VALIDATION OF MULTI-BODY MODELS FOR SIMULATIONS IN AUTHORISATION OF RAIL VEHICLES

O. Polach[1], A. Böttcher[2], D. Vannucci[3], J. Sima[4], H. Schelle[5], H. Chollet[6], G. Götz[7], M. Garcia Prada[8], D. Nicklisch[9], L. Mazzola[10], M. Berg[11], M. Osman[12]

[1)]Bombardier Transportation (Switzerland) AG, Switzerland, [2)]Alstom Transport Deutschland GmbH, Germany, [3)]Ansaldobreda, Italy, [4)]Siemens AG, Germany, [5)]TU Berlin, Germany, [6)]IFSTTAR, France, [7)]Bombardier Transportation GmbH, Germany, [8)]CAF, Spain, [9)]DB Netz AG, Germany, [10)]Polimi, Italy, [11)]KTH, Sweden, [12)]RSSB, UK

Received: September 12, 2013

ABSTRACT

An application of multi-body simulations is to reduce the amount of vehicle on-track testing and present an opportunity for saving the time and costs of vehicle acceptance in regard to running characteristics. One of the objectives of the EU project DynoTRAIN was to define criteria and limits for vehicle model validation. The paper presents investigations carried out by comparing simulations with measurements from a testing campaign using a test train with 4 types of vehicles and a total of 10 force measuring wheelsets and accompanied with continuous measurement of track irregularities and rail profiles. The simulations were performed by using several vehicle models, built in different simulation tools by different partners. The results of the investigations and the criteria and limits proposed for the validation of multi-body vehicle models, intended for simulations of on-track tests, in the framework of railway vehicle authorisations are presented.

Keywords: Model validation, multi-body simulation, railway vehicle, running dynamics, running characteristics, acceptance, authorisation, certification, homologation.

1. INTRODUCTION

Cost and duration of vehicle testing for the acceptance of running characteristics according to EN 14363:2005 [1] could be reduced by using multi-body simulations which have already been employed in rolling stock design and development for several years. This, however, is only possible if there is confidence that the simulation results have been produced by using a validated railway vehicle model [2], [3]. The recent revision prEN 14363:2013 [4] considers application of multi-body simulations, but without specifying quantitative limits for a successful model validation; an assessment by an independent reviewer is required instead. A development of method, criteria and limits for validation of vehicle models intended for simulations for the acceptance of running characteristics of railway vehicles was a topic investigated in Work Package 5 of the research project DynoTRAIN.

These investigations were carried out by comparing simulations with measurements from a testing campaign carried out in four European countries in October 2010 and accompanied with continuous measurement of track irregularities and rail profiles. The following vehicle models were assessed:

- 2 models of locomotive DB BR 120 (in simulation tools Simpack and VOCO)
- 2 models of DB passenger coach Bim (in simulation tools Simpack and VOCO)
- 2 models of empty freight wagon Sgns with Y25 bogies (in simulation tools Simpack and VOCO)
- Model of laden freight wagon Sgns with Y25 bogies in Simpack

- Laas freight unit consisting of two 2-axle flatbed freight wagons with UIC link suspension modelled in Simpack.

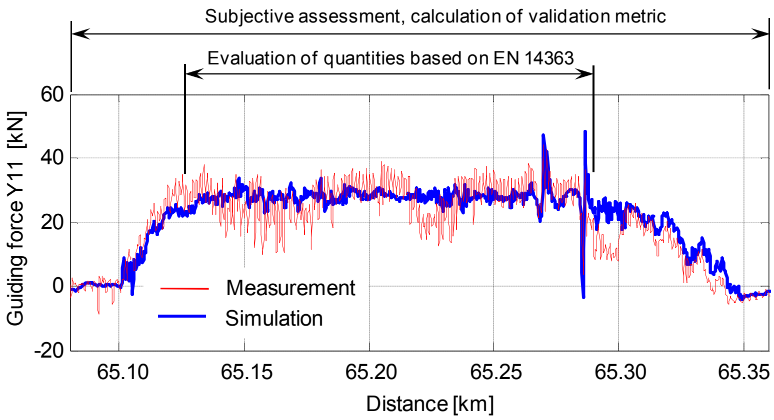
Furthermore, other models of two recently developed vehicle types were assessed using measurement results provided by the suppliers of vehicles.

