# METHODS FOR RUNNING STABILITY PREDICTION AND THEIR SENSITIVITY TO WHEEL/RAIL CONTACT GEOMETRY

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## ABSTRACT

This paper concentrates on the feasibility and limitations of nonlinear calculation methods applied for the prediction of bogie stability during railway vehicle engineering. Different types of methods as they can, or may be used in industrial applications are introduced. The results for varying wheel/rail contact geometries with high equivalent conicity are compared and discussed.

*Keywords:* bogie stability, wheel/rail contact

## 1. INTRODUCTION

The *bogie instability* or *bogie hunting* constitutes a safety criterion [1, 2]. The stability assessment plays therefore a major role in dynamic investigations during railway vehicle engineering. Due to the wide range of input conditions and possible methods of analysis, the stability prediction provides the most diversified type of running dynamics analysis.

Running stability depends decisively on the wheelset/track contact geometry, as characterised by the so-called equivalent conicity. The critical speed, at which the speed-dependent kinematic natural oscillations are no longer damped and a limit cycle occurs, will therefore be investigated and described in the conicity function, see Fig. 1. In general, two areas possessing low critical speed exist.

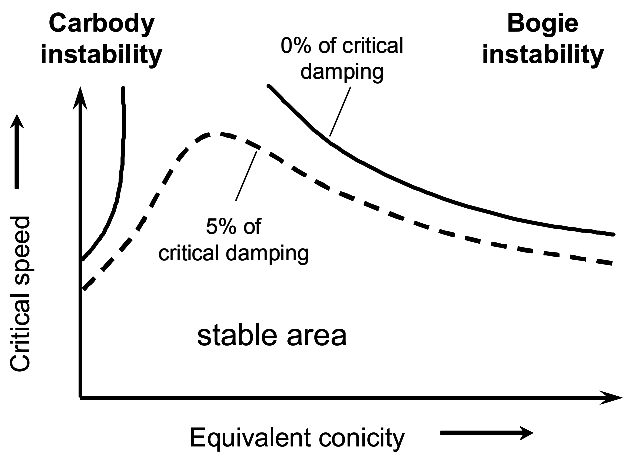


Fig. 1 Example of typical stability map (stability diagram)

For high values of equivalent conicity, the limiting mode is the bogie instability. As bogie stability decreases with increasing conicity, the bogie stability should mainly be investigated for upper range of equivalent conicity anticipated in operation. The bogies are unstable for all speeds higher than the critical speed.

In the low conicity range the limiting mode is a combined movement of carbody and bogies – *carbody instability*. If the low frequency bogie movement is coupled to the carbody movement, a deterioration of the lateral comfort behaviour by low damped carbody modes or by carbody instability can be observed. In comparison to the bogie hunting, the carbody instability can usually be suppressed with increasing speed.

This paper concentrates on the *bogie stability* prediction. A comparison of the diversified methods for prognosis and assessment of stability applied during the development of the bogies and vehicles is presented, as well as an investigation of the influence of the contact geometry.

## 2. NONLINEAR METHODS FOR THE STABILITY PREDICTION AND THE COMPARISON OF SAME

The selection of nonlinear method concerning stability is manifold. From a mechanical viewpoint, a system possessing the capability to oscillate can be viewed as stable if the oscillations decrease following discontinuation of the excitation. Should a limit cycle having constant amplitude arise at a particular running speed, this speed is defined as a critical speed. However, in railway practice and in the specifications concerning the authorisation of the vehicles for operation [1, 2] the stability of the bogies is defined by way of the limit values of the measuring quantities. Should the limit value be exceeded, the running behaviour can be described as being unstable.

In addition to the differing definitions of the stability limits in mechanics and in railway practice, various wheelset/track and vehicle models, and varying types of excitations can be applied. According to the type of excitation applied, differentiation can be made between analyses

- without excitation (running on ideal track, starting from the limit cycle and reducing the speed until a stable bogie motion is achieved)
- with excitation by a singular irregularity, followed by an ideal track (or with short irregularity sequence followed by an ideal track), with or without variation of the excitation amplitude
- with excitation by stochastic (measured) track irregularity.

