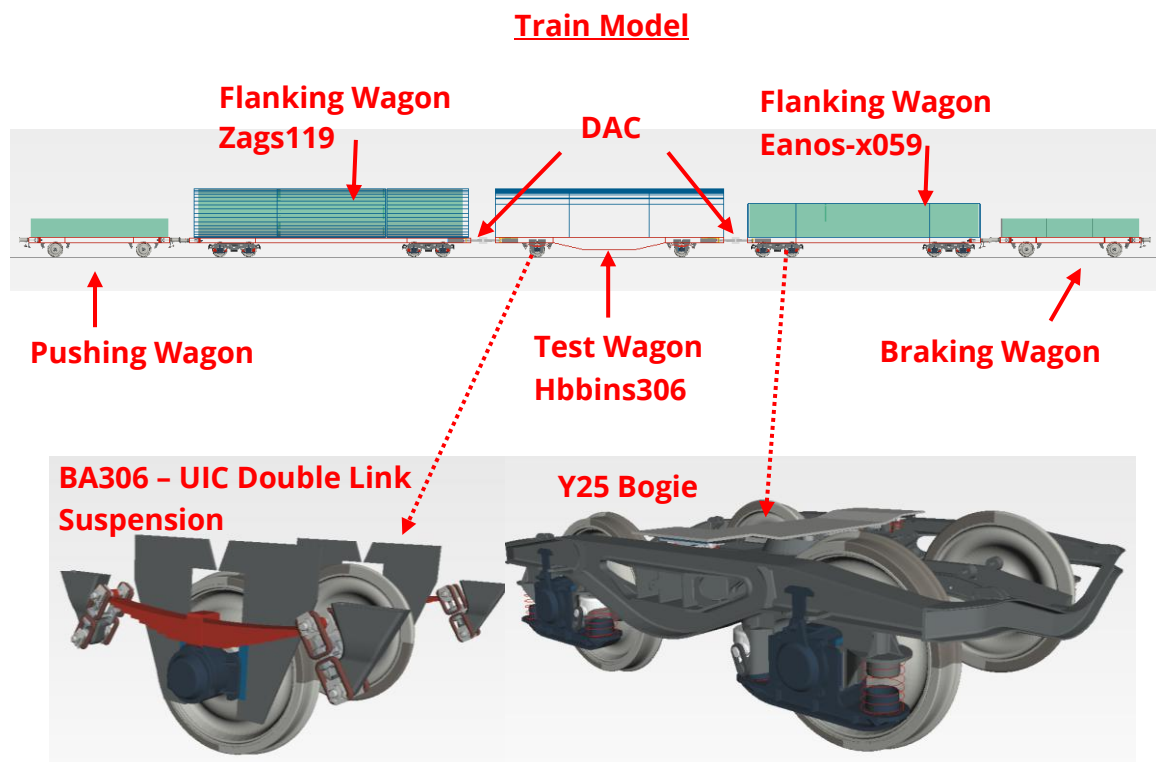


Figure 7-2: Train and Running Gear Models

The models of the flanking wagons consisting of car bodies with consideration of torsional stiffness and simplified Y25 bogie models. The car body model of the Hbbins306 also respects torsional stiffness. The running gear is a complex model of a UIC double link

suspension where kinematics, plays between wheelset and wheelset guidance, guidance stiffnesses and spring characteristics are considered (see Figure 7-2).

The wheelsets consider the nominal wheel diameter, the wheel profile EN13715:2020 – S1002 and a friction coefficient of 0.4 in rail wheel contact.

The tests runs 486 – 493 with the Dellner coupler were carried out with a joint without a stabilising function. Therefore the modelling of this coupling device can be done with a relatively simple approach in comparison to the coupler with stabilizing joint. This simple approach also leads to less result influencing parameters from couplers side. The Voith coupler has a stabilising joint, which is considered in the submodel of the coupler. Not all parameters which are influencing the stabilising function of the Voith coupler joint are known. One of the most important parameter for stabilising function, beside the geometrics, is the possible rotational thrust plate movement around vertical ($\Delta\gamma_{TP}$) or lateral ($\Delta\beta_{TP}$) axis (see Figure 7-3). Modelling parameters for thrust plate rotational movement are derived from bench tests [50] with an identically constructed coupler. Most of the modelling parameters are derived from technical drawings, data sheets or bench tests. Assumptions are made for unknown but necessary input parameters.

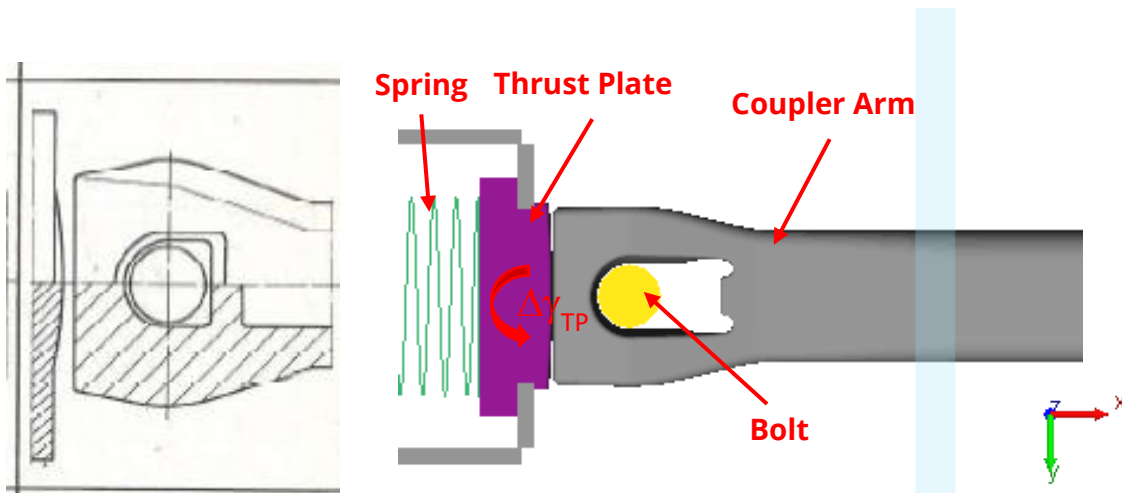


Figure 7-3: DAC-Model and Thrust Plate Angle

The modelling of the track respects a constant track gauge of 1455 mm (specification for test according UIC530-2 is 1450 – 1465 mm), no superelevation nor track irregularities are considered. Curvature of track model is shown in Figure 7-4. Due to the infrastructure of the Goerlitz test track a switch in front of the S-curve is also included. The rail profile is set to EN13674-1 60E1.

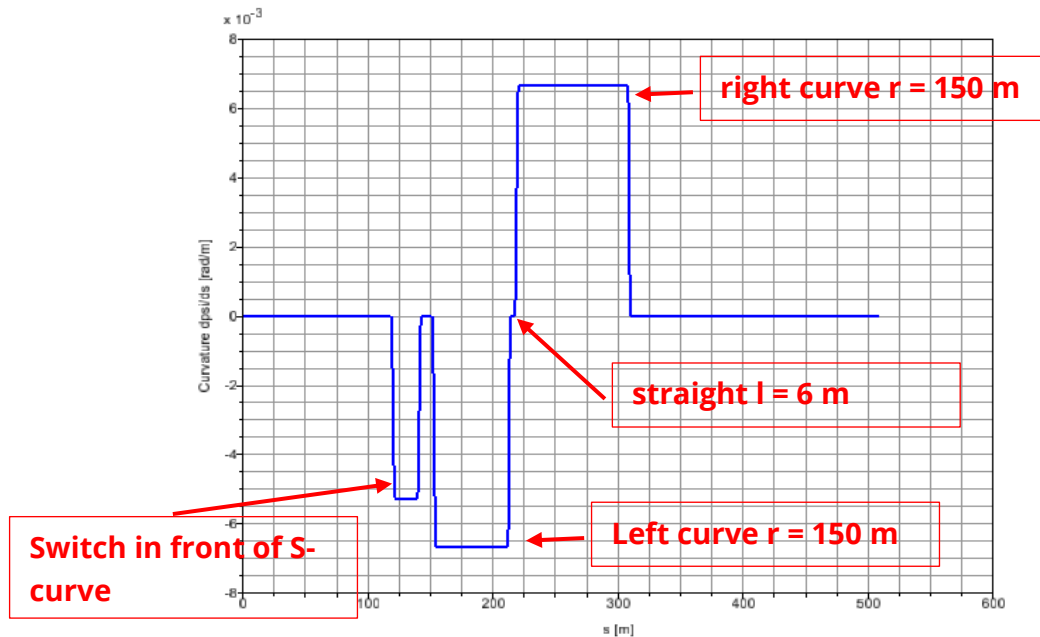


Figure 7-4: Curvature Simulation Model

The comparison focusses on the comparable evaluation values for eLCF calculation (see 5.2.3). Instead of axle box forces, lateral wheelset forces will be compared. Measurements for axle guard deformations are not available.

The first comparison is about the Dellner tests without stabilising joint. Figure 7-5 shows the lateral wheelset forces of the measurements of test runs with Dellner coupler 486 – 493 (dotted lines) and the simulation results with Dellner coupler (solid lines). The signals of the lateral wheelset forces are filtered with a 20 Hz LP Butterworth filter 4th. order and with a sliding mean filter with window length 2 m and step length 0.5 m. Section “1” is the left curve of the S-curve, section “2” is the right curve of the S-curve. By comparing test runs “D492” and “D493” with specified LCF of 225 kN to simulation “D250kN” with an LCF of 250 kN (orange solid line), there is a good correlation in amplitude and phase for both wheelsets of the tested wagon. During Test “D493” a derailment of the first wheelset happened in the left curve in front of the straight (see Figure 7-5 (3)). The outer wheel climbed up and derailed. In simulation with an LCF of 250 kN the derailment was not reproducible even though lateral (see Figure 7-6 (1)) and vertical (see Figure 7-7 (1)) wheel forces are showing good correlation. A reason for those differences could be, that track irregularities and rail-wheel profiles were not considered in simulation. Because of the occurring high lateral forces in tight curves the rail profile of the Goerlitz test track shows heavy wear (see Figure 7-8).

A simulation of Dellner setup with 350 kN of LCF (“D350kN”) shows a derailment at the beginning of the right curve. Critical wheel lift of the inner wheels (see Figure 7-9 (1)) in combination with full unloading of vertical wheel forces at inner wheels (see Figure 7-7 (2)) leads to the assumption of an “overturning” movement towards the outside of the

curve as mentioned in chapter 5.3.3. This simulation stopped because of a derailment, limit values for evaluation values were already exceeded before derailment. In this example the lateral wheelset forces of both wheelsets exceed the limit value of 72.7 kN before derailment (see Figure 7-5 (4,5)). Therefore the 350 kN LCF must not be interpreted as eLCF for the Dellner coupler. The calculated eLCF of the Dellner coupler by the algorithm of the simulation environment is at 325 kN. For more details (see section 7.3.2).