2. VALIDATION EXERCISES

The comparisons between the simulation and the measurement were carried out for all vehicle models and model configurations under the same conditions and in the same manner for selected sections of test runs, called validation exercises. One validation exercise consists of one curve passing scenario including both transitions and parts of straight track; in this context the word "section" means a part of track; it does not mean section according to the definition in EN 14363:2005 [1]. A total of 17 validation exercises were selected from DynoTRAIN measurements, representing all 4 track zones from straight track down to very small radius curves (250 m ≤ R ≤ 400 m). They were from 3 countries: Germany (11 sections), Italy (4) and Switzerland (2).

The assessment by comparisons between the simulation and the measurement results contained (see an example in Fig. 1):

- Assessment based on measured quantities, filtered and processed by analogy with EN 14363:2005 [1].
- Subjective engineering assessment using simple "Yes/No" method by project partners as well as during a workshop with invited experts, where a set of selected plots were assessed by 26 workshop attendees.
- Validation metrics, i.e. quantitative measures comparing simulation and measurement in the time histories with the aim to maintain agreement with engineering judgement [5].



Quasi-static guiding force Y_{qst}	Simulation	28.09 kN
	Measurement	27.81 kN
	Difference	0.28 kN
	Rel. difference	1.0%
Maximum guiding force Y_{max}	Simulation	46.19 kN
	Measurement	43.17 kN
	Difference	3.02 kN
	Rel. difference	7.0%
Positive assessment workshop		73%
Positive assessment partners		80%
Validation metric	M_{SG}	0.019
	P_{SG}	0.080
	C_{SG}	0.082

Fig. 1 Example of validation diagram and assessment results: Guiding force on the leading wheel of passenger coach Bim at 68 km/h in a curve with 312 m radius

The analyses of about 1 000 simulation runs considered about 50 000 pairs of values evaluated by analogy with EN 14363, together with more than 6 000 plots assessed subjectively by the project partners as well as 120 selected plots during the workshop. Each of the plots comparing the time or distance histories was assessed by calculating the validation metrics values by Sprague and Geers and by Russell: Magnitude error factor M_i, phase error factor P_i and comprehensive error factor C_i, where indices i = SG for validation metrics by Sprague and Geers and i = R for validation metrics by Russell; see [5] for error factors definitions.

3. EVALUATION OF VALIDATION CRITERIA AND LIMITS

Correlations between the quantities evaluated by analogy with EN 14363, the assessments by validation metrics and the subjective assessments of plots were analysed. The relationship between the assessments and the simulation results achieved was investigated in order to specify criteria and limits ensuring reliable model validation and at the same time allowing a successful validation applying the state of the art modelling and simulation, see Fig. 2. The effects of using the actual track data (measured track irregularities, rail profiles) as opposed to random track data and the use of stationary tests for the model validation in regards to simulation of the on-track tests were also investigated.