The methods of nonlinear stability analysis were compared with the aid of four differing examples of wheelset/track contact geometries with high equivalent conicity. At a wheelset lateral movement amplitude of 3 mm, two of the contact geometries demonstrate the same equivalent conicity of 0.4 (04A, 04B) and the other two the equivalent conicity of 0.6 (06A, 06B). Although the conicity at an amplitude of 3 mm is the same, the progression of the conicity as a function of the lateral amplitude demonstrates significant differences. In the case of the quasi-elastic contact [4], which demonstrates realistic contact conditions and is therefore applied during simulations, one of the combinations beneath 3 mm demonstrates with lateral amplitude increasing equivalent conicity (04A, 06A) whilst the other demonstrates decreasing equivalent conicity, see Fig. 2.

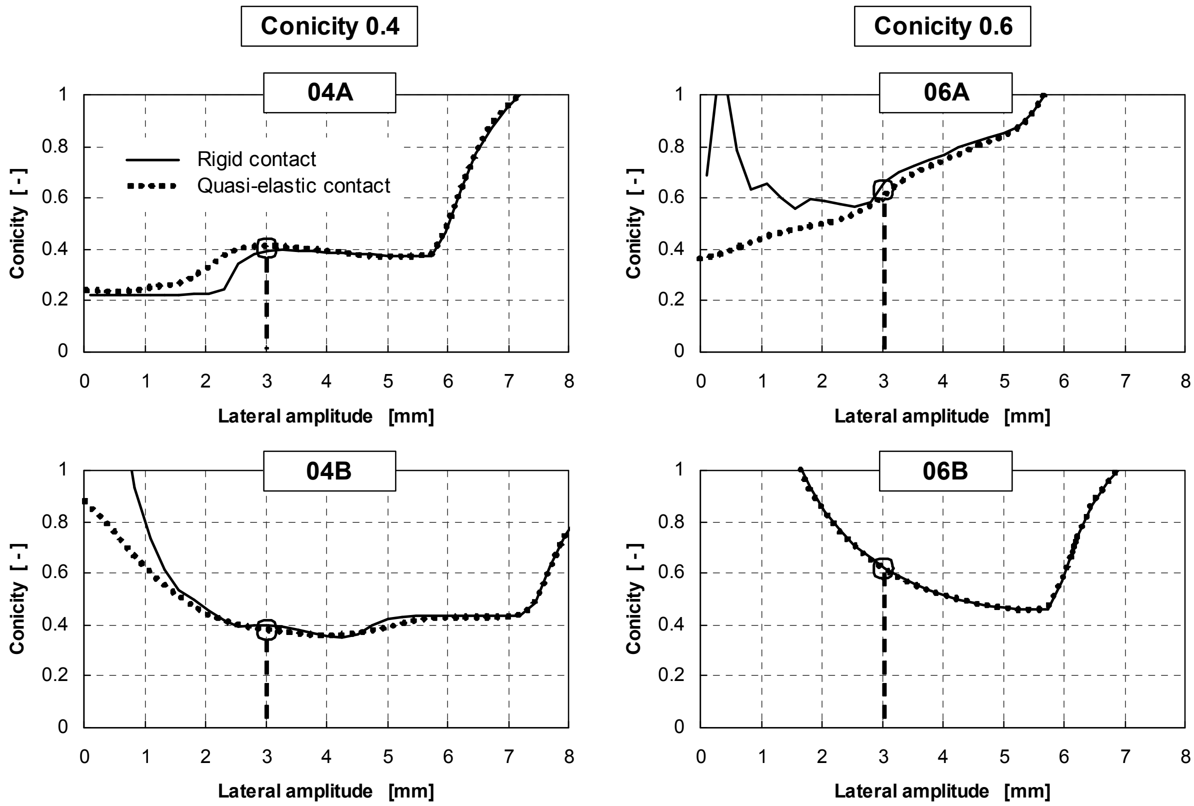


Fig. 2 Conicity diagram of examined combinations wheelset/track

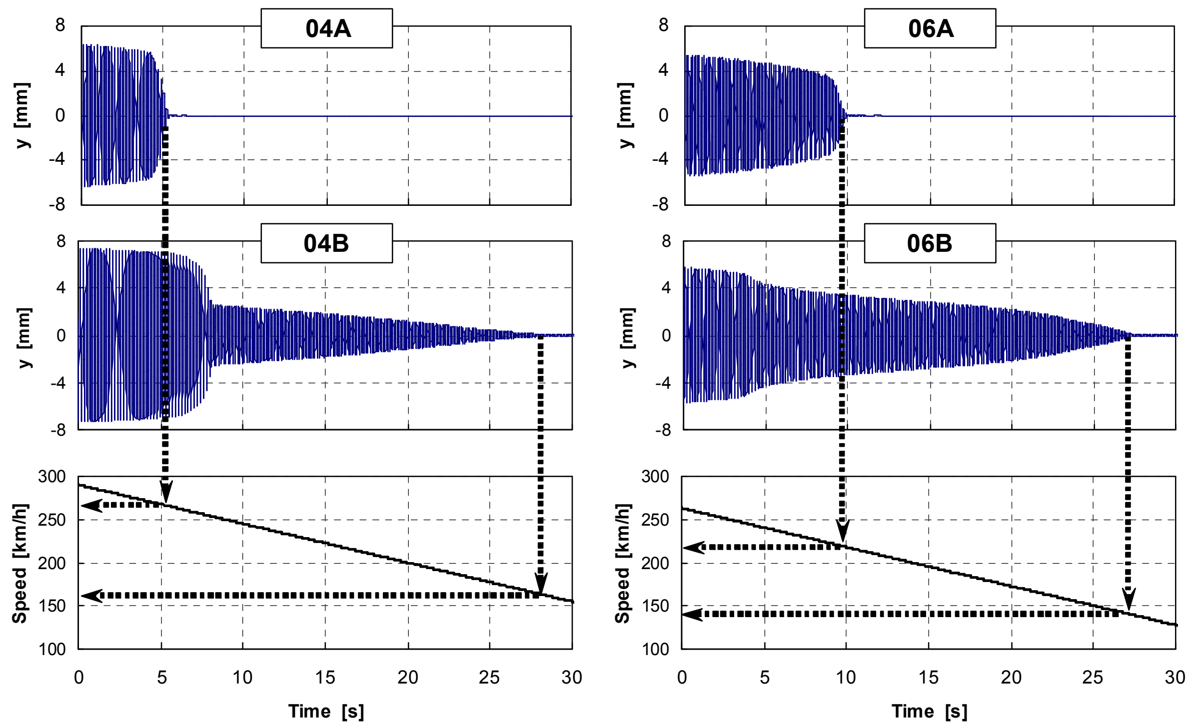


Fig. 3 Simulations of run with decreasing speed

To compare the methods, a model of a four-car articulated vehicle in simulation tool SIMPACK was used. The friction between wheel and rail was set to 0.4 (dry rail). The results are given for the trailing wheelset of the first bogie, at which the stability limits are first reached.

***Method without excitation (running on ideal track):***

In this case a high speed during which the bogie moves in a limit cycle is used as initial condition and a continuous speed reduction takes place [5]. The speed at which the vibrations subside is designated as being the critical speed, see Fig. 3. In one case (04A, 06A) the vibrations stop abruptly, whereas in the other case (04B, 06B) the wheelsets continue to vibrate in a small limit cycle, only stabilising at a significantly lower speed, which subsequently leads to differing critical speeds at the same conicity.

***Methods with single excitation:***

Investigating damping behaviour following a single lateral track excitation, stability can be assessed; however the damping behaviour at the same conicity can differ for various contact geometries as can be seen in Fig. 4 for the investigated examples of contact geometries.