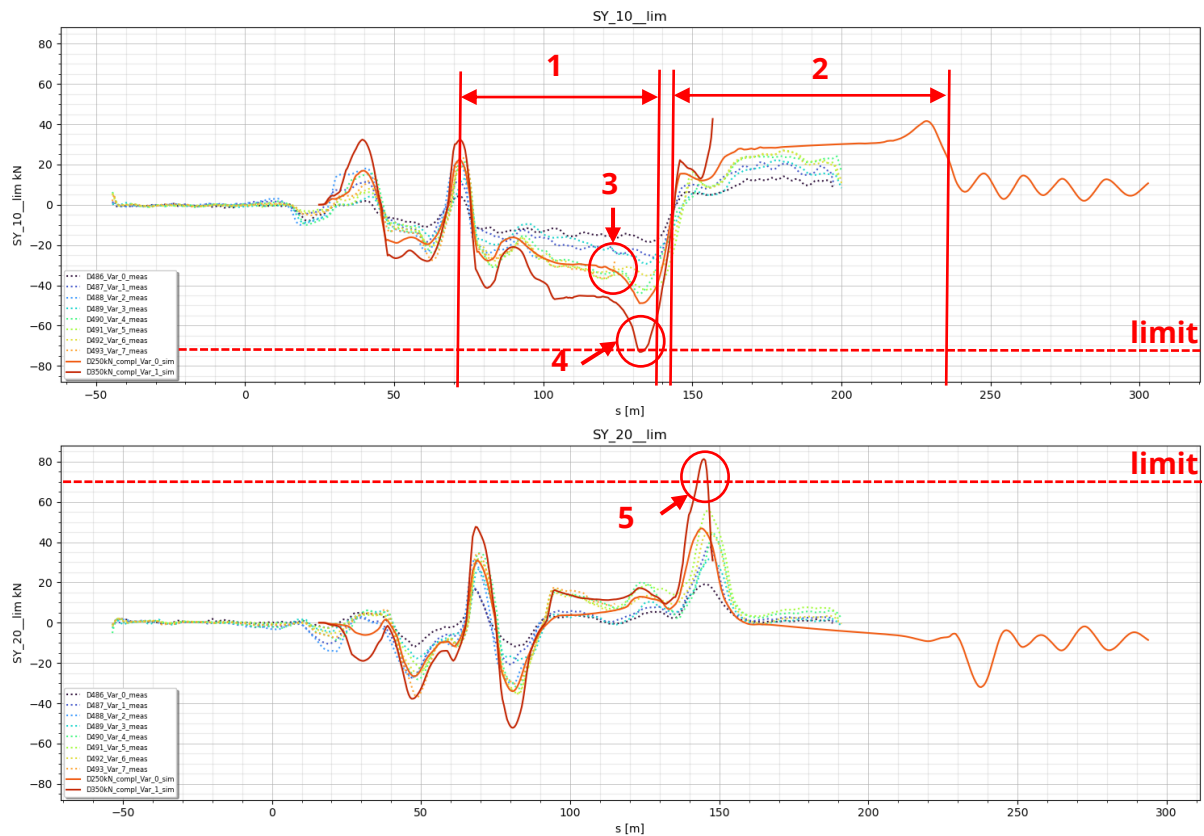


Figure 7-5: Dellner 2020 Lateral Wheelset Forces

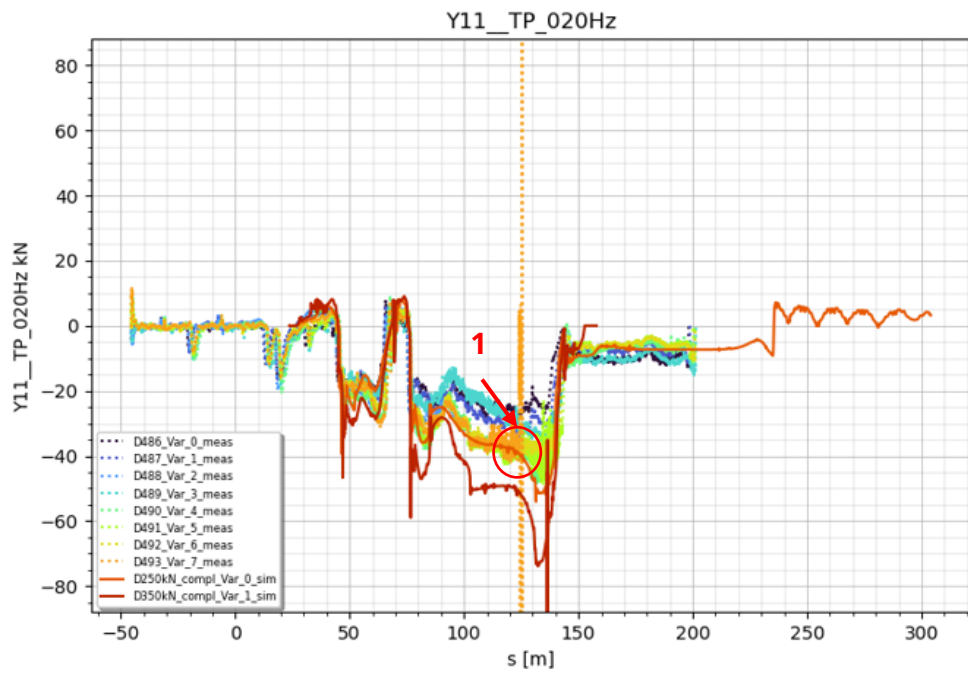


Figure 7-6: Dellner 2020 Lateral Wheel Forces Front Right

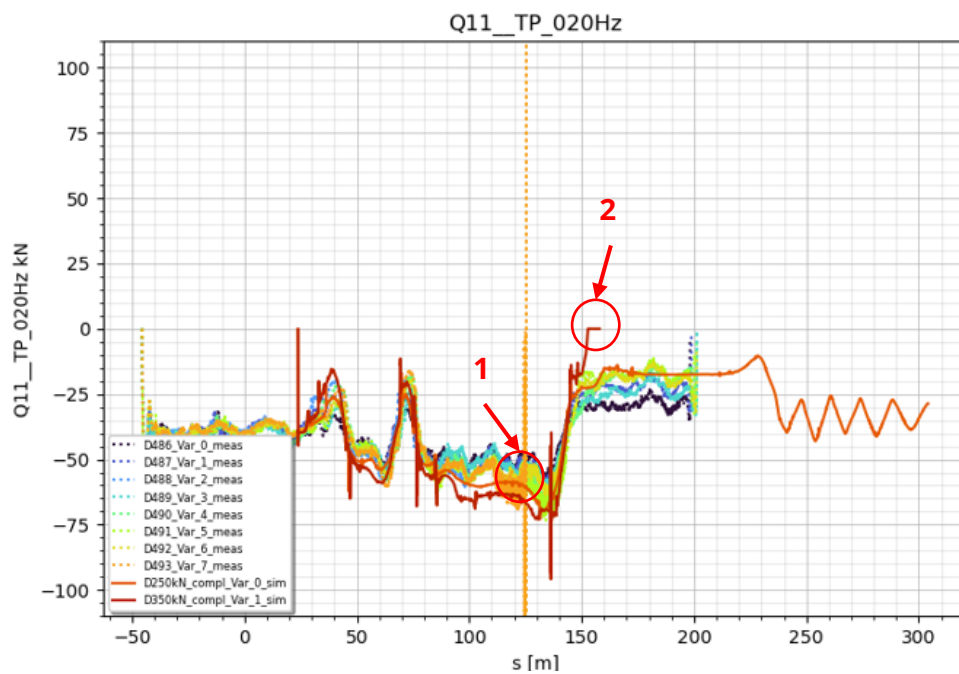


Figure 7-7: Dellner 2020 Vertical Wheel Forces Front Right

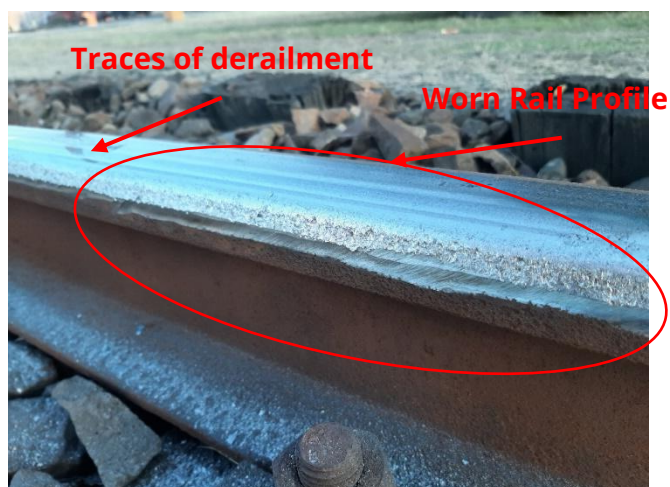


Figure 7-8: Wear of Rail Profile Outer Rail Left Curve

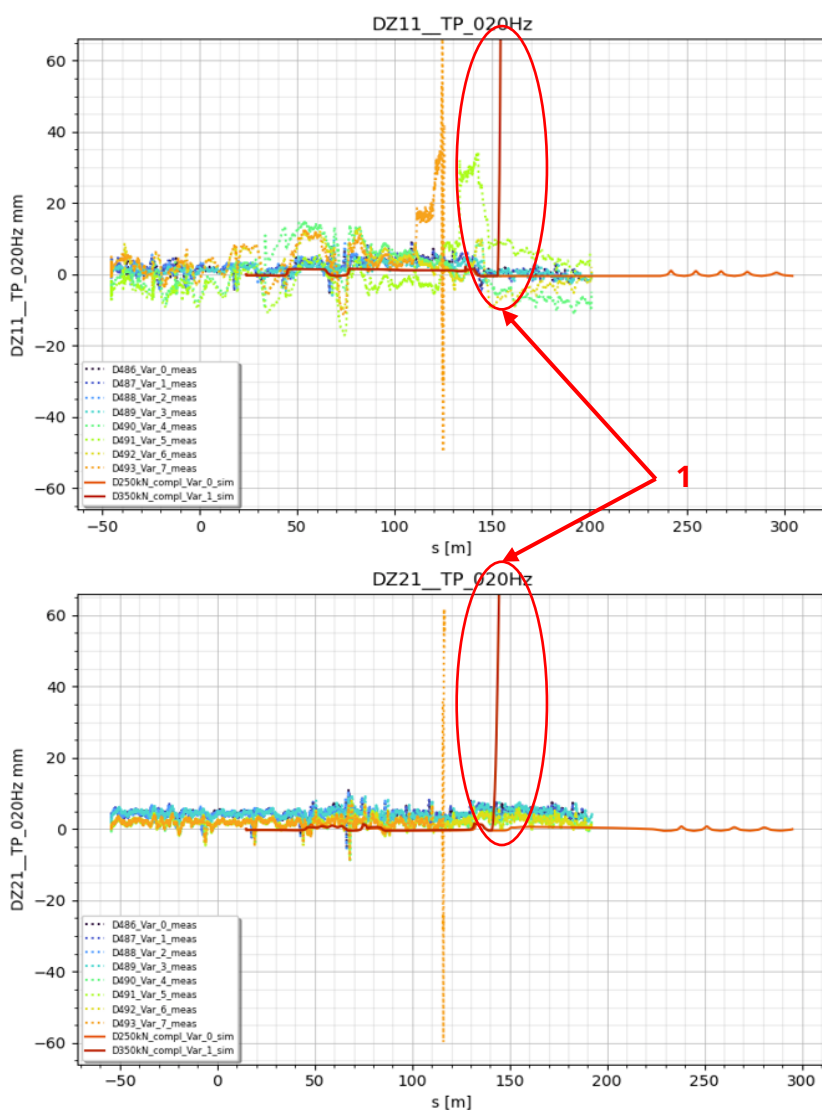


Figure 7-9: Dellner 2020 Wheel Lift

The following plots show the results of the test runs 539 - 551 with Voith coupler with stabilising joint (dotted lines) in comparison to simulation results “V500kN_compl” and “V500kN_DoF” (solid lines). During the tests LCFs from 150 kN to 500 kN were induced. In the simulation the LCF is at 500 kN. The simulation variants differ in possible degree of freedom between bodies of the coupler. The configuration used in model “V500kN_DoF” shall represent a coupler configuration with rather high values of play but must not be interpreted as worst case. In contrast the variant “V500kN_compl” has no representation of play between chosen bodies. This variation should show the influences of different modelling approaches on the evaluation values but must not be interpreted as worst case conditions in either way.

Figure 7-10 shows the lateral wheelset forces. The signals of the leading wheelset SY_10 showing significant differences in phase (see Figure 7-10 (1)) and amplitude (see Figure 7-10 (2)) between simulation and measurement. The signals of the second wheelset matching better, especially regarding the maximum occurring