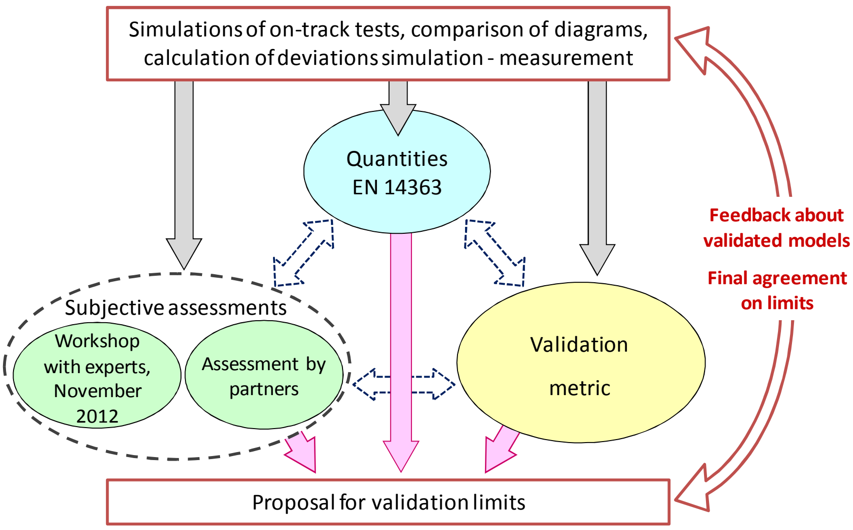


Fig. 2 Evaluation of validation criteria and limits carried out in DynoTRAIN

The model validation criteria and limits should take into account errors in the measurement of running dynamics quantities, measurement of track layout and track irregularities, measurement of rail profiles and wheel profiles, scatter of test conditions as e.g. friction coefficient between wheel and rail as well as generally stochastic character of the test results. The investigations showed that the quantities based on EN 14363:2005 so far provide the best potential for quantitative criteria and objective validation assessment. An application of these criteria on a few single pairs of compared simulation – measurement values, however, does not provide sufficient information about an overall model performance considering the stochastic character of the test results. It is therefore proposed to assess a whole set of simulation – measurement pairs for each quantity. The proposed model validation process considers an assessment of 12 quantities based on measured forces between wheel and rail and vehicle body accelerations, evaluated on a minimum of 12 test sections. The validation is assessed comparing the mean and standard deviation of differences between simulation and measurement for each particular quantity with the validation limits.

4. PROPOSED VEHICLE MODEL VALIDATION

The proposed validation assessment is based on quasi-static values and maximum values of wheel/rail contact quantities (*Y*, *Q*, *Y/Q* and *ΣY*) and rms and maximum values of vertical and lateral car body accelerations. The simulation and measurement results of these quantities should be compared on at least 12 test sections, called validation exercises. The selected validation exercises shall contain sections from all 4 curvature zones according to EN 14363, at least 3 sections from each zone.

Each quantity should be evaluated using at least two signals, e.g. vertical acceleration above the leading and trailing bogie, thus, at least 24 simulated values S_v compared to the corresponding measured values M_v of each quantity. Each compared simulated as well as measured quantity is filtered and processed according to the requirements in Table 1, whereby the frequency values (%-values) are calculated from the cumulative curve. For the maximum value calculated as 0.15% or 99.85%-value, the higher magnitude of the 0.15%- and 99.85%-values (absolute value) is used. The 50%-values (medians) are applied with their sign to approve the agreement of both magnitude and direction of those quantities.

The difference D_v between the simulated value S_v and the corresponding measured value M_v is to be evaluated for each value and each quantity, whereby this difference is transformed so that, if the magnitude of the simulation value is higher than the magnitude of the measurement (simulation overestimating the measurement), the difference is positive, and vice versa:

$$D_v = (S_v - M_v)\frac{M_v}{|M_v|} \qquad \text{for} \quad M_v \neq 0 \tag{1}$$

$$D_v = S_v \qquad \text{for} \quad M_v = 0$$

The following values are calculated for the whole set of differences D_v between the simulation and measurement for each quantity (e.g. for all Y_{qst} values):

- Mean of differences between simulation value S_v and measurement value M_v
- Standard deviation of the same set of differences.

The standard deviation of the set of differences between simulation value S_v and the measurement value M_v for each quantity should be below their validation limit shown in Table 1. For each quantity the mean of the set of differences between the simulation value S_v and the measurement value M_v should be lower than a validation limit equal to 2/3 of the related limit for the standard deviation. The validation limits for accelerations (standard deviation as well as mean of differences) for freight vehicles and vehicles without bogies or without secondary secondary suspension are twice the relevant limit values for other vehicles.

Fig. 3 illustrates the calculation of differences between the simulation values S_v and the measurement values M_v for the example quantity rms-value of vertical acceleration at the vehicle body. The left diagram displays the simulation values S_v and the measurement values M_v. The right diagram shows the differences D_v, and their mean value and standard deviation, which are used for comparisons with the validation limits specified in Table 1.