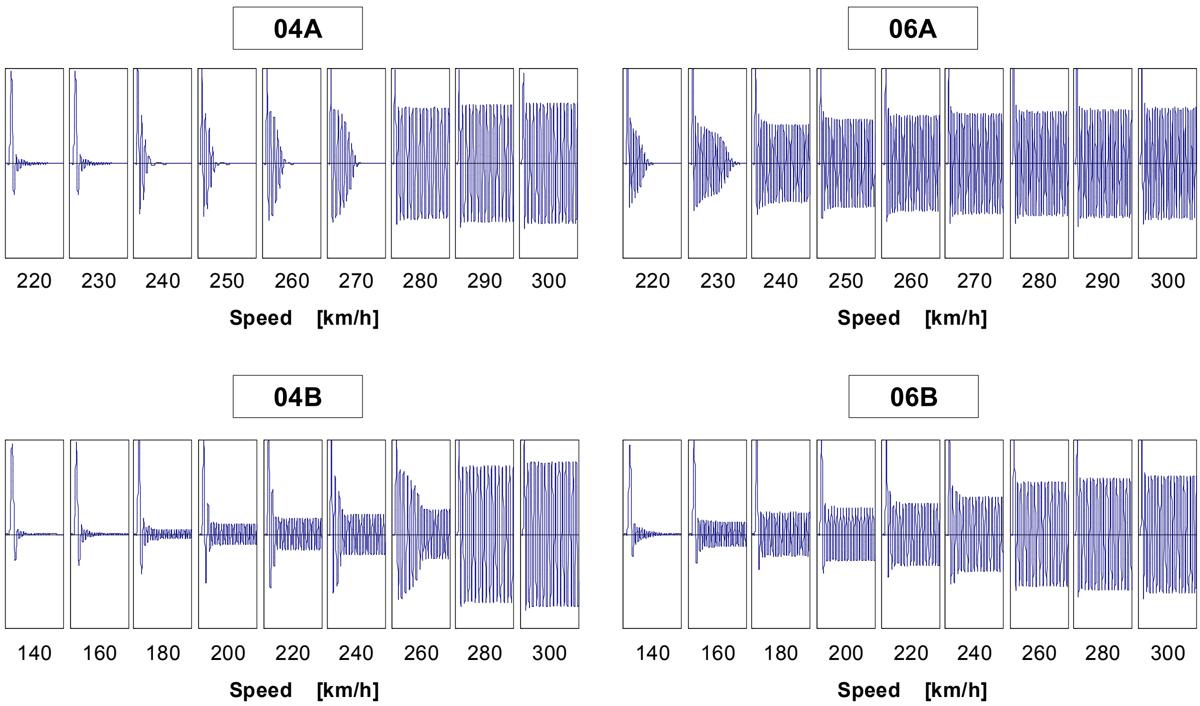


Fig. 4 Lateral wheelset displacement following a single lateral excitation

By varying the amplitude of single excitation, the dependency of critical speed on the level of excitation can be investigated. If the amplitude of the stable limit cycle is presented in function of speed, a bifurcation diagram [6, 7] results, see Fig. 5. In certain cases, depending on the excitation amplitude, the solution can vary between a damped movement and a limit cycle. In accordance with the profile combination, the bifurcation diagram assumes two basically divergent forms, see Fig. 6. In the first case (profile combinations 04A, 06A) an unstable attractor develops, whereas in the other case (04B, 06B) the amplitude of the limit cycles increases continuously.

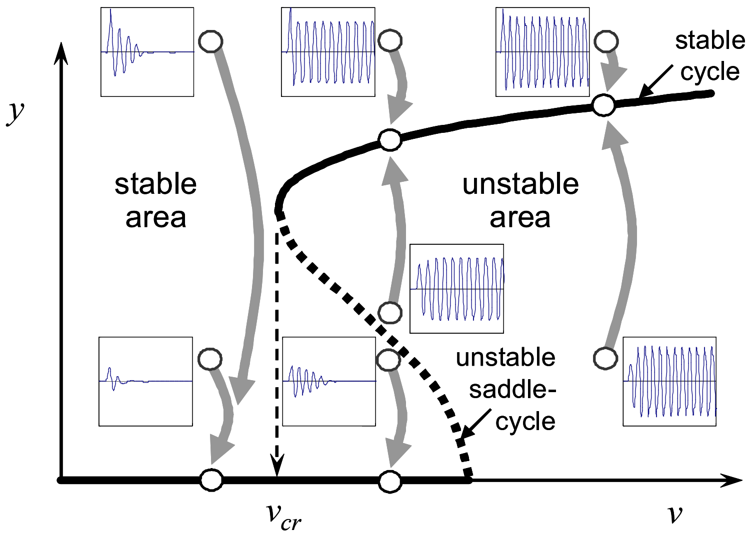


Fig. 5 Bifurcation diagram as result of the damping behaviour after an excitation