values in S-curve (see Figure 7-10 (3,4)) and phase. By comparing simulation variants among each other, the different modelling approaches are leading to significant influences in amplitude and phase of signals. Therefore, detailed information about possible plays between bodies of DAC are necessary to represent the stabilising function more precise.

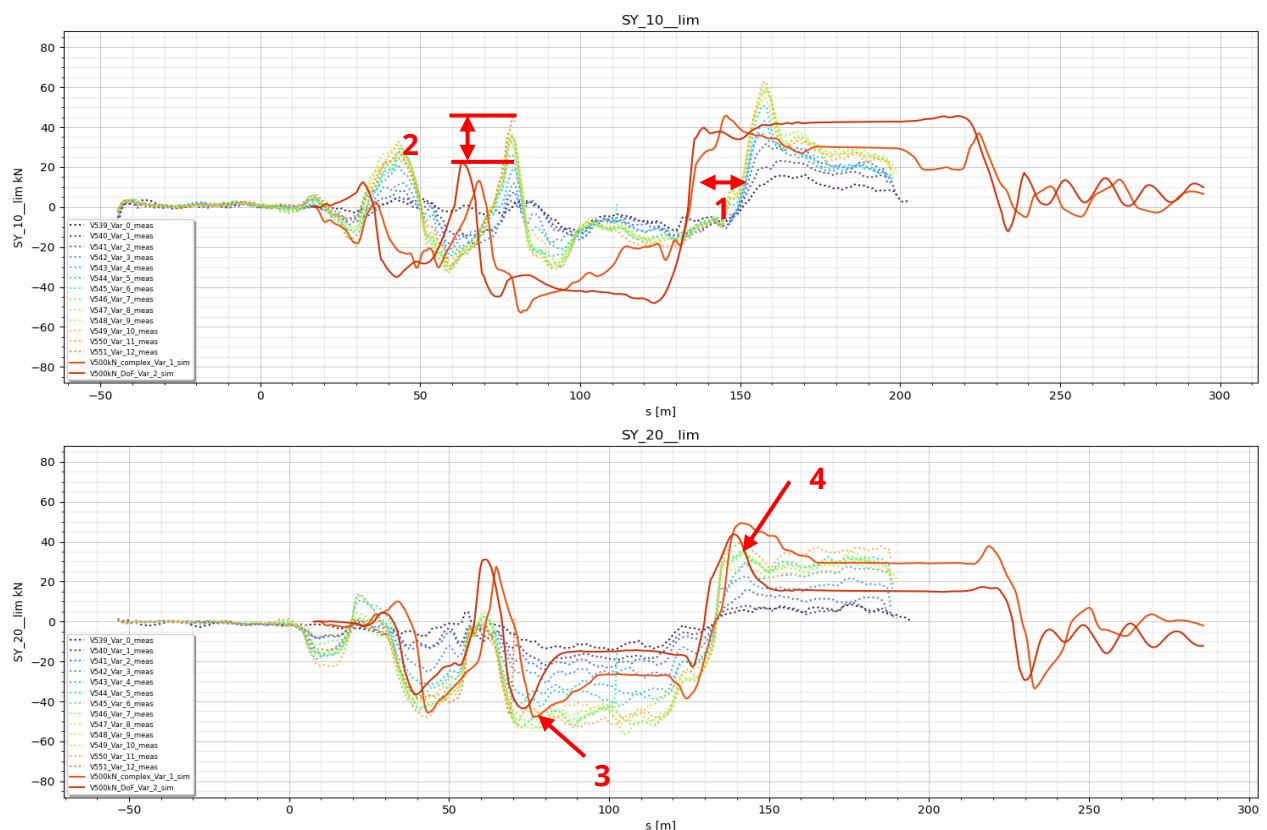


Figure 7-10: Voith 2020 Lateral Wheelset Forces

Comparing the lateral wheel forces, which are shown in Figure 7-11, significant differences between measurements and simulation are shown. Reasons for deviation may be insufficient detailed modelling of the coupler or insufficient modelling of running gear. While the running gear model has shown reliability, because the same model was used in the Dellner simulations, it is also possible that the test object may differ from nominal values in example in wheelset guiding influencing parameters. This may be possible, because two different Hbbins306 wagons were used as test wagons for Dellner and Voith tests in 2020. Additional measurements concerning wheelset guidance would deliver necessary information for evaluation.

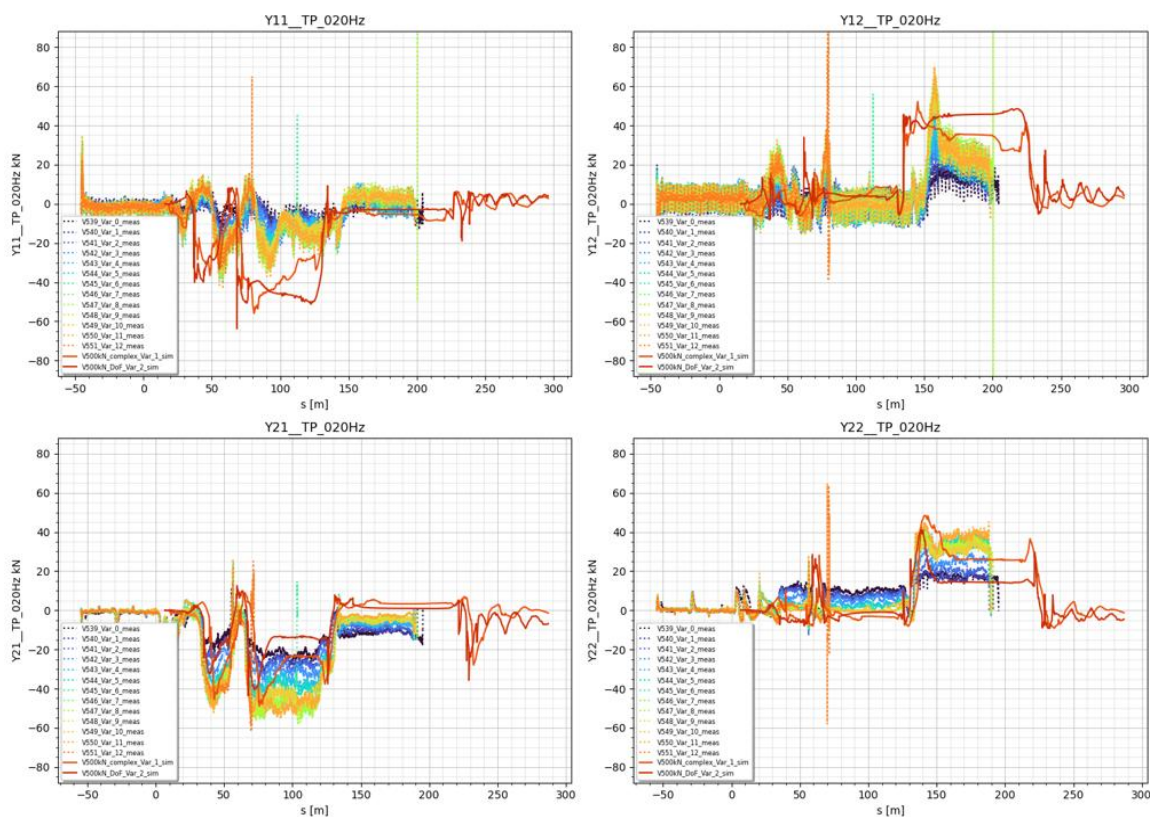


Figure 7-11: Voith 2020 Lateral Wheel Forces

During test “V551” a derailment happened with 500 kN LCF. The derailment happened at the entrance of the first curve of S-curve. Neither of the simulation runs with 500 kN LCF lead to derailment. The calculated eLCF with the algorithm of the simulation environment is 540 kN for the “V500kN_complex” model configuration more details in section 7.3.1.