Quantity	Notation	Unit	Filtering	Processing	Validation limit for standard deviation *)
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 quotient 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	99.85%-value ***)	6 (1+0.01 Q_0) Q_0 - static wheel load [kN]
Quotient Y/Q, maximum	$(Y/Q)_{max}$	-	Sliding mean (2 m window)	0.15%/99.85%-value ***)	0.10
Sum of guiding forces, maximum	ΣY_{max}	kN	Sliding mean (2 m window)	0.15%/99.85%-value ***)	9
Car body lateral acceleration, rms	$\ddot{y}^*_{rms}$	m/s^2	Band-pass filter 0.4 to 10 Hz	rms-value	0.15 k_a **)
Car body vertical acceleration, rms	$\ddot{z}^*_{rms}$	m/s^2	Band-pass filter 0.4 to 10 Hz	rms-value	0.15 k_a **)
Car body lateral acceleration, max.	$\ddot{y}^*_{max}$	m/s^2	Band-pass filter 0.4 to 10 Hz	0.15%/99.85%-value ***)	0.40 k_a **)
Car body vertical acceleration, max.	$\ddot{z}^*_{max}$	m/s^2	Band-pass filter 0.4 to 10 Hz	0.15%/99.85%-value ***)	0.40 k_a **)

*) Validation limit for mean of differences simulation-measurement is 2/3 of the limit for standard deviation
**) k_a - coefficient in regard to vehicle design; freight vehicles and vehicles without bogies or without secondary suspension, respectively: $k_a = 2$, other vehicles: $k_a = 1$
***) Absolute values of simulated value S_v and measured value M_v

Table 1 Quantities compared, their filtering and processing and the proposed limits for model validation in regard to simulation of on-track test

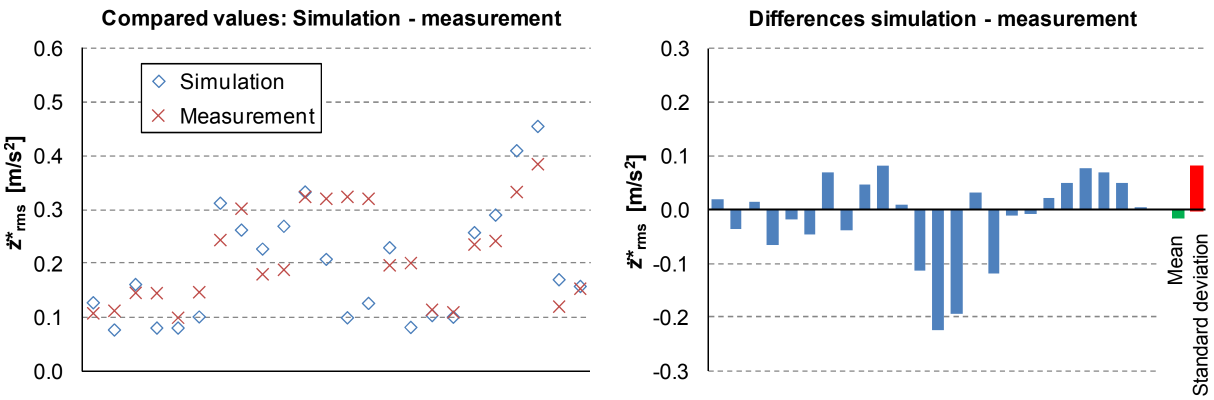


Fig. 3 Example of differences between simulated and measurement values (left diagram) and calculation of their mean and standard deviation (right diagram)

5. DICSUSSION OF VALIDATION RESULTS

An advantage of the proposed validation procedure is that this assessment represents an overall assessment of a large number of data. It is not practical to carry out such an assessment by using engineering judgement of the plots, as it would involve having to display, check and document the approval of such a large number of diagrams. The calculation of characteristic parameters of mean and standard deviation of differences between the simulation values S_v and the measurement values M_v, and their comparison with the validation limits, however, allows a fast identification of quantities with large deviation.

The specified set of 12 quantities covers the quasi-static as well as dynamic behaviour of the vehicle in regard to the vehicle acceptance, which is the intended range of the application for a validated model. The vehicle's safety relevant behaviour and the track loading results are validated by comparing quantities measured using force measuring wheelsets. The representation of vehicle ride is validated by comparing the rms values and maximum values of car body accelerations. The signal processing is carried out by analogy with EN 14363 for both the measurement and simulation, thus allowing direct use of the acceptance tests data. The only additional requirement on the measurement evaluation is the calculation of quasi-static values of the sum of guiding forces and *Y/Q* ratios.

