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A NEW APPROACH TO DEFINE CRITERIA FOR RAIL VEHICLE MODEL VALIDATION

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Abstract

Validation of railway vehicle models is an important condition for the application of multi-body system simulations in the context of vehicle acceptance. Validation investigations carried out in the DynoTRAIN project represent a unique investigation. The measurements, received from a set of vehicles running through 4 European countries equipped with a simultaneous recording of track irregularities and rail profiles, were compared with simulations using vehicle models built in two different simulation tools by several partners. The presented analyses provide a proposal for validation criteria and limits intended for application in the vehicle acceptance process.

1. INTRODUCTION

The time and costs of testing for the acceptance of running characteristics regarding railway vehicles can be reduced by “virtual testing” using computer simulations, which have already been employed in rolling stock design and development for several years. Applications of multi-body systems (MBS) using vehicle dynamics simulations for vehicle acceptance purposes were introduced in UIC 518:2009 [1]; standard EN 14363 [2] will also contain this option in the next revision. Good agreement between the behaviour of a real vehicle and its MBS model is the crucial requirement, when using MBS simulations. To approve this agreement is the aim of the model validation [3], [4]. Unfortunately, no quantitative limits for a successful model validation are specified in [1]; an assessment by an independent reviewer is required instead. Publications on a common methodology for validation of MBS vehicle models for simulations of running dynamics are rare, too. The study by Jönsson et al. [5] can be mentioned as an example presenting a trial carried out during the preparation of UIC 518:2009.
This paper presents a new approach to define measurable criteria and quantitative limits for the validation of railway vehicle models in the context of vehicle acceptance as investigated in Work Package 5 of the DynoTRAIN research project. This investigation is a unique approach analysing 4 types of vehicles tested under the same conditions, which are simulated by different partners using different simulation software tools, compared with on-track measurements and assessed by all project partners.

2. VALIDATION EXERCISES CARRIED OUT IN THE DYNOTRAIN PROJECT

The validation exercises used measurements carried out in DynoTRAIN Work Package 1 in October 2010. The test train with 4 types of tested vehicles was equipped with a total of 10 force measuring wheelsets and a number of other sensors recording over 300 measured signals. This train travelled for a total of 20 days of test runs through Germany, France, Italy and Switzerland reaching speeds up to 120 km/h with freight wagons connected and up to 200 km/h without the freight wagons. Measuring vehicles integrated in the test train continuously recorded the track irregularities and rail profile shapes during all test runs.
The following vehicle models were assessed:

- Locomotive DB BR 120 – model by Siemens in simulation tool Simpack
- Locomotive DB BR 120 – model by IFSTTAR in simulation tool VOCO
- DB passenger coach Bim – model by Bombardier Transportation in Simpack
- DB passenger coach Bim – model by IFSTTAR in VOCO
- Empty freight wagon Sgns with Y25 bogies – model by Technical University Berlin in Simpack
- Empty freight wagon Sgns with Y25 bogies – model by IFSTTAR in VOCO
- Laden freight wagon Sgns with Y25 bogies – model by Technical University Berlin using Simpack
- Laas 2-axle flatbed wagon unit with UIC link suspension modelled by Alstom in Simpack.

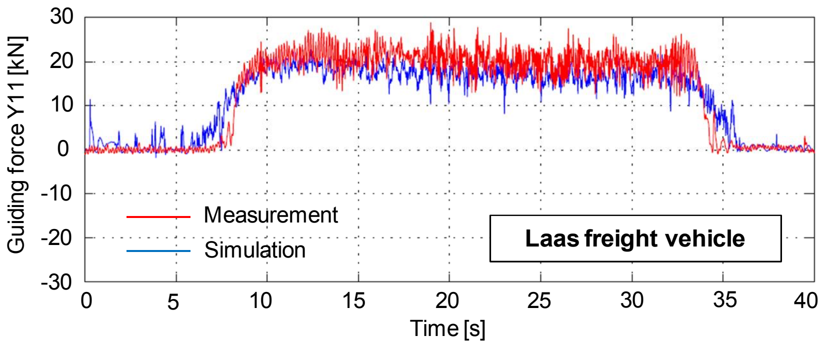
The comparisons between simulation and measurement were carried out for all vehicle models and model configurations under the same conditions over selected track sections of the test runs, called validation exercises; in this context the word “section” does not mean a section according to the definition in EN 14363, but simply a part of track. One validation exercise consists either of a part of straight track or of one curve passing scenario