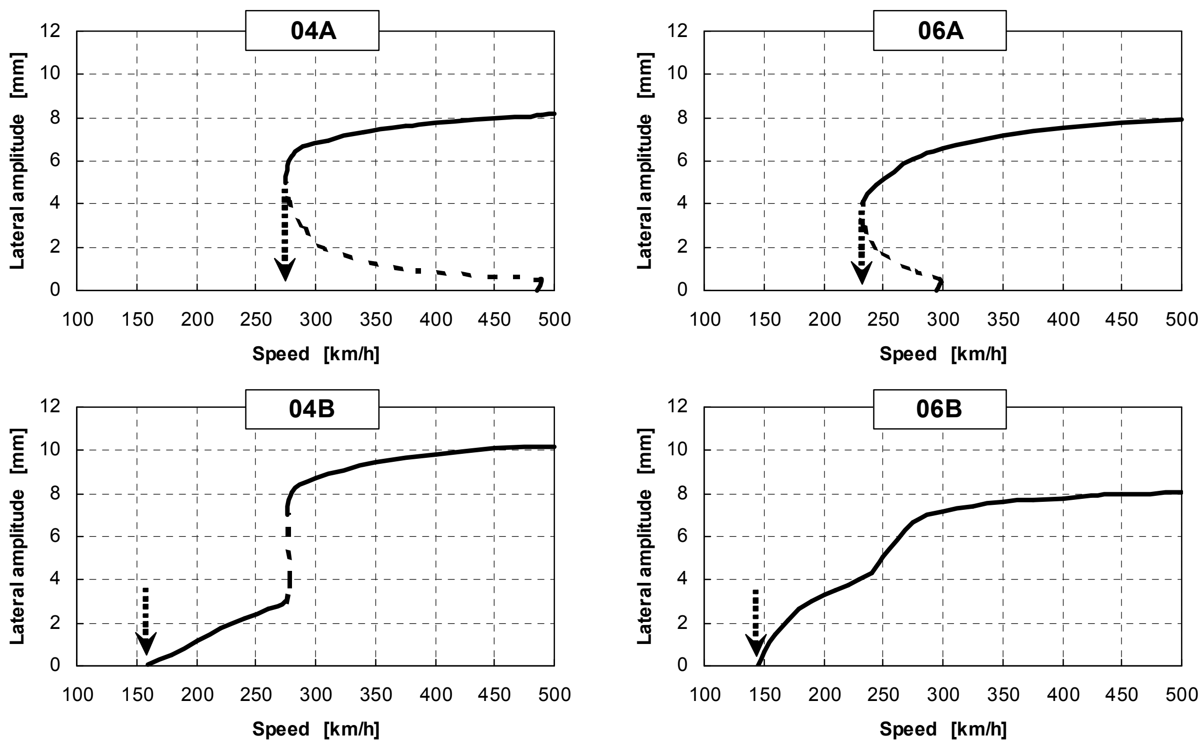


Fig. 6 Bifurcation diagrams for investigated profile combinations

***Methods with stochastic excitation due to track irregularity:***

In order to predict bogie stability, methods specified for measurements and acceptance tests can also be applied. Running on straight track with measured irregularities is simulated and instability criteria for vehicle acceptance tests of vehicles having bogies [1, 2] are applied for assessment:

- rms value of the sum of guiding forces (normal measuring method)
- rms value of lateral acceleration at bogie frame (simplified measuring method).

Another criterion still applied for on-line surveillance is the peak value of lateral acceleration on the bogie frame, as defined in the (now invalid) version of UIC 515 [3]. The limit value is seen to be exceeded when the value 8 m/s² occurs during more than 6 consecutive cycles (in the diagrams: 0% = not exceeded, 100% = exceeded).

An evaluation of limit exceedance for the wheel/rail combination 04A is illustrated in Fig. 7. A comparison of the results using different criteria mentioned is given in Fig. 8. The criteria investigated are comparable against each other; however the criterion of the rms value of lateral acceleration at bogie frame leads to a slightly lower permissible speed for the investigated vehicle. In contrast to the method without excitation, the results for both contact geometries for the same value of equivalent conicity lie close to each other in this case.

In order to investigate the influence of track irregularity, for profile combination 04A the applied track irregularities were scaled with factors of 0.25, 0.5 and 2.0 and compared with simulation results of previous track irregularities. Fig. 9 clearly illustrates that, at increasing amplitude values, the difference between the value of the examined criterion and limit value decreases. However, the stability limit exceedance only relocates itself slightly. An exception is constituted by the track irregularity with factor 0.25, which demonstrates more than 50% reserve to limit value at 310 km/h; but alters abruptly at 320 km/h to an exceedance of the limit values. This behaviour can be explained with the aid of the bifurcation diagram (diagram 04A in Fig. 6). Should the scale factor 0.25 be applied, the highest peak-to-peak lateral excitation achieves approx. 2 mm. At this excitation below 310 km/h the wheelset vibration subsides and springs to the stable attractor. This example demonstrates that, in order to decisively investigate the stability limit, the excitation must be sufficiently large.

In order to interpret the interrelationships between the measurement limit values, the calculations with an excitation by single irregularity with 8 mm amplitude are carried out, and the behaviour of the vehicle evaluated according to measurement criteria after the transient have subsided, see Fig. 10. If the illustrated values are greater than zero, this indicates that the wheelset is vibrating with a limit cycle. As demonstrated in Fig. 10, in one case a limit cycle evolves abruptly, leading to exceedance of the limit values for bogie instability, whereas in another case limit cycles evolve at a significantly lower speed, which however lie beneath the limit values and slowly increase at rising speed. Should only the exceedance of the limit values be compared, both the above cases will achieve approximately the same critical speed at the same conicity. However, should the presence of a limit cycle be viewed as constituting the stability limit, the critical speeds will differ significantly even at the same conicity.