The weakness of the model in question can be identified by displaying normalised validation criteria, as it can be seen in Fig. 4 – 9. The mean and standard deviation of differences between simulation and measurement are normalised by the proposed validation limits (see Table 1). A vehicle model is thus validated if magnitudes of all values are lower than 1.

Fig. 4 shows examples of model validation results for vehicles tested in DynoTRAIN project. These initial models were developed using available parameters including measured profiles of wheels and rails and measured track irregularities, however without any model adjustments. From the four vehicle models compared, only the initial model of the Bim coach fulfils the validation limits. The other vehicle models must be adjusted to be validated.

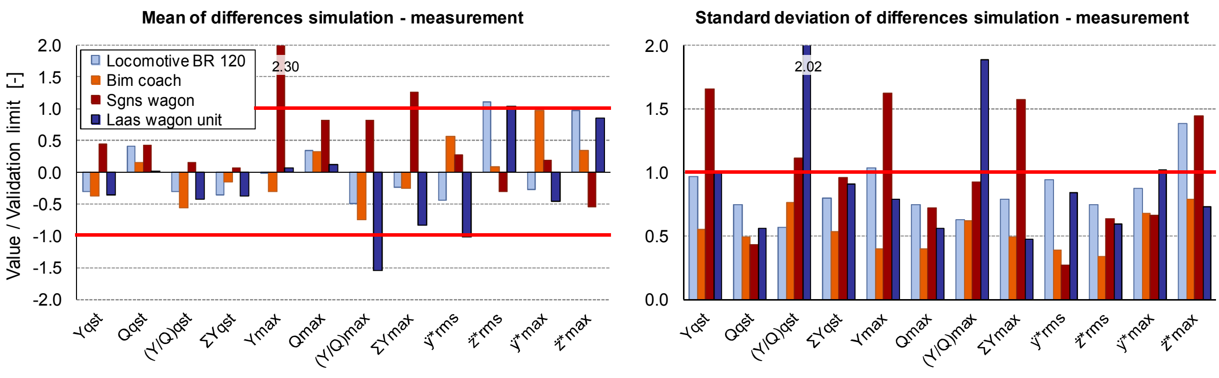


Fig. 4 Normalised values of mean and standard deviation of differences between simulation and measurement for the initial models of locomotive (Siemens), Bim coach (Bombardier Transportation), laden freight wagon Sgns (TU Berlin) and freight wagon unit Laas (Alstom)

Fig. 5 displays the validation results of initial models of vehicles tested as part of the delivery contract by vehicle suppliers. In this case, neither track irregularities nor rail profiles measurement were available, and models failed the validation criteria.

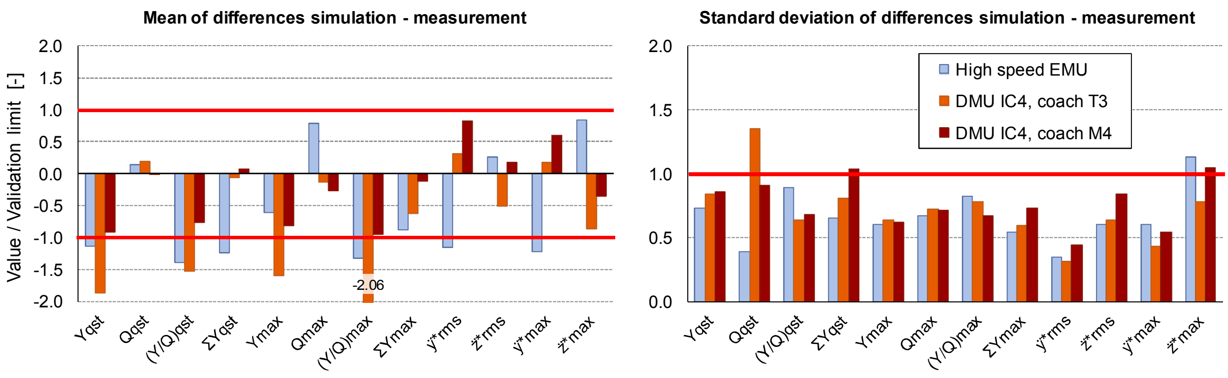


Fig. 5 Normalised values of mean and standard deviation of differences between simulation and measurement for the initial models of vehicles tested as part of the delivery contract by vehicle suppliers: High Speed EMU (CAF) and two different coaches of DMU IC4 (Ansaldobreda)