7.2.2 DAC4EU Tests 2023

In 2023, propelling tests were carried out with an empty Uas wagon with side stakes as test wagon. In contrast to previous DAC4EU propelling tests, the wagon under test was a four-axle bogie wagon. The coupler used in this test was, concerning the stabilising function, the same type as used in the Voith tests in 2020. The coupler model is identical to the model used in simulations “V500kN_compl” (see section 7.2.1). In front of the test wagon was a loaded flanking wagon of type Eanos-x059 and in the rear of the test wagon was a loaded flanking wagon of type Zags119 (Figure 7-12). The test track was the same track as used in tests in 2020. The LCF was induced by braking units in front of the Eanos-x059 in combination with two pushing locomotives type Vectron Dual. The train was equipped with measuring devices to record data for selected evaluation values. Further details to the tests can be found in report [51]. Table 7.2 shows the test runs and simulations, for which the comparison between measurement and simulation is done. The runs mainly differ in LCF. The simulation was done with 500 kN of LCF.

Table 7.2: Compared Tests and Simulations 2023

Test	Simulation	Coupler	Test Wagon	Comment
001D,002D,009D,014D,019D	015D_sim	Voith	Uas	With stabilising joint



Figure 7-12: Test Setup 2023

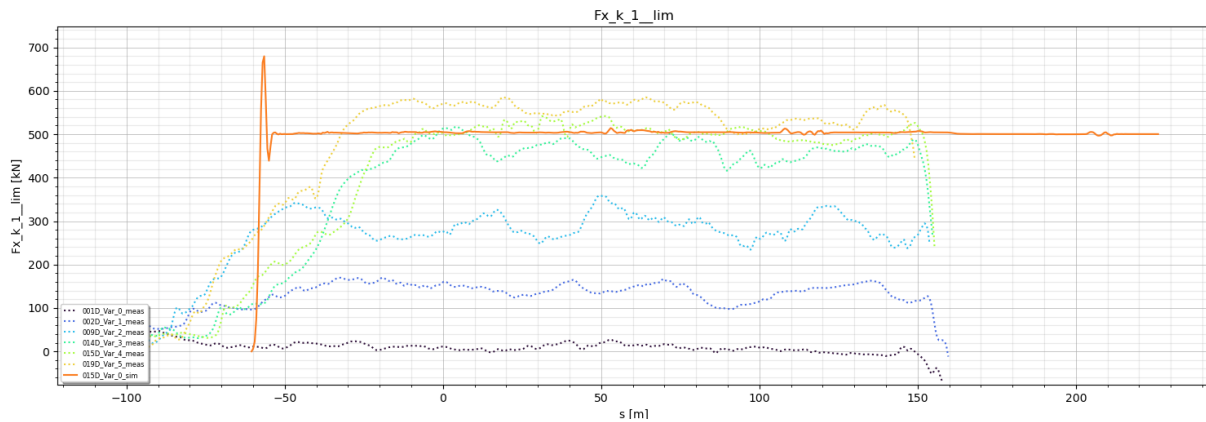


Figure 7-13: Voith 2023 Induced LCF

Figure 7-13 shows the induced LCF during tests (dotted lines) and simulation (solid line). Comparable variants regarding induced LCF are test run “015D_Var_4_meas” (light green) and “015D_Var_0_sim” (orange). During test runs a wide range from 0 kN to 550 kN was induced.

The line graphs in Figure 7-14 show the lateral wheelset forces of the Uas test wagon. The simulation results of the lateral wheelset forces representing the lateral wheelset forces from the test runs better compared to Voith 2020 comparisons, even though the 2020 comparisons were done with the same submodel of coupler. Especially the occurring forces on the leading wheelsets (SY_10, SY_30) of the bogies while entering first (LC: left curve) and second (RC: right curve) curve of S-curve are on the same level comparing measurement and simulation results (see Figure 7-14 (1,2)). The lateral wheelset forces of the second wheelsets (SY_20, SY_40) of the bogies are showing a qualitative alignment between simulation and measurement. The amplitudes at curve entrance between simulation and measurement for the second wheelsets have larger differences than for the leading wheelsets (see Figure 7-14 (3,4)).

In Figure 7-15 the wheel lift of the wheels of the leading bogie is shown. In general, there is a good correlation between simulation (solid line) and measurement (dashed lines), when considering that there are no track irregularities in simulation model. Additionally, no critical wheel lift occurs neither in simulation nor in one of the test runs.

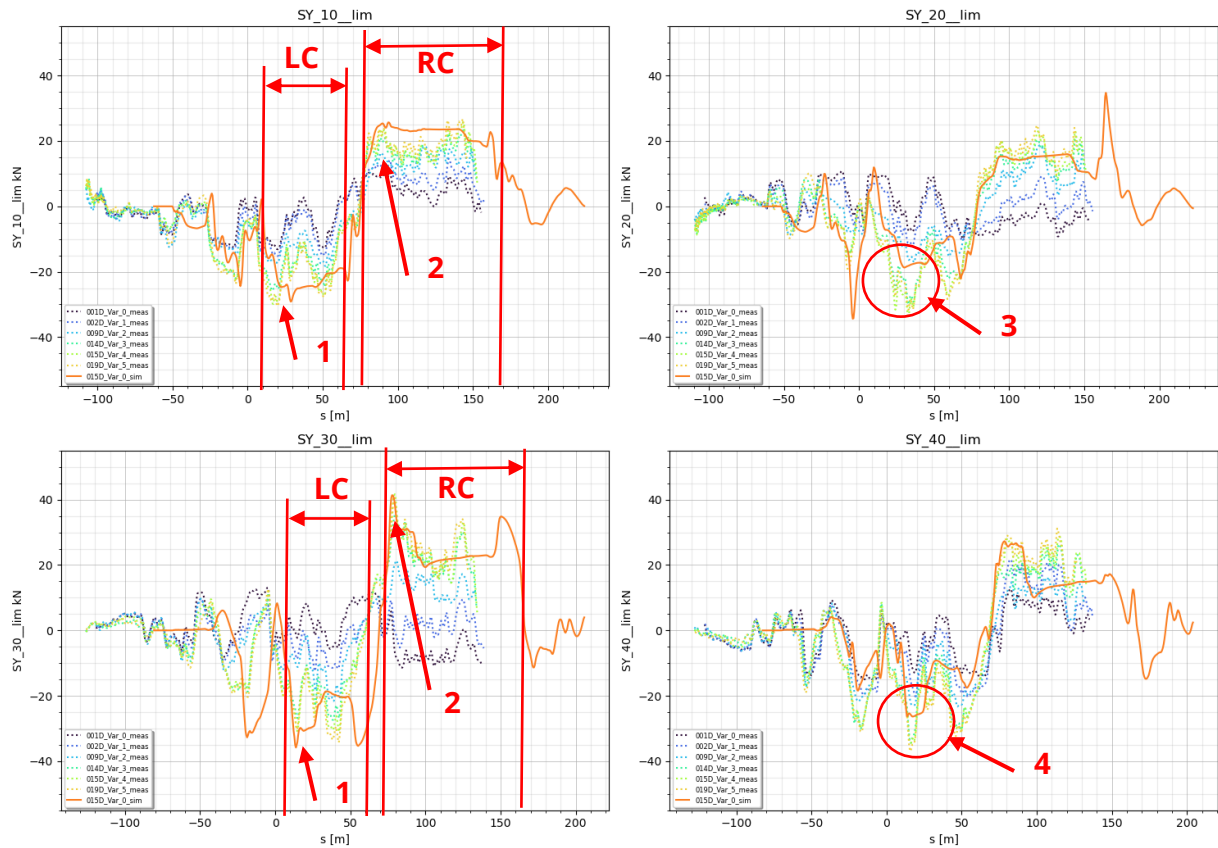


Figure 7-14: Voith 2023 Lateral Wheelset Forces

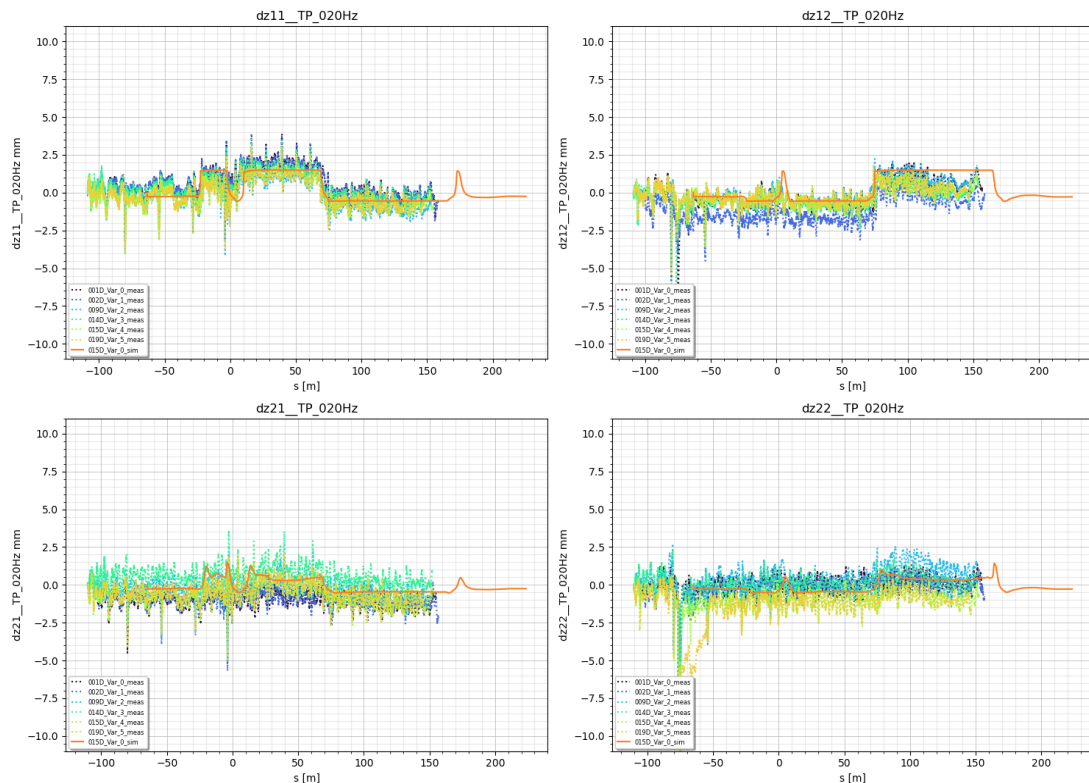


Figure 7-15: Voith 2023 Wheel Lift Leading Bogie

Figure 7-16 shows the gamma angle (rotation of thrust plate around vertical axis of car body) of the front (upper diagram) and rear (lower diagram) coupler of the test wagon. The dotted lines are from measurements, the solid line is from simulation. This angle has significant influence on stabilising function. Thus, good alignment between measurement and simulation is vital. The modelling of rotational movement for front and rear coupler is the same. The alignment in the area of the S-curve is good for rear thrust plate (see Figure 7-16 (4,5)). The alignment between simulation and measurement for the front thrust plate is good for the first curve (see Figure 7-16 (2)) of S-Curve but in simulation the angle is too large in the second curve (see Figure 7-16 (1)) of the S-curve. Measurements of the front thrust plate are showing offsets (see Figure 7-16 (3)) at the beginning of the track, so there is a possibility that a synthetic offset needs to be applied on measurement values before comparing values to simulation. These offsets would lead to worse alignment in the first curve but better alignment in the second curve and to overall slightly lower thrust plate angles for the front thrust plate comparing measurement to simulation.