including both transitions and parts of straight track. Overall 17 validation exercises represent all 4 track zones according to EN 14363 [2]: Straight track and very large curves are represented by 5 sections, large radius curves (R > 600 m) by 2 sections; four sections are from small radius curves (400 m ≤ R ≤ 600 m) and 6 from very small radius curves (250 m ≤ R ≤ 400 m). They are from 3 countries: Germany (11), Italy (4) and Switzerland (2).
In order to assess the effect of using the actual measured infrastructure parameters like track layout, track irregularities and rail profiles, several model configurations were compared. Besides the model configuration applying measured input data, the configurations with estimated rail profiles and estimated track irregularities data were investigated. In this context the term "estimated rail profile" means nominal, i.e. design rail profile and rail inclination of the particular country; similarly "estimated wheel profile" represents design wheel profile S1002. The "estimated track irregularity" data used by partners are either generated based on the power spectral density according to ORE B176 [6] or random track irregularities from other measurements. The selection of track irregularity data to be used instead of the actual measured data was the responsibility of each partner.
The effect of using the results of stationary tests for the model validation in regard to the simulation of the on-track tests were also investigated by comparing the simulation results using vehicle models before and after adjustments based on the comparisons with the stationary tests.

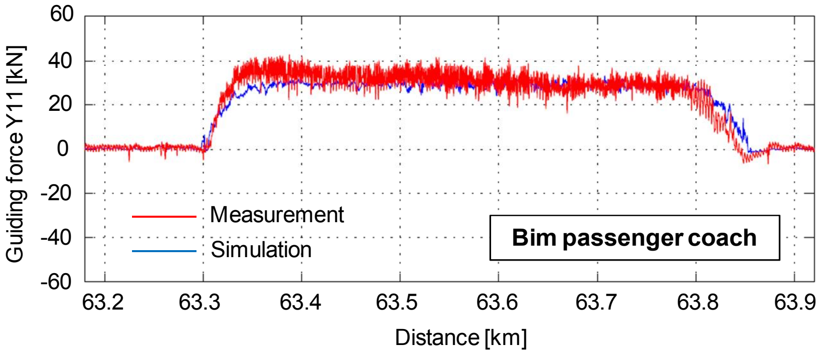
3. VALIDATION ASSESSMENTS COMPARED

3.1 Assessments based on quantities processed by analogy with EN 14363

The results of numerical quantities from simulations were filtered and processed using the EN 14363 requirements and compared to their measured counterparts. This evaluation considers constant curvature track sections only. Overall, there were 48 compared quantities per model configuration consisting of quasi-static as well as dynamic wheel-rail forces and vehicle body as well as bogie frame accelerations.
Comparisons of time domain plots (time or distance diagrams) and power spectral density diagrams were carried out for a selection of vertical and lateral forces between wheel and rail, the derailment ratio *Y/Q* and for accelerations (20 plots per model configuration). The signals were post-processed by a low-pass filter of 20 Hz and compared for the full length of the validation exercise, i.e. including both curve transitions.
Examples of comparisons between simulation and measurement as well as assessment results for two tested vehicles – passenger coach Bim and freight wagon unit Laas – are shown in Figures 1 and 2. The presented models of model configurations F1 use actual measured wheel and rail profiles as well as measured track irregularities. This model configuration represents the first model development level using available parameters, but no model adjustments by comparisons to stationary tests or to on-track test measurements.

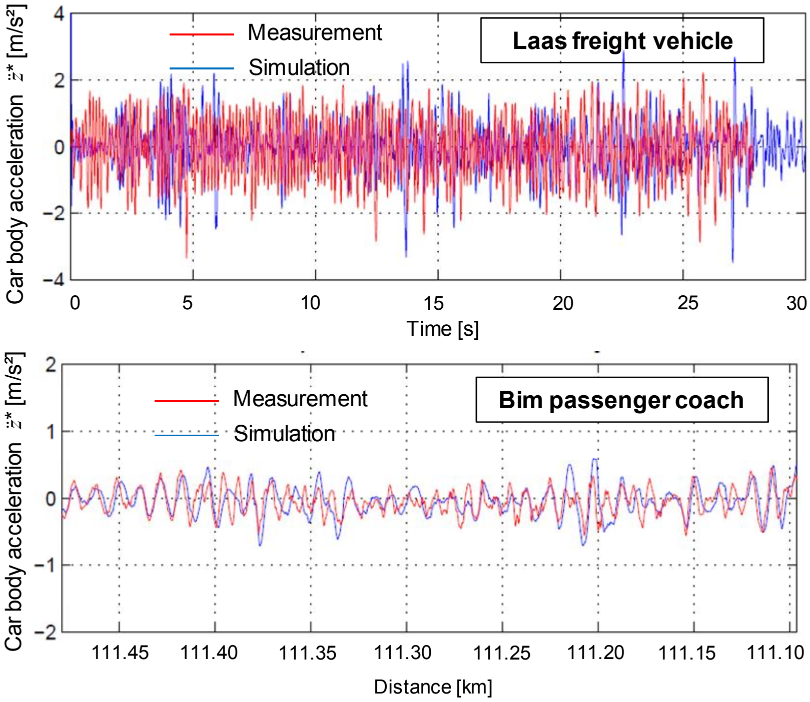


Quasi-static guiding force Y_{qst}	Simulation	17.18 kN
	Measurement	20.55 kN
	Difference	-3.37 kN
	Rel. difference	-16.4%
Maximum guiding force Y_{max}	Simulation	21.87 kN
	Measurement	27.53 kN
	Difference	-5.66 kN
	Rel. difference	-20.6%
Positive assessment workshop		n.a.
Positive assessment partners		50%
Validation metric	M_{SG}	-0.135
	P_{SG}	0.074
	C_{SG}	0.155