Fig. 6, 7 and 8 show results of vehicle models adjusted by comparisons with both stationary and on-track tests together with the results of the initial models. Fig. 6 presenting the results of the locomotive BR 120 by Siemens demonstrates the importance of the measurement and modelling of tractive effort at a traction vehicle used to haul the test train during the measurements.

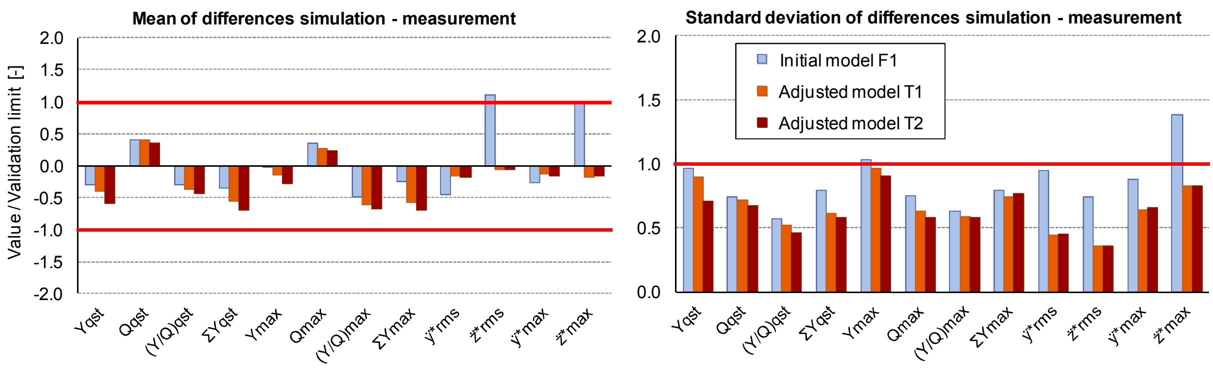


Fig. 6 Example of locomotive BR 120 by Siemens: F1 – initial model, T1 – model after adjustments by comparisons with both stationary and on-track tests, T2 – model configuration T1 extended with the modelling of tractive effort

Fig. 7 displays results of the Bim coach model by Bombardier Transportation. The model adjusted by comparison with stationary tests was further improved by adjustment of the estimated height of the car body centre of gravity identified from the comparisons with the on-track tests results. This adjustment of the uncertain parameter of the car body centre of gravity could possibly be identified from the stationary sway test; however, this test was not available. The validation results of the same vehicle modelled by IFSTTAR (Fig. 8) exceed the validation limits even after the model adjustment; thus, this model failed the proposed validation criteria.

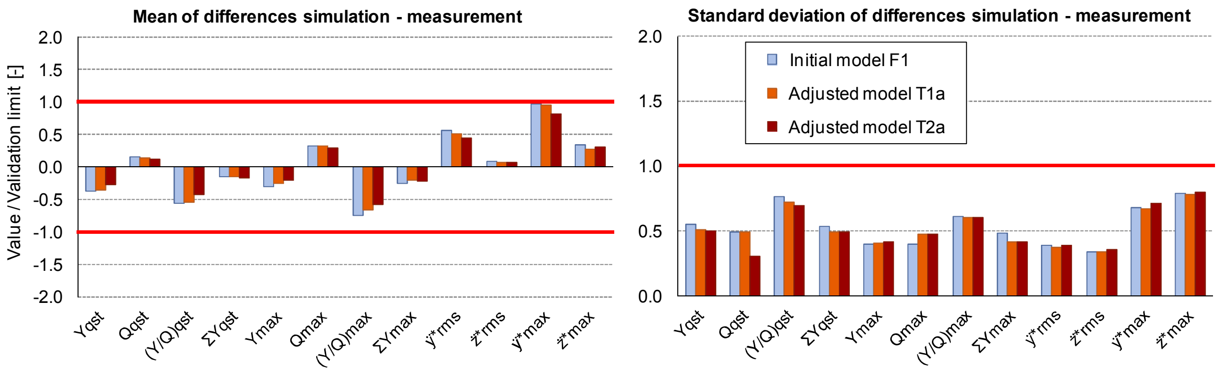


Fig. 7 Example of Bim passenger coach by Bombardier Transportation: F1 – initial model, T1a – model after adjustments by comparisons with stationary tests, T2a – model configuration T1a further adjusted by comparisons with on-track tests