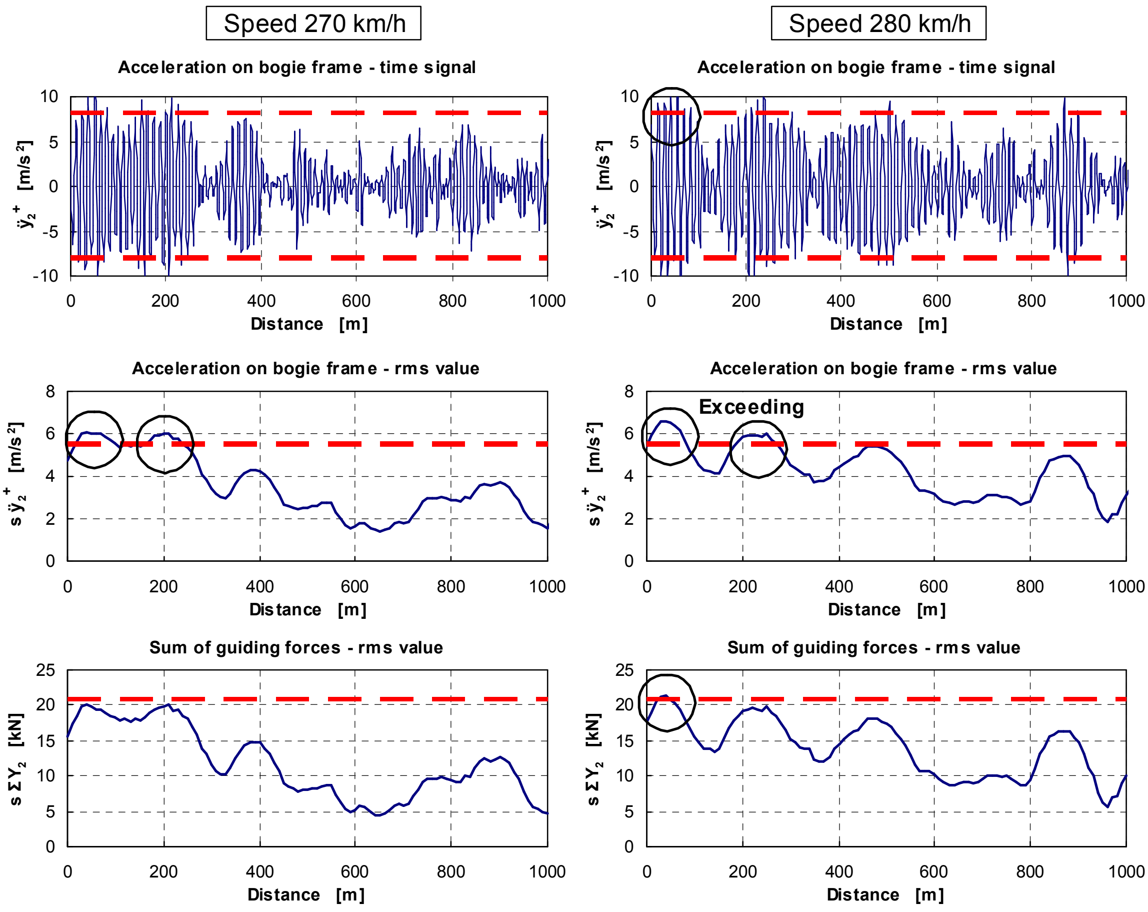


Fig. 7 Stability analysis by simulation of run on track with irregularities (case 04A)