Quasi-static guiding force Y_{qst}	Simulation	29.38 kN
	Measurement	31.01 kN
	Difference	-1.63 kN
	Rel. difference	-5.3%
Maximum guiding force Y_{max}	Simulation	33.05 kN
	Measurement	41.69 kN
	Difference	-8.64 kN
	Rel. difference	-20.7%
Positive assessment workshop		n.a.
Positive assessment partners		80%
Validation metric	M_{SG}	-0.072
	P_{SG}	0.057
	C_{SG}	0.092

Figure 1 Validation examples: Exercise F1.01, Germany, curve radius 282 m, speed 68 km/h



Quasi-static car body acceleration $\ddot{z}^*_{rms}$	Simulation	0.73 m/s²
	Measurement	0.83 m/s²
	Difference	-0.10 m/s²
	Rel. difference	-12.0%
Maximum car body acceleration $\ddot{z}^*_{max}$	Simulation	2.87 m/s²
	Measurement	2.44 m/s²
	Difference	0.43 m/s²
	Rel. difference	17.6%
Positive assessment workshop		n.a.
Positive assessment partners		50%
Validation metric	M_{SG}	-0.138
	P_{SG}	0.494
	C_{SG}	0.513

Quasi-static car body acceleration $\ddot{z}^*_{rms}$	Simulation	0.23 m/s²
	Measurement	0.16 m/s²
	Difference	0.07 m/s²
	Rel. difference	40.1%
Maximum car body acceleration $\ddot{z}^*_{max}$	Simulation	0.77 m/s²
	Measurement	0.48 m/s²
	Difference	0.29 m/s²
	Rel. difference	58.4%
Positive assessment workshop		100%
Positive assessment partners		80%
Validation metric	M_{SG}	0.117
	P_{SG}	0.528
	C_{SG}	0.541

Figure 2 Validation examples: Exercise F1.15, Switzerland, curve radius 294 m, speed 74 km/h

3.2 Subjective assessment by engineering judgement

The project partners were asked to assess diagrams with comparisons of measurement and simulation signal quantities by using a simple "Yes/No"-method. Assessing a diagram with "Yes" states, that for the displayed signal quantities of the particular diagram the assessor considers the model as validated. The complete simulation model would be confirmed as validated, if all or at least a large majority of diagrams are classified as validated. Overall 16 time or distance plots and 4 power spectral density diagrams were provided for the subjective assessment of each model validation exercise (compare examples in Figures 1 and 2).
Furthermore, a workshop was held in November 2012, during which 26 European running dynamics experts assessed a selection of 120 diagram plots using the same Yes/No-method.
The analyses of the partners' as well as workshop assessment show a large variation of the assessors' strictness. Moreover, the presentation of the provided measurement and simulation results, such as different diagram axis scaling or change of front or back plane presentation of the signals, is strongly influencing the reviewers' assessments. Therefore, it can be concluded, that a subjective assessment by engineering judgement is not ensuring the feasibility of an objective model validation.

3.3 Validation metrics

As an alternative option to replace the subjective engineering judgement about the agreement between measurement and simulation, the application of so-called "validation metrics" was investigated. Using these metrics the curves of the simulation and measurement signals were compared with each other quantity by quantity in the time or distance domain by an integral approach, described by Magnitude, Phase and Comprehensive error factors proposed by Sprague and Geers (see [7], [8]). Following the explanations of [8] and investigations carried out in the DynoTRAIN project the better the agreement between simulation and measurement signals is, the lower the error factor values shall be, i.e. error factor values near to zero demonstrate perfect agreement between simulation and measurement signals while high values represent disagreement. Since for vehicle homologation there are no applicable limits available to separate validated simulation models from non-validated ones, the evaluated validation error factors were combined with the partners' subjective assessments in order to check existing correlations for developing such validation limits.

4. EVALUATION OF VALIDATION CRITERIA AND LIMITS

4.1 Comparison of model configurations

Several variations of model input data, model adjustments and modelling depth together with variations of track input data result in a total of 78 model configurations and more than 1 000 simulations of validation exercises. The comparisons between simulation and measurement using values based on EN 14363 represent more than 50 000 single comparisons. The evaluation of time or distance as well as power spectral density diagrams comparing the simulation and measurement totalled more than 21 000 plots. About 6 800 plots of selected model configurations have been assessed by project partners and 120 selected plots by invited experts during the workshop.