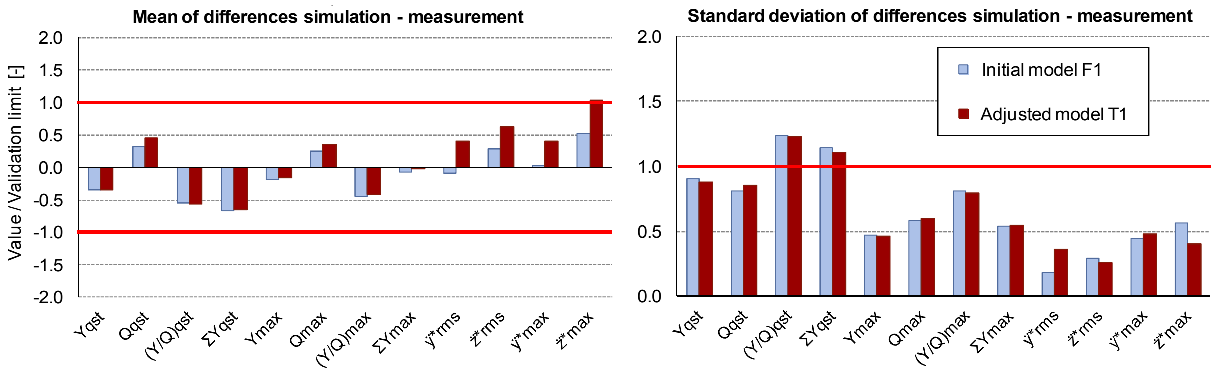


Fig. 8 Example of Bim passenger coach by IFSTTAR: F1 – initial model before comparisons with stationary tests, T1 – model after adjustments by stationary tests

Fig. 9 shows the effect of the vehicle model adjustments by comparisons with stationary tests on the validation results of the High Speed EMU for TCDD (Turkey) conducted by CAF. The stationary tests were divided in to 2 groups. The validation results are shown for the model before the comparisons and adjustments using stationary tests, but considering the measured static wheel loads, for the model after adjustments using the twist test (wheel unloading test) and for the model further improved by comparisons with the remaining available stationary tests (bogie rotational resistance test, measurement of roll coefficient and sway test). As can be seen, the model improvements by comparisons with the stationary tests are rather marginal; occasionally, the results for some quantities are even worse than before the adjustment. It is believed that this rather small model improvement by stationary tests is due to well known model parameters of this recently developed vehicle compared to older vehicles which were tested in the DynoTRAIN project. Nevertheless, the High Speed EMU model failed the validation. This can be explained by the missing data of track irregularities and rail profiles, which were replaced by estimated data. The presented examples demonstrate the importance of actual data, both infrastructure data as well as vehicle parameters, for a successful model validation.