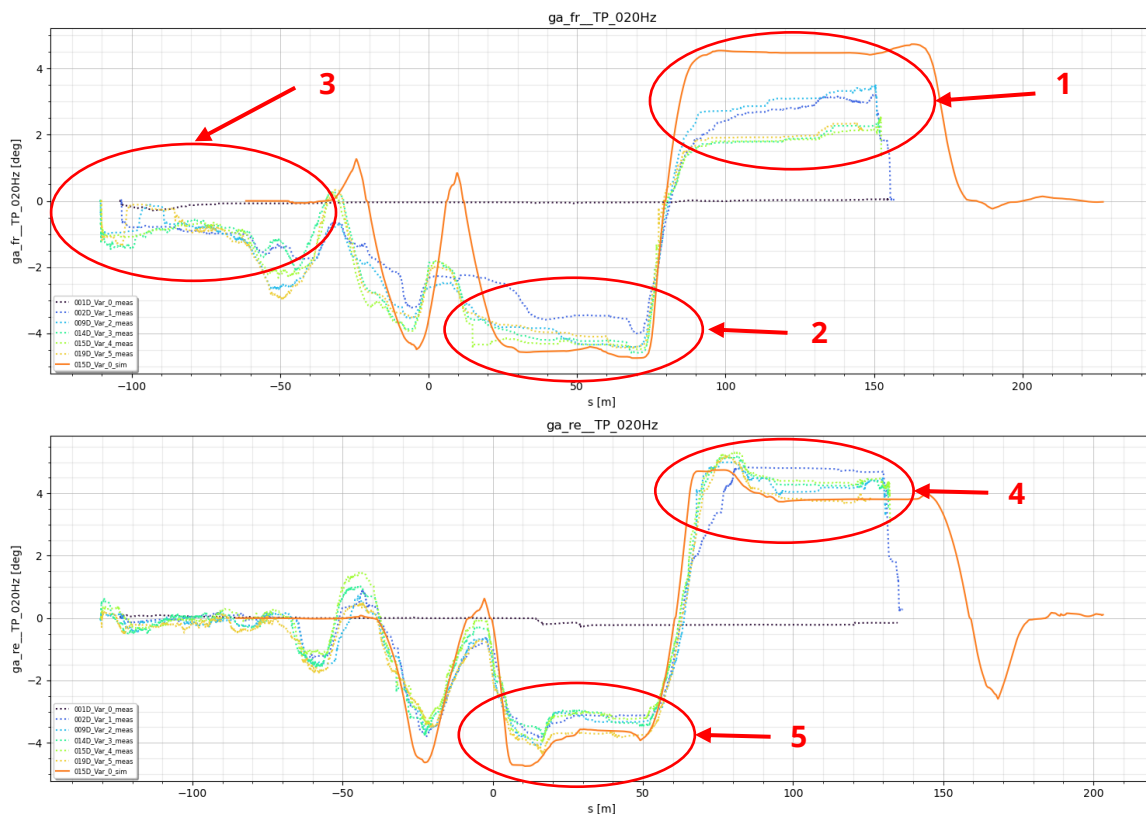


Figure 7-16: Voith 2023 Gamma Angle of Thrust Plate

7.2.3 DACtiVate Tests 2025

The FP5DACtiVate project conducted propelling tests in summer of 2025. During this campaign, DACs that were developed within the FP5TRANS4M-R project were tested in various configurations.

A new simulation model for the Voith coupler was set up for the simulation of these tests. The new model uses optimised force elements and is based on both geometry data that can be measured on the real object and test rig data for force-stroke characteristics.

The real-life tests were performed with the two-axle Hbbins 306 as wagon under test, the Eanos-x 059 as front flanking wagon and the Zags 119 as rear flanking wagon. The simulation model was set up accordingly. Compared to the simulations of the 2020 DAC4EU tests, the model of the Hbbins 306 was refined. Specifically, parameters of the running gear were set to exact values for this wagon type. Previously, generic parameters had been used.

Furthermore, measured deviations of the gauge of track of the test facility in Görlitz were incorporated in the simulation model of the track. The induced LCF in the simulation was taken from the actual LCF during the test runs.

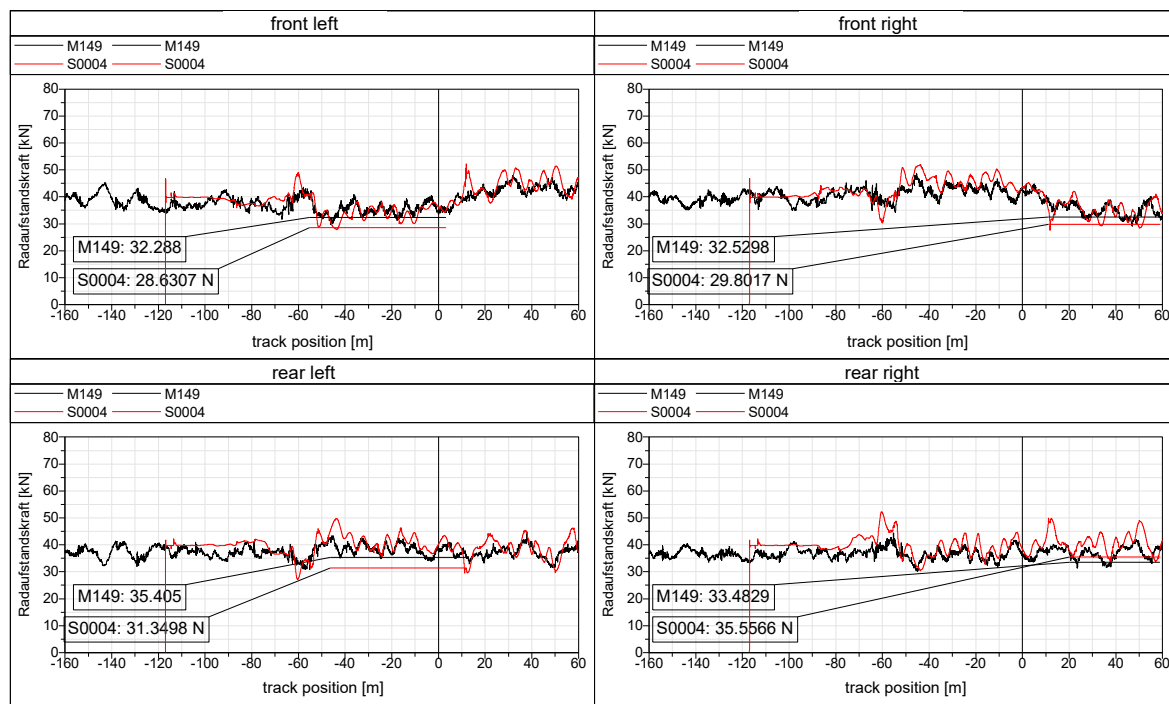


Figure 7-17: Comparison of vertical wheel forces (Q) between test (black) and simulation (red) for initial test with Voith couplers only and without LCF of 2025 test campaign

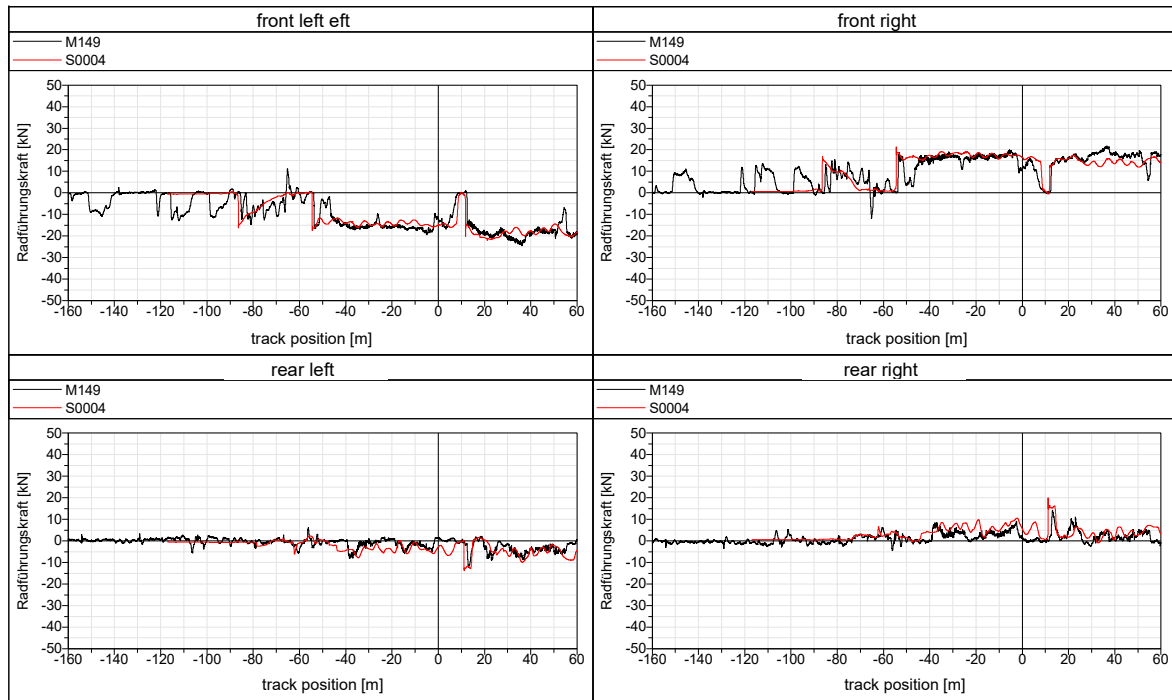


Figure 7-18: Comparison of lateral wheel forces (Y) between test (black) and simulation (red) for initial test with Voith couplers only and without LCF of 2025 test campaign

Figure 7-17 and Figure 7-18 show the comparison of vertical and lateral wheel forces between test (black) and simulation (red) for the initial test without LCF. In this test, the wagon group was pushed through the S-shaped test track without brake application of the brake wagons. All couplers between wagon under test and flanking wagons were from supplier Voith. There is a good alignment between simulation and test. This gives a good indication that wagon and track parameters have been correctly modelled.

Figure 7-19 and Figure 7-20 show analogue comparisons for tests with a target LCF of 550 kN. Again, we can see a good match between simulation and tests. The simulation matches the overall shape of the curves very well and also the amplitudes are close to each other. Only the vertical forces of the rear right wheel show larger deviations, both in shape and amplitude. The reason for this is not yet known.