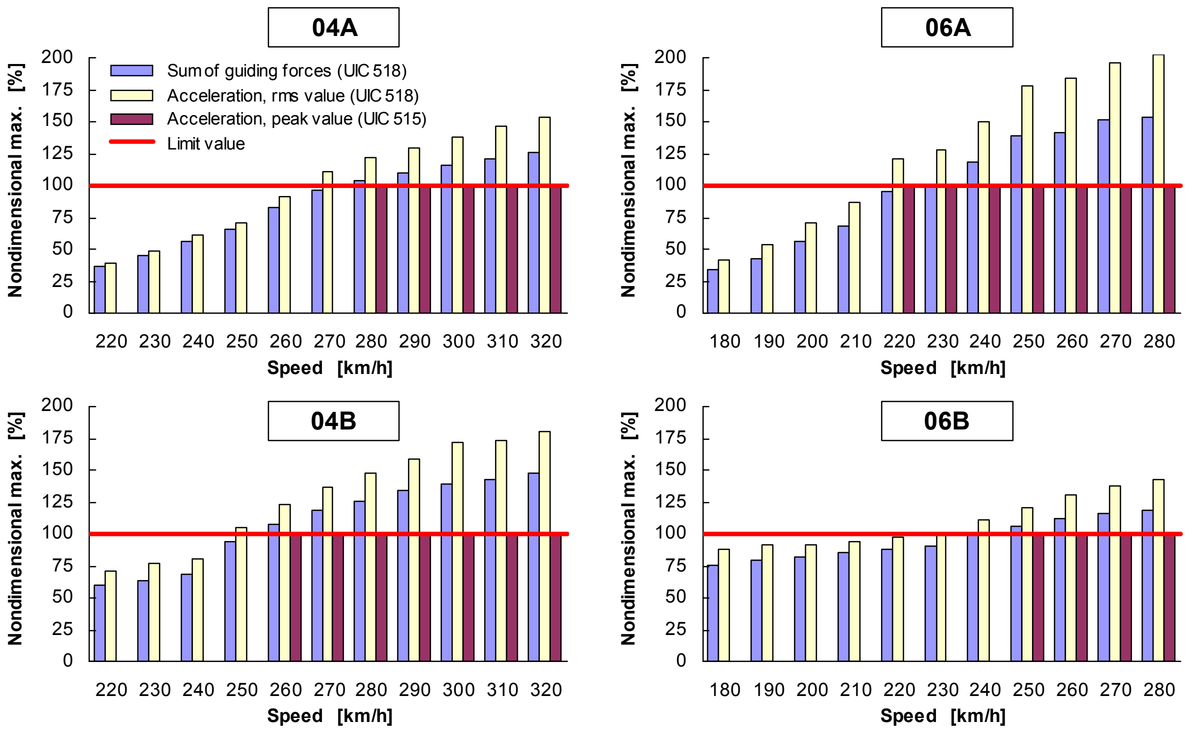


Fig. 8 Results of stability analysis running on track with irregularities

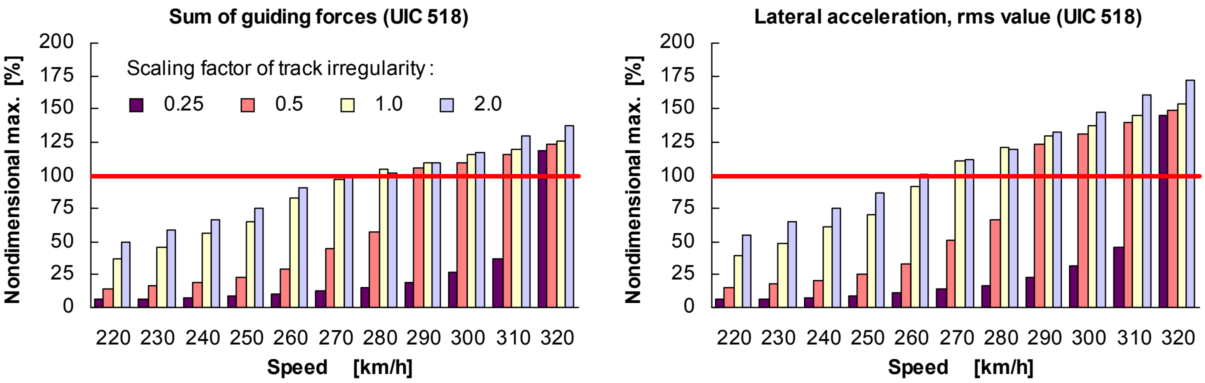


Fig. 9 Influence of track irregularity on the results of the stability analysis (case 04A)