The assessments based on quantities according to EN 14363 were carried out using a common preliminary set of validation limits, which was evaluated from the proposals provided by project partners. The proposals deviated significantly as it is schematically shown in Figure 3 displaying the area satisfying the validation condition. If the simulated value S_v and measured value M_v are identical, the point is on the diagonal line. A deviation from this diagonal line characterises the deviation between simulation and measurement. A deviation acceptable for a successfully validated model is defined by the limit conditions displayed in Figure 3.

The following in principle differing definitions of the limit condition were proposed by the project partners:

- Deviation limit as a percentage of measured value (relative deviation limit) → cyan area inside the blue dotted lines
- Deviation limit decreasing with measured value increasing towards the limit for vehicle acceptance according to EN 14363 → yellow area inside the red dashed line
- Constant deviation limit (absolute deviation limit) → pink area inside the parallel violet lines.

A reasonable justification can be provided for each of these differing proposals. Any deviation or error is usually considered in regard to the relative deviation hence supporting the first approach. However, as the vehicle is intended to be used for simulation of vehicle acceptance tests, it is important to achieve good agreement for values, which are close to the limit values for vehicle acceptance, thus supporting the third, contradicting approach. Finally, it was agreed to use constant validation limit values (limits for absolute deviation simulation - measurement), which is rather easy and at the same time the most appropriate compromise of the proposals discussed during the investigations.

A preliminary set of validation limits has been agreed based on the partners' proposals. These preliminary validation limits were then applied for the comparison of model configurations and for the investigation of a possible approach for validation. The effects of input data, like measured track irregularities, measured wheel and rail profiles, adjustment of model parameters by comparisons with stationary tests or differing depth of modelling, were compared and the quality of the model configuration was evaluated.

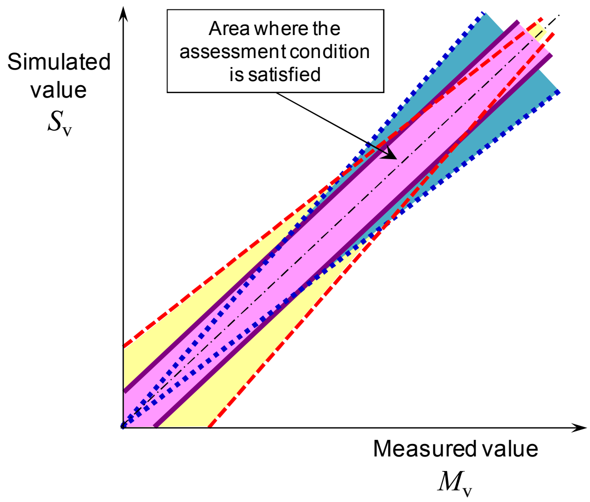


Figure 3 Principles of validation limit definitions proposed by project partners

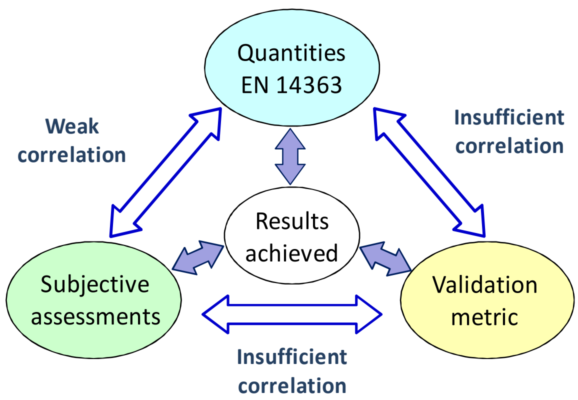


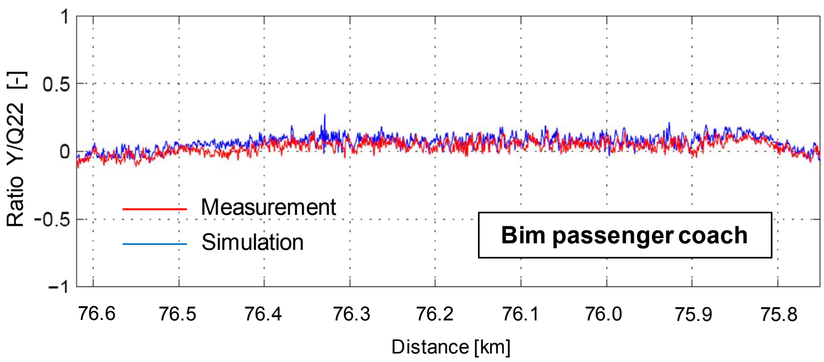
Figure 4 Correlation studies and investigations carried out in regard to identification of validation limits

4.2 Evaluation of method and criteria suited for model validation

The assessment methods compared and evaluated (EN 14363 quantities, subjective assessments, validation metrics) are shown in Figure 4. The correlations between the different groups of assessment as well as the relationship between the assessments and the achieved results were investigated, see Figure 4. They provided the following knowledge.