Overall, the comparisons between this test campaign and the respective simulations show a significantly better match than the comparisons for the 2020 campaign described in Section 7.2.1. This can in large parts be attributed to more available input data and more experience with the models.

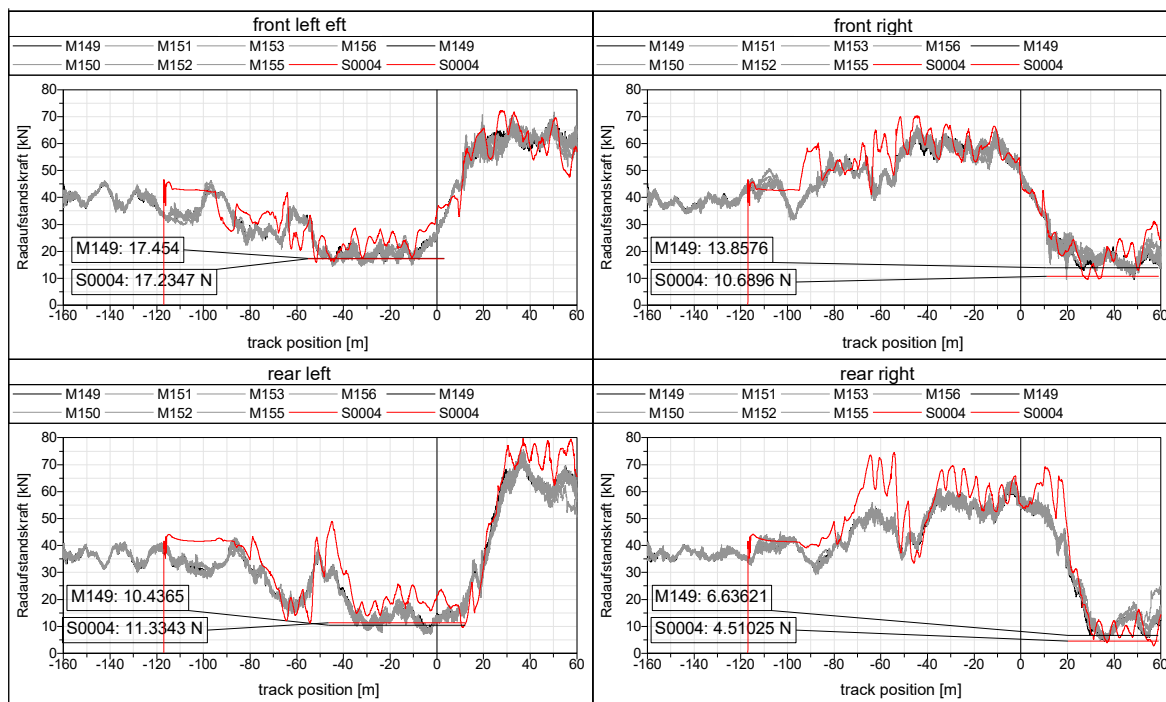


Figure 7-19: Comparison of vertical wheel forces (Q) between tests (grey) and simulation (red) for all tests with Voith couplers only and with LCF = 550 kN of 2025 test campaign

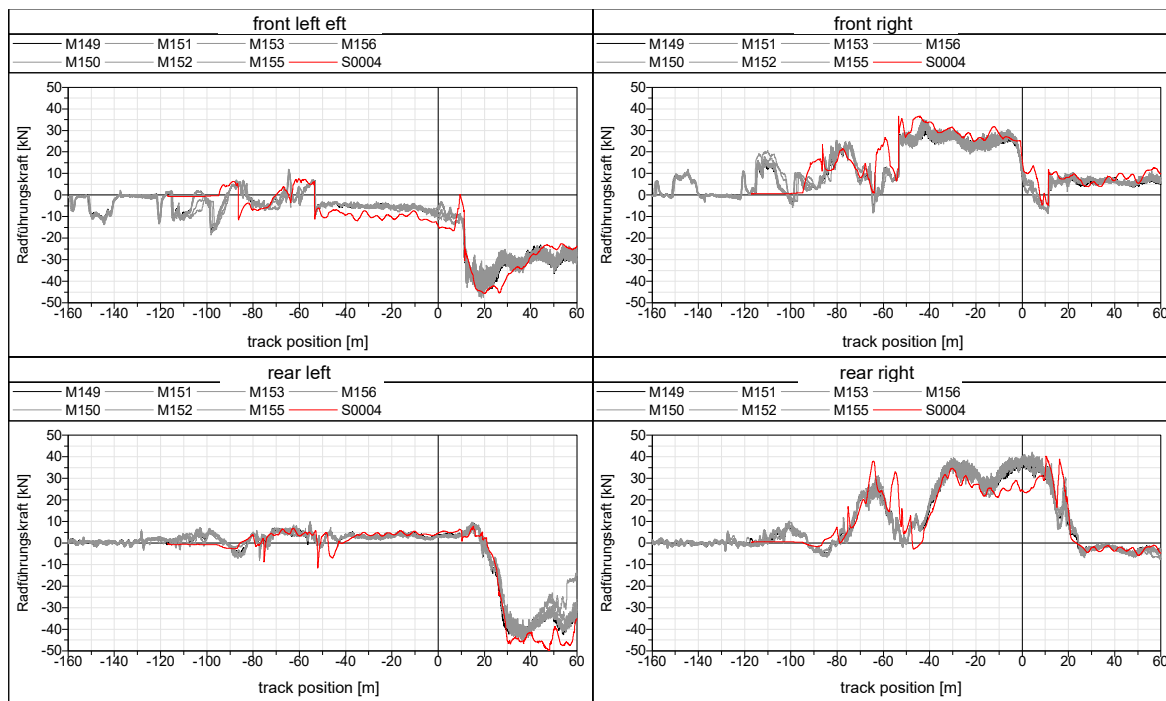


Figure 7-20: Comparison of lateral wheel forces (Y) between tests (grey) and simulation (red) for all tests with Voith couplers only and with LCF = 550 kN of 2025 test campaign

7.2.4 Validation Summary

All in all, the comparisons between measurement and simulation results show a qualitative alignment for most evaluation values. The comparisons of the Dellner 2020 tests to simulation results of these tests are showing good alignments. The Dellner coupler had no stabilising joint and could be modelled with a simple approach. Therefore, there aren't as many influencing parameters on evaluation values from coupler side compared to a model with stabilising joint. The derailment, which happened during test runs with a nominal LCF of 225 kN couldn't be replicated in simulation, although derailment connected evaluation values are showing good alignment. There is evidence that rail profile, which wasn't included in simulation, had significant influence on the derailment process.

The comparisons of the Voith 2020 tests to simulation results show partial significant differences between simulation and measurements, especially for evaluation values connected to the leading wheelset. Reasons for those differences may be caused by coupler model, differences of test wagon to its nominal condition or other boundary conditions, which were not considered in simulation. The derailment, which happened during testing with a nominal LCF of 500 kN couldn't be replicated in simulation. The eLCF of this configuration, determined with the eLCF calculation algorithm (section 6.3.6), is 540 kN (section 7.3.1 DAC4EU configuration).

The simulations of the Voith 2023 tests had been done with the same coupler model as used in the simulations of the 2020 Voith tests. The compared evaluation values show good qualitative alignments. This leads to the assumption, that the coupler model in general is usable for LCF simulations.

The simulations of the 2025 DACTivate tests with Voith couplers show a very good alignment. This can in large parts be attributed to the availability of more and better-quality input data that was in some parts specifically collected for the purpose of simulations and its validation.

A good qualitative and quantitative alignment between simulation and measurement will be necessary for acceptance of validation. The consideration of influencing boundary conditions in simulations is crucial in this context. Influencing boundary conditions are for example:

- Rail-Wheel-Profiles
- Wheel diameter
- Track irregularities
- Track curvature
- Track gauges
- Track superelevation

Additionally, it is crucial to have detailed input parameters about coupler geometry and characteristics. While some of these can be externally measured, others are to be provided by the suppliers. While modelling the various test campaigns, it became obvious that more generic models of couplers will lead to simulation results that still reflect the underlying relationships. However, for a detailed comparison of measurement and simulation, it is absolutely necessary to have precise information about the couplers in the test. Simulation experience in this specific area also plays a role. Since some of these parameters may vary due to manufacturing tolerances or wear and tear during operation, additional parameter variations should be performed. This allows specific case studies to be generalized to a broader context. Section 7.3 shows examples for such parameter studies.

A final validation of the approach has yet not been finished. However, the exemplary comparisons of the 2025 test campaign and the respective simulations clearly demonstrate the capability of the simulation to model the relevant forces in the rail-wheel-contact.

7.3 Parameter Studies

In this section results from first parameter studies are shown. The used simulation models for this parameter studies are built with the generic simulation environment and the eLCF is determined with usage of the calculation algorithm or with simulation results and regression analysis according EN15839 section 7.3.6 [20]. The Hbbins306 is the test wagon in all shown variants. The influences of changing the following boundary conditions on the eLCF are shown:

- Configuration of test train (section 7.3.1)
- Coupler parameters (section 7.3.2)
- Wagon mass (section 7.3.3)
- Curve Radius (section 7.3.4)

For models containing a coupler with stabilising joint, the same coupler model as in simulations for validation variants Voith 2020 "V500kN_compl" and Voith 2023 "015D_sim" is used. The track is modelled according EN15839 section 7.3.1 [20], with a constant track gauge of 1455 mm and no track irregularities.

It is recommended to perform further investigations on the influences of different input parameters. For example:

- Torsional stiffness of car body
- Primary suspension parameters
- Further test train configurations
- Further track parameters (irregularities, track gauges, rail profiles)

7.3.1 Configuration of Test Train

The bar chart in Figure 7-21 shows the calculated eLCF for two different configurations of test train with different flanking wagons (rear flanking wagon, test wagon, front flanking wagon). The eLCF calculated with the test train configuration DAC4EU (Zags119-Hbbins306-Eanos-x059) is 540 kN. The eLCF calculated with the test train configuration according EN15839 Table 3 [20] (Rs680-Hbbins306-Tdgs930-) is 545 kN.

Table 7.3: Differences in Flanking Wagons

Parameter	Rear wagon		Front wagon	
	Zags119	RS680	Eanos-x059	Tdgs930
Type	4 axle bogie	4 axle bogie	4 axle bogie	2 axle
Distance between bogie centers / running gears in m	12.1	13	10.7	6
Length over buffer	17.56	18.66	14.5	8.4
Height difference to test wagon in mm	25	30	25	53

The influences of those different test train configurations on eLCF are rated as insignificant. It has to be underlined, that the used coupler model for these comparisons has an maximum angle of thrust plate of about 4.81 deg. The maximum angle according UIC524 section 2.5 [52] is 1.25 deg (under defined conditions).