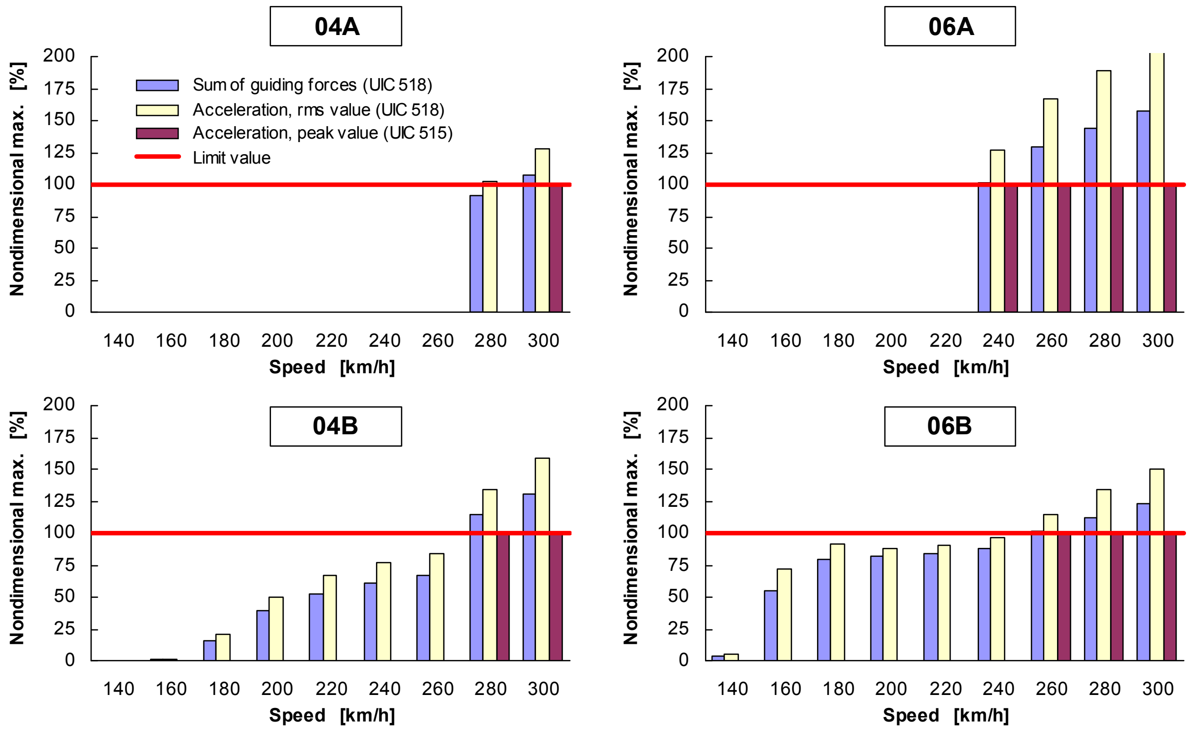


Fig. 10 Stability analysis using single lateral excitation and criteria from measurements

## 3. COMPARISSON OF RESULTS AND DISCUSSION

A comparison of the critical speeds (round-up to 5 km/h) determined by individual nonlinear methods is shown in Table 1. The lowest critical speeds will usually be achieved in cases without excitation, if the simulation at a high speed commences with a limit cycle and the vehicle is stabilised through a decrease in speed.

The greatest deviations from the critical speed take place when small limit cycles occur (04B, 06B) and these are taken into account for the evaluation in conformance with the principles of mechanics (results printed in bold-type in Table 1).

| Wheel/rail contact geometry | Conicity (quasi-elastic contact) | Without excitation, starting from a limit cycle and reducing the speed | Single lateral excitation 8 mm | | | | | Measured track irregularity | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bifurcation diagram | Oscillation fully damped after few seconds | Instability criteria for measurements | | | Instability criteria for measurements | | |
| | | | | | Sum of guiding forces (UIC 518) | Acceleration, rms value (UIC 518) | Acceleration, peak value (UIC 515) | Sum of guiding forces (UIC 518) | Acceleration, rms value (UIC 518) | Acceleration, peak value (UIC 515) |
| 04A | 0.41 | 265 | 275 | 275 | 290 | 280 | 280 | 275 | 265 | 280 |
| 04B | 0.39 | **160** | **165** | **160** | 275 | 265 | 270 | 255 | 250 | 260 |
| 06A | 0.60 | 220 | 230 | 230 | 235 | 235 | 240 | 230 | 215 | 220 |
| 06B | 0.62 | **140** | **145** | **150** | 260 | 245 | 250 | 240 | 230 | 250 |

Table 1: Critical speeds predicted by differing methods and criteria

In other cases the resultant critical speeds achieve similar values for all methods. However, in the example presented the differences can amount up to 20% at the same equivalent conicity depending on the method and the contact geometry applied. This uncertainty in the stability prediction must be taken into consideration during the design of the vehicle.