The assessments by project partners as well as during the workshop with experts demonstrated that subjective assessments vary significantly. Although some tendencies can be confirmed, the final assessment of each single comparison as well as the total assessment finally depends on the strictness of the assessor.

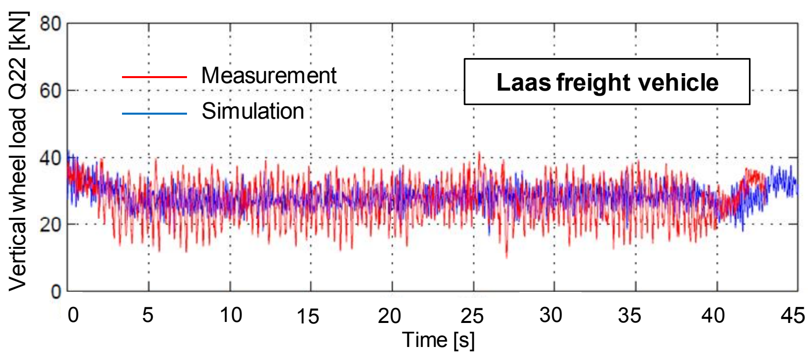
Therefore, a measurable assessment is required. Unfortunately, the evaluated correlation between subjective assessment and validation metrics is not suited to establish limits distinguishing between validated and not validated simulation models. Deviations between simulation results and measurements are often neglected using engineering judgement, if these deviations occur at very small values close to zero or well within the limits for vehicle acceptance according to EN 14363. Since the validation metric error factors are based on a relative deviation, they do not regard effects like this, see Figure 5.



Quasi-static ratio Y/Q_{qst}	Simulation	0.083
	Measurement	0.052
	Difference	0.031
	Rel. difference	60.1%
Maximum ratio Y/Q_{max}	Simulation	0.174
	Measurement	0.133
	Difference	0.041
	Rel. difference	30.4%
Positive assessment workshop		n.a.
Positive assessment partners		100%
Validation metric	M_{SG}	0.447
	P_{SG}	0.246
	C_{SG}	0.510

Figure 5 Validation example: Exercise F1.04, Germany, curve radius 580 m, speed 110 km/h

Another drawback of the validation metric is a strong influence on Phase error factor by the level of synchronisation between simulation and measurement signals. Since perfect synchronisation is neither easy to achieve nor always requested by the evaluating assessor, a good correlation between the Phase as well as the Comprehensive error factor and the subjective assessment cannot be expected.
Moreover, combined deviations such as the simulation signal's size of its quasi-static value combined with its dynamic amplitude deviation from the measured signal, can result in low validation metric error factors suggesting a good agreement (see Figure 6), although a subjective acceptance for positive validation is small.



Quasi-static wheel load Q_{qst}	Simulation	27.84 kN
	Measurement	26.87 kN
	Difference	0.97 kN
	Rel. difference	3.6%
Maximum wheel load Q_{max}	Simulation	36.02 kN
	Measurement	40.44 kN
	Difference	-4.42 kN
	Rel. difference	-10.9%
Positive assessment workshop		n.a.
Positive assessment partners		20%
Validation metric	M_{SG}	0.015
	P_{SG}	0.076
	C_{SG}	0.077

Figure 6 Validation example: Exercise F1.13, Italy, curve radius 292 m, speed 76 km/h

Summarising the correlation analyses and other project results, it is believed that the comparisons of simulation and measurement using quantities based on EN 14363 represent the means for a more objective assessment. The validation metric, which was considered as suitable for replacement of subjective assessment, does not show any valuable improvement and is thus not used in the proposal. Further investigations and modifications of the validation metrics would be required for its future applications in context with the validation of railway vehicle models.
The project investigations demonstrated that assessments of single comparisons between simulation and measurement do not provide relevant information about the model quality in regard to validation. To approve the model validity, it is more important to assess an overall agreement between simulation and measurement, than to concentrate on maximum differences in individual comparisons.

4.3 Proposed validation criteria and limits

The investigations resulted in a proposal of analysing 12 quantities covering the quasi-static and dynamic wheel/rail force measurements and vertical and lateral accelerations in the car body, filtered and processed by analogy with EN 14363, to be compared on at least 12 test sections. A "section" means either a test section according to EN 14363 or a part of test track longer than the minimum length specified for test sections in the

particular test zone according to EN 14363. The selected validation exercises shall contain sections from all 4 test zones, at least 3 sections from each test zone.
Each quantity shall be evaluated using at least two signals, e.g. the vertical acceleration above the leading and the trailing bogie, thus at least 24 simulated values can be compared with their measured counterparts for each quantity, see Figure 7. Each measured as well as simulated quantity shall be filtered and processed according to the requirements in Table 1. The differences between the simulation and measurement shall be evaluated for each value and each quantity. The sign convention when calculating these differences should be selected so that a positive difference represents the case when the magnitude of simulation overestimates the magnitude of the measurement and vice versa.
The following values shall be calculated for the whole set of differences between the simulation and measurement for each quantity (e.g. for all Y_{qst} values):

- Mean value
- Standard deviation.