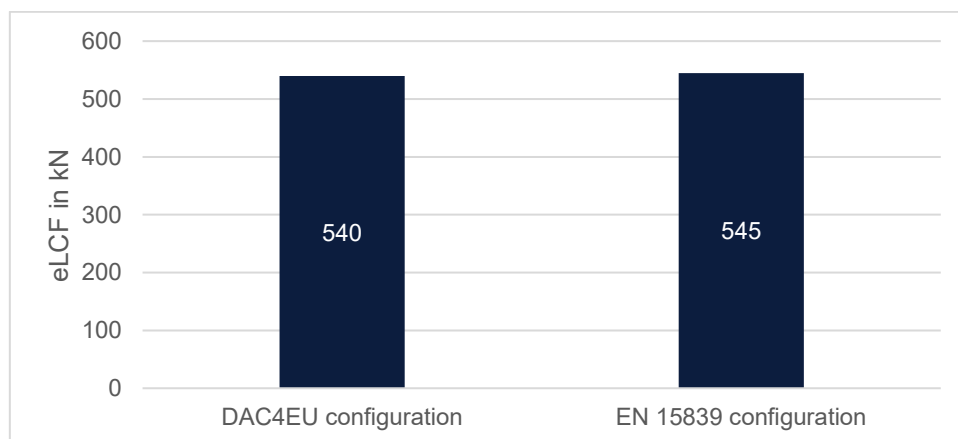


Figure 7-21: Comparison of Hbbins 306 eLCF between DAC4EU und EN 15839 configuration

7.3.2 Coupler Parameters

The bar chart in Figure 7-22 shows the influences of different coupler modelling parameters on eLCF. The test train is the DAC4EU configuration (see section 7.3.1). For the following three parameter sets eLCF was evaluated:

1. No stabilising joint: Dellner model (see section 7.2.1)

2. With stabilising joint TP angle 4.81: Voith model "V500kN_complex", "015D_sim (see section 7.2.1,7.2.2)
3. With stabilising joint TP angle 1.5

Variants 2 and 3 only differ in maximum allowed beta and gamma angle (see Figure 7-3) of thrust plate to car body. With an eLCF of 325 kN, the variant without a stabilising joint has the lowest eLCF. A variant with stabilising joint with with possible thrust plate angle of 4.81 degree reaches an eLCF of 540 kN. The variant with a stabilisation joint with better mounting properties (max. thrust plate angle 1.5 degree) reaches an eLCF of 713 kN according the simulation results. For the variants with stabilising joint the lateral axle box forces of wheelset two exceed limit values. For the variant without stabilising joint on the one hand also the lateral axle box forces exceed limit values and on the other hand a derailment happened in simulation. The results showing the importance of stabilising function on eLCF.

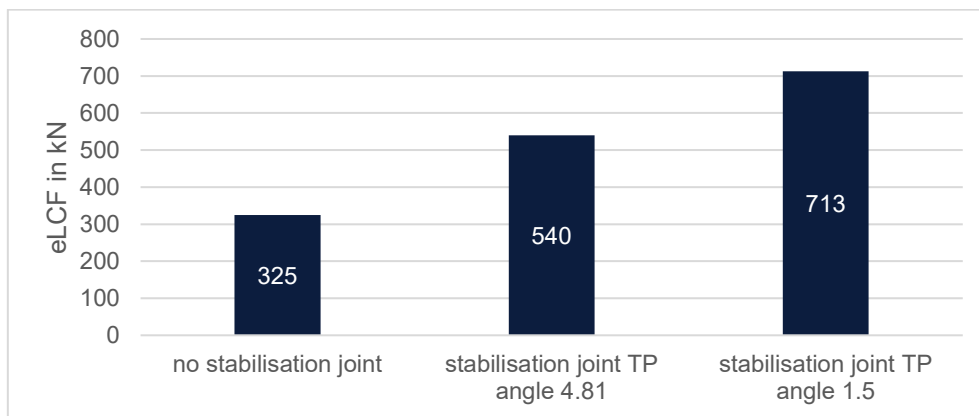


Figure 7-22: Influence of Coupler Parameters

7.3.3 Total Wagon Mass

This section deals with the influence of total wagon mass of test wagon on eLCF. The test train configuration in this investigation is the DAC4EU configuration. The same coupler model as in simulations for validation variants Voith 2020 "V500kN_compl" and Voith 2023 "015D_sim" is used. Three variants are compared.

1. Test wagon without additional load (empty)
2. Test wagon with 7.1 t of additional load (25 % of maximum load)
3. Test wagon with 14.2 t of additional load (50 % of maximum load)

The bar plot in Figure 7-23 shows the simulation results of eLCF. Additional load has positive influence on eLCF according simulation results. With an empty Wagon the eLCF is at 540 kN, with 7.1 t additional load the eLCF is 780 kN and with an additional load of 14.2 t the eLCF is at 960 kN. The sum of lateral axle box is the evaluation value which exceeds limits in all three variants. The limit value for the sum of lateral axle box forces raises with additional loading, because it is directly connected to vertical wheel forces.

The fact that larger vertical wheel forces lead to larger eLCF has already been shown by the ORE working group B125 (see section 5.2.4).

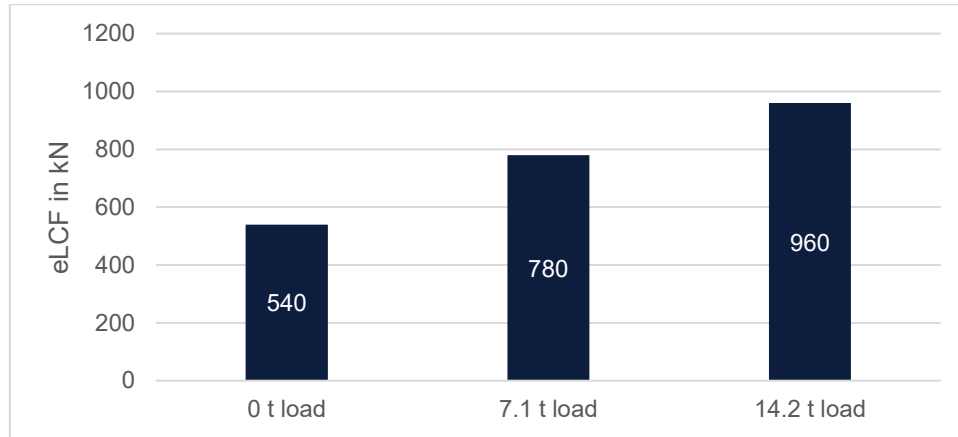


Figure 7-23: Increase of Hbbins 306 eLCF with increasing total mass

7.3.4 Curve Radius

This section deals with the influence test track curvature on eLCF. The test train configuration in this investigation is the DAC4EU configuration. The same coupler model as in simulations for validation variants Voith 2020 "V500kN_compl" and Voith 2023 "015D_sim" is used. Three variants are compared.

1. 150 m S-curve
2. 190 m S-curve
3. 250 m S-curve

The test tracks have no track irregularities and a constant track gauge of 1455 mm.

Figure 7-24 shows the eLCF based on the simulation results. An increase of eLCF with increasing curve radius is visible. The range of eLCF reaches from 540 kN (150 m curve radius) to 713 kN (250 m curve radius). For all variants the sum of lateral axle box forces at wheelset two were the limit exceeding evaluation values.

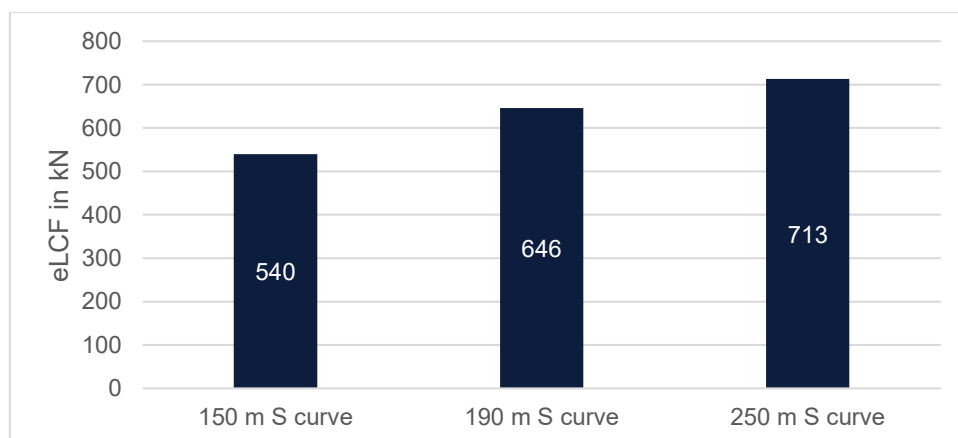


Figure 7-24: Increase of Hbbins 306 eLCF with increasing curve radius

8 From the Methodology to Simple, Practical Guidelines (“the Tool”)

8.1 Introduction

The methodology presented in section 6 can be interpreted as a manual for carrying out virtual propelling tests. However, it becomes obvious that the setup of models and the execution of the actual simulations requires specialised engineers. These works cannot be performed by just any stakeholder within the railway sector. Therefore, the simulation environment itself is not the DAC running safety assessment tool. Instead, the simulations are the foundation for building a database. This database can in turn then be used for deriving simple practical guidelines that will ultimately form the tool. This process is described in more detail in the following subsection.

8.2 Derivation of Guidelines

Easy-to-use guidelines are the goal for the DAC running safety assessment. This is what EN 15839 delivers for wagons with side buffers and the annexes of UIC leaflet 530-2 for wagons with UIC centre buffer couplers (see sections 5.2.2 and 5.2.4). The derivation of such guidelines for wagons with DAC requires the result data of several performed propelling tests – both real-world tests and virtual tests.

While the approach is very straight forward from a pure technical standpoint, there are other factors that should be accounted for:

- Setting up reliable coupler models requires detailed input data that the respective coupler supplier might not want to share amongst competitors
- Ownership of result data and access rights to this data must be defined
- The generation of virtual test data will take some time. Early DAC applications might need an assessment before simple, practical guidelines are available

Because of these reasons, it might be useful to split the process of deriving guidelines into several steps in combination with defined interfaces and responsibilities. As an example, Figure 8-1 shows one possibility to distribute the process of deriving simple, practical guidelines among various stakeholders.