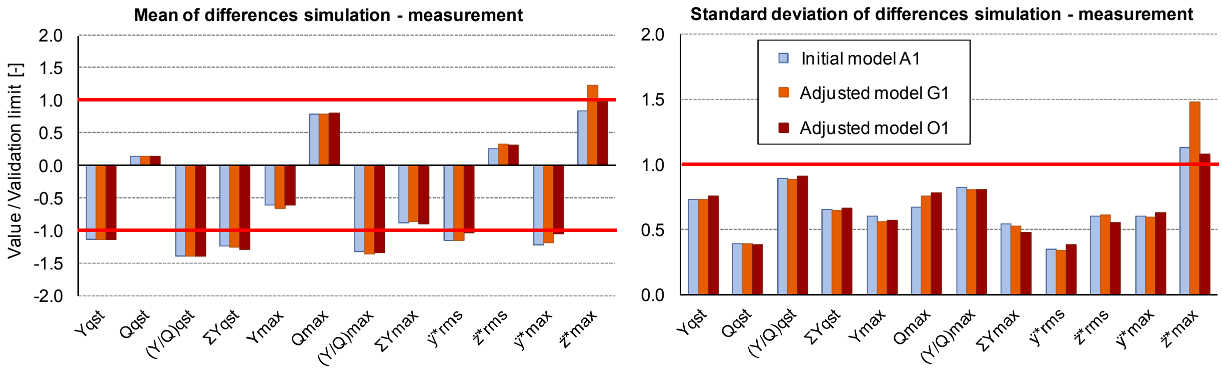


Fig. 9 Effect of model adjustments by comparisons with stationary tests on the validation results of the High speed EMU modelled by CAF: A1 - initial model before adjustments by stationary tests, G1 - model after adjustment by comparison with the twist test (wheel unloading test), O1 – model G1 further adjusted by comparison with bogie rotational resistance test, roll coefficient measurement and sway test

6. CONCLUSIONS

Investigations in the DynoTRAIN project compared simulations of several vehicle models with measurements from a testing campaign using a test train consisting of 4 types of vehicles and a total of 10 force measuring wheelsets, accompanied with continuous measurement of track irregularities and rail profiles. The analyses of these comparisons were used to develop criteria and limits proposed for the validation of multi-body vehicle models intended for simulations of on-track tests in the railway vehicle authorisation process.

The proposed model validation criteria and limits take into account errors in the measurement of running dynamics quantities, measurement of track layout and track irregularities, measurement of rail profiles and wheel profiles, scatter of test conditions as e.g. friction coefficient between wheel and rail as well as generally stochastic character of the test results. They 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 simulation – measurement is evaluated using values based on EN 14363 from at least 12 sections which represent all 4 test zones according to EN 14363 from straight track to curves with very small radius. The agreement between simulation and measurement is assessed comparing the mean value and standard deviation for a set of differences between simulated and measured values of each quantity with the proposed validation limit.

The proposed validation method allows identification of model weaknesses and a model improvement by adjusting uncertain model parameters. The investigations of the importance of comparisons with stationary tests showed, that the model adjustments using stationary tests results may be useful to identify unknown model parameters. The model improvement using stationary tests in regard to simulation of the on-track tests is often marginal if reliable vehicle model data is available; moreover, the model results can be even worse than before the model adjustment. A comprehensive comparison with the on-track tests is indispensable for reliable validation of a vehicle model intended for the simulation of on-track test. This validation may require not only measured track irregularity data and measured wheel and rail profiles, but possibly also additional measurements. For example, if the tested vehicles are used as propelling vehicles during the on-track test, a measurement of the longitudinal creep forces or the driving torque and an appropriate modelling of the tractive effort in simulations may be necessary for a successful model validation.

7. ACKNOWLEDGEMENTS

This abstract describes work undertaken in the context of the DynoTRAIN project, Railway Vehicle Dynamics and Track Interactions: Total Regulatory Acceptance for the Interoperable Network (www.triotrain.eu). DynoTRAIN is a collaborative project – medium-scale focused research project supported by the European 7th Framework Programme, contract number: 234079 and is led by UNIFE.

8. REFERENCES

[1] EN 14363:2005 Railway applications—Testing for the acceptance of running characteristics of railway vehicles—Testing of running behaviour and stationary tests, CEN, Brussels, 2005

[2] **Evans, J. - Berg, M.**: Challenges in simulation of rail vehicle dynamics, Vehicle System Dynamics 47 (2009), pp. 1023-1048

[3] **Bruni, S. - Vinolas, J. - Berg, M. - Polach, O. - Stichel, S.**: Modelling of suspension components in rail vehicle dynamics context. Vehicle System Dynamics 49 (2011), pp. 1021-1072

[4] prEN 14363:2013 Railway applications—Testing and simulation for the acceptance of running characteristics of railway vehicles—Running behaviour and stationary tests. CEN, Brussels, June 2013

[5] **Schwer, L.E.**: Validation metrics for response histories: perspectives and case studies. Engineering with Computers (2007) 23, pp. 295–309, Springer-Verlag London.