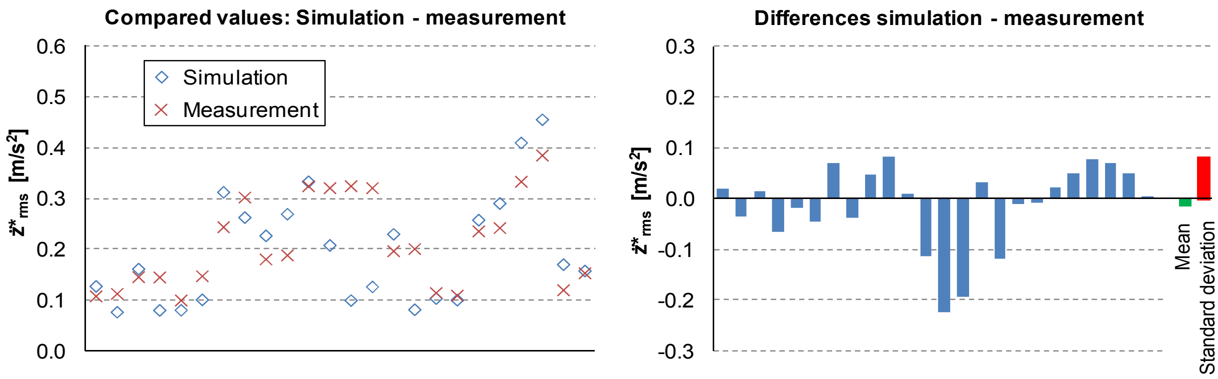


Figure 7 Example of evaluation of differences between simulated and measured values

Quantity	Notation	Unit	Filtering	Processing	Validation limit: Standard deviation of differences simulation - measurement
Quasi-static guiding force	Y_{qst}	kN	Low-pass filter 20 Hz	50%-value (median)	5
Quasi-static wheel load	Q_{qst}	kN	Low-pass filter 20 Hz	50%-value (median)	4 (1+0.01 Q_0) Q_0 - static wheel load [kN]
Quasi-static ratio Y/Q	$(Y/Q)_{qst}$	-	Low-pass filter 20 Hz	50%-value (median)	0.07
Quasi-static sum of guiding forces	ΣY_{qst}	kN	Low-pass filter 20 Hz	50%-value (median)	6
Guiding force, maximum	Y_{max}	kN	Low-pass filter 20 Hz	0.15%/99.85%-value	9
Wheel load, maximum	Q_{max}	kN	Low-pass filter 20 Hz	0.15%/99.85%-value	6 (1+0.01 Q_0) Q_0 - static wheel load [kN]
Ratio Y/Q, maximum	$(Y/Q)_{max}$	-	Sliding mean (2 m window, step 0.5 m)	0.15%/99.85%-value	0.10
Sum of guiding forces, maximum	ΣY_{max}	kN	Sliding mean (2 m window, step 0.5 m)	0.15%/99.85%-value	9
Car body lateral acceleration, rms-value	$\ddot{y}^*_{rms}$	m/s^2	Band-pass filter 0.4 to 10 Hz	rms-value	0.15
Car body vertical acceleration, rms-value	$\ddot{z}^*_{rms}$	m/s^2	Band-pass filter 0.4 to 10 Hz	rms-value	0.15
Car body lateral acceleration, maximum	$\ddot{y}^*_{max}$	m/s^2	Band-pass filter 0.4 to 10 Hz	0.15%/99.85%-value	0.40
Car body vertical acceleration, maximum	$\ddot{z}^*_{max}$	m/s^2	Band-pass filter 0.4 to 10 Hz	0.15%/99.85%-value	0.40

Table 1 Quantities and limits proposed for model validation in regard to simulation of on-track test

The proposed evaluation of the differences between simulation – measurement as well as the signal filtering and processing is shown in Table 1. This table also presents the draft of the proposed validation limits based on the investigations in the DynoTRAIN project. The validation limits for the standard deviation of the differences between simulation – measurement are given in Table 1; the limits for the mean value of the differences simulation – measurement are equal to 2/3 of the limits for the standard deviation. The validation limits for accelerations (mean as well as standard deviation) for freight vehicles or vehicles without secondary suspension are twice the relevant limit values stated in Table 1.