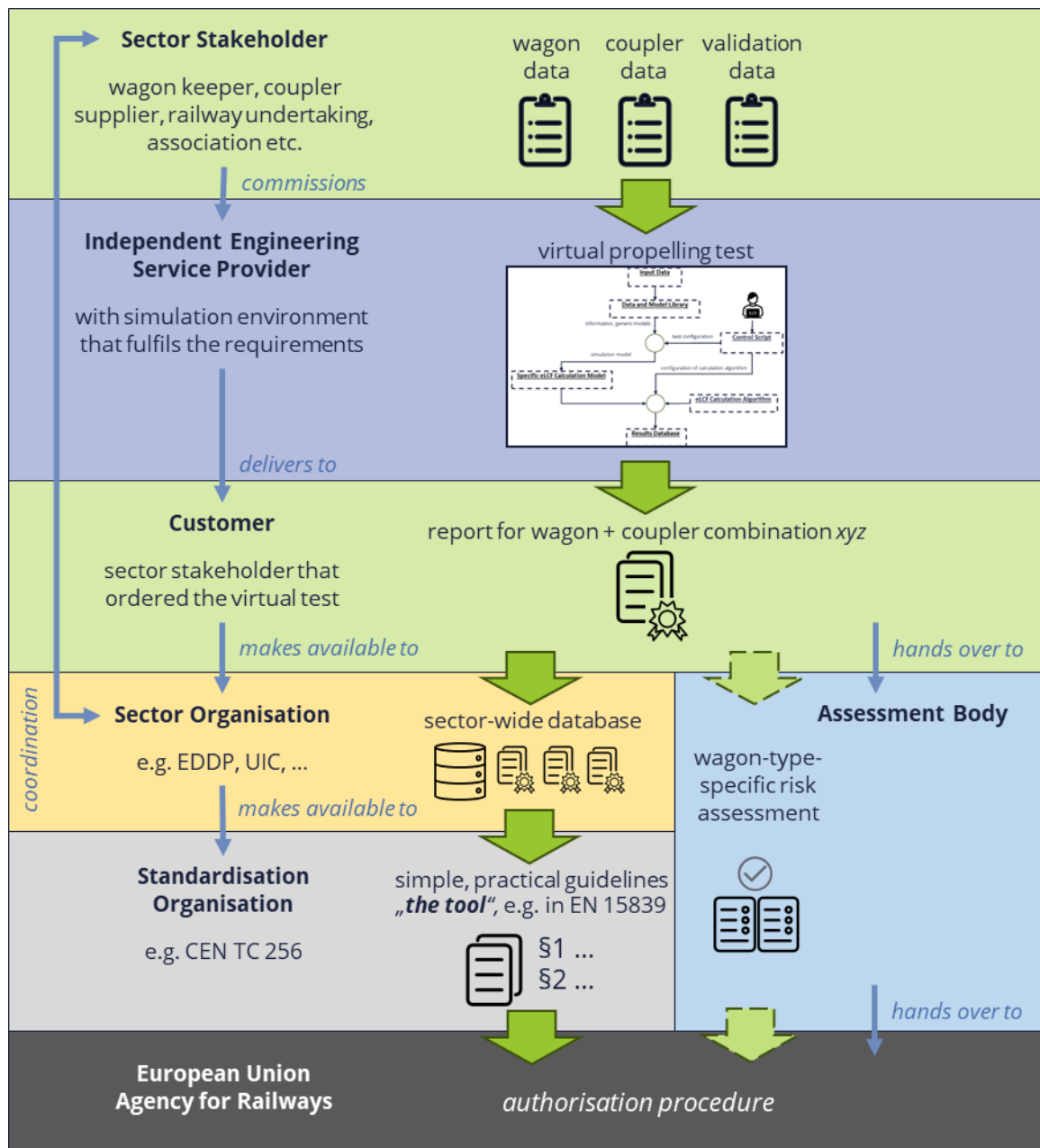


Figure 8-1: Exemplary distribution of the process of deriving simple, practical guidelines among various stakeholders

A wagon keeper, railway undertaking, or coupler supplier could collect the data of a specific wagon and a specific coupler. Additionally, this sector stakeholder would need access to applicable validation data. He could then commission an independent engineering service provider to perform virtual propelling tests that fulfil the requirements lined out in section 6. This provider would then deliver a report of the results of the virtual tests that is specific to the wagon and coupler combination. This report is the property of the commissioning stakeholder who then has two options to proceed further. One option would be to hand over the report (amongst other information) to an assessment body in the context of a vehicle-specific authorisation

procedure. This option is potentially relevant for the very first wagons with DACs to be authorised.

The second option is to make the vehicle and coupler specific results available to a sector organisation that collects these results from multiple stakeholders. The aim here is to provide a result database as the foundation for deriving simple, practical guidelines to the entire sector. This sector organisation could then make the database available to a standardisation organisation that would ultimately derive simple practical guidelines. These would ideally become part of a standard (e.g. EN 15839). The guidelines could then directly be used in following vehicle authorisation procedures.

The method described is probably more time-consuming than a variant in which one actor carries out all the steps. However, it offers a way of better distributing the financial outlay and clearly defining ownership rights. Again, it should be interpreted as one of multiple options.

In addition to the aspects mentioned above, however, there are specific technical issues that can and should be addressed independently of organisational clarification. These are described in the following section.

8.3 Proposed Future Works

8.3.1 Simulations for First Wagons with DACs to be Authorised

Simulations for the first wagon and DAC configurations to be authorised (i.e. the Pioneer DAC Trains) can be commissioned and prepared as soon as these configurations are known. Validation can then happen as soon as validation data from tests is available (see previous section). Of course, no simulation is necessary if the configuration is tested in real-life tests.

8.3.2 Fast and Efficient Work on Stage 1 (At Least Same Minimum eLCF)

As mentioned already in section 6.2, we recommend using a two-stage procedure for deriving generalised rules. The first stage is to prove that (all) wagons with DAC achieve at least the minimum eLCF as required for the side buffer system. This would allow the operation of DAC wagons under the same operational conditions as with side buffer wagons. The second stage is the derivation of generalised rules for higher eLCF to enable modified operations.

As of today, both simulations and real-life tests show higher eLCF for wagons with DAC as for the same wagons with side buffers. There is currently no indication that wagons with DAC have lower eLCF if the DAC has a stabilising joint.

Depending on the results of the real-life propelling tests, the simple practical rule

(all) wagons with DAC achieve at least the minimum eLCF as required for the side buffer system

can probably be quickly derived. If the real-life propelling tests alone do not deliver enough proof for this rule, additional virtual propelling tests can be used to generate additional results.

8.3.3 Proof of oLCF Hypothesis

To use the rule of at least the same minimum eLCF described in the previous section, the oLCF hypothesis mentioned in section 5.1.2 must be proven. The same minimum eLCF as in the side buffer system are only sufficient, if the oLCF are not influenced by the DAC. This proof can be made by comparative measurements and/or simulations.

9 Conclusions

The running safety of freight wagons under longitudinal compressive forces must be assessed to mitigate the risk of derailment. A key value for the assessment is the endurable longitudinal compressive force (eLCF). This is a property of the wagon and its coupler system. The current European rules for the assessment of eLCF are not directly applicable to wagons with DAC.

There has been intensive research in Europe in the past decades. Centre buffer couplers with certain design features enable much higher eLCF than wagons with side buffers. A so-called stabilising joint plays a major role. Wagons with higher eLCF are favourable for railway undertakings to have as they allow for longer and heavier trains in more effective brake positions. Longer/heavier/faster freight trains generally lead to increased in-train forces during operation. These forces are referred to as occurring longitudinal compressive forces (oLCF).

The recommended assessment methodology for the eLCF of wagons equipped with DACs is based on various proven procedures of the past combined with the possibilities of modern multi body simulations. Central component are virtual tests to determine the eLCF of a wagon and coupler combination. Automated simulations allow for a large number of virtual tests. The simulations and the build-up of generic models take place in a commercial multi body simulation software. The used software should be broadly available and well proven for railway applications.

Verification and validation are an essential part of the methodology. In a broader scope, they are part of a risk management process. The standard prEN 17833 "Railway applications – Simulation credibility" gives more detailed information regarding verification and validation. An important parameter here is the target credibility level which defines the structure and the necessary steps of the verification and validation. An independent assessment has yielded the target credibility level 3 for the eLCF simulations. A fault tree analysis is performed to systematically identify all verification and validation tasks.

The recommended methodology for the eLCF assessment is not proprietary. It can be implemented by any stakeholder who has the necessary capacities and expertise. It should be noted that prEN 17833 makes demands regarding the organisation and the process. The proposed methodology is valid to be used to assess the running safety of DAC-equipped wagons under longitudinal compressive forces. It has been presented to representatives of the European Agency for Railways (ERA) who have signalled to accept this methodology.

All results shall be stored in a database and serve as basis for generalised, simple and practical guidelines. These are assignments of (minimum) eLCF to clusters of wagon parameters. This procedure is very similar to European rules for the assessment of

wagons with side buffers. We recommend using a two-stage procedure for deriving generalised rules. The first stage is to prove that (all) wagons with DAC achieve at least the minimum eLCF as required for the side buffer systems. This would allow the operation of DAC wagons under the same operational conditions as with side buffer wagons. The second stage is the derivation of generalised rules for higher eLCF to enable modified operations. As of today, both simulations and real-life tests show higher eLCF for wagons with DAC as for the same wagons with side buffers. There is currently no indication at all that wagons with DAC have lower eLCF if the DAC has a stabilising joint.

The generalised rules should serve the entire European railway sector. Their derivation requires a results database of both real-life and virtual propelling tests. The creation of such a database requires financial efforts and includes the exchange of potentially sensitive information. We propose to split the process of deriving guidelines into several steps in combination with defined interfaces and responsibilities. The database could for example be owned by a sector organisation like the EDDP.

The exemplary comparison between test results of the 2025 FP5DACtiVate test campaign and the respective simulations show a very good alignment between measurement and simulation. Simulations of earlier tests with previous DAC prototypes partially showed some deviations. The better match for the DACtiVate results can in large parts be attributed to the availability of input data that was specifically collected to be used in simulations and its validation. This highlights the importance of high-quality input data for model validation.

Exemplary parameter variations for DAC-equipped wagons show results that fit to previous research. Trends for heavier wagons and/or larger curve radii are the same as for wagons with screw couplers. This means that DAC-equipped wagons behave in the same principal way as when equipped with standard couplers or other central buffer couplers. They do not exhibit any unusual behaviour.

As the next step, we propose to derive the proof that (all) wagons with DACs achieve at least the minimum eLCF values as wagons with side buffers. Datapoints that are not provided by real-life tests (i.e. wagons with extreme parameters) can be delivered by virtual propelling tests. Virtual propelling tests for specific wagons (i.e. wagons used in Pioneer DAC Trains) can be performed in parallel.

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