The evaluated values of the mean and the standard deviation of differences between simulation – measurement can be normalised by the proposed validation limits to visualise the weaknesses of the investigated models. Figure 8 shows such an assessment for the Bim passenger coach and the Laas freight wagon unit. Three model configurations of each vehicle with differing knowledge of wheel and rail profiles were compared. The passenger vehicle Bim provides values with lower magnitude than the Laas freight vehicle. As the Bim coach's magnitudes of all values are below the validation limit, all three model configurations are considered as validated. The validation of the Bim coach model could thus be demonstrated also without measured rail and wheel profiles. The Lass unit is not validated, because of exceeding the Y_{qst}, $(Y/Q)_{qst}$, $(Y/Q)_{max}$ and exceeding the vehicle body accelerations. In spite of the fact, that with measured wheel and rail profiles the model configuration of the Laas unit provides better results than other Laas vehicle model configurations, the exceeding of validation limits occur for the same quantities. Thus, the Laas wagon unit cannot be confirmed as validated. This example also demonstrates the difficulties of modelling freight vehicles with large uncertainties of friction suspension parameters.

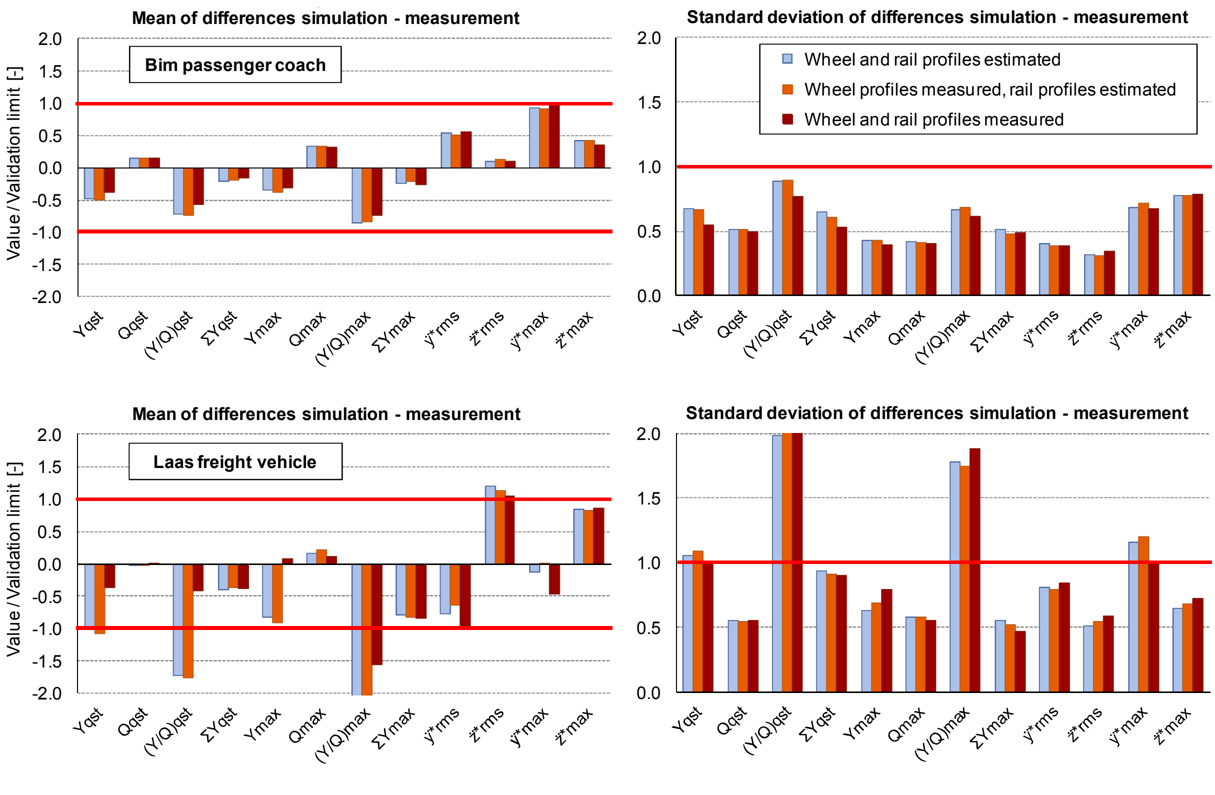


Figure 8 Normalised mean and standard deviation of differences between simulated and measured values for the validation of two vehicle models using actual measured wheel and rail profiles as opposed to estimated profiles

Figure 9 shows validation results without the actual measured track irregularities (i.e. using estimated track irregularity data) in comparison to the model configurations F1 with the actual measured track irregularities. The profiles of rails and wheels use the actual measured data in both cases. As expected, the comparisons show better agreement when the actual measured track irregularities are applied. But it is interesting to see that the differences are smaller than one probably would expect. The model of Bim coach fulfils the proposed validation limits using measured track irregularities and fails without the measured data, however, the exceeding of the validation limit is only marginal. The Laas freight vehicle fails in both model configurations because of exceeding the Y_{qst}, $(Y/Q)_{qst}$, $(Y/Q)_{max}$ and exceeding the vehicle body accelerations. As expected, larger deviations between simulation – measurement occur without the measured track irregularities.

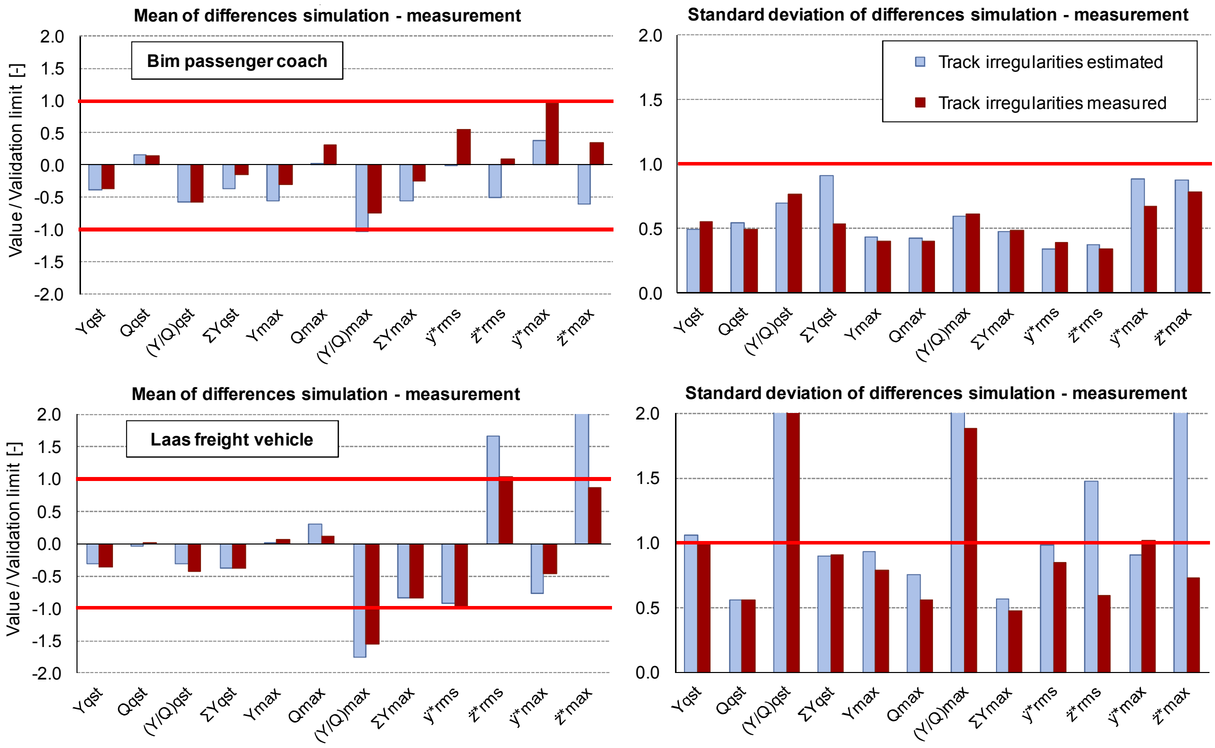


Figure 9 Normalised mean and standard deviation of differences between simulated and measured values for validation of two vehicle models using the actual measured track irregularities as opposed to random ones

5. CONCLUSIONS AND OUTLOOK

The paper presents investigations of the validation process, the criteria and the limits for the validation of multi-body system vehicle models in regard to simulations of on-track acceptance tests carried out in the DynoTRAIN project. These investigations represent unique work in regard to both simulations as well as measurements. The analyses are carried out using measurements with a test train with 4 types of vehicles and 10 force measuring wheelsets, running over 20 days through 4 European countries and being equipped with simultaneous recording of track irregularities and rail profiles. The simulations, comparisons with measurements and evaluations were conducted using vehicle models built in two different simulation tools by several partners.
The proposed criteria and validation limits are based on 12 quantities covering the quasi-static and dynamic wheel/rail force measurements and vertical as well as lateral vehicle body accelerations. For each quantity a set of at least 24 comparisons between simulation – measurement is evaluated using values based on EN 14363 from at least 12 sections, which represent all 4 zones from straight to curves with very small radius. It is intended to introduce these criteria in to the revision of EN 14363 and to gain experience with this method in future projects.
The validation metric is analysed, too, but does not provide better and more reliable assessment than subjective assessments. This can be explained by the identified drawbacks of validation metrics. Future investigations could remove these drawbacks by modification of validation metrics in regard to railway vehicle dynamic behaviour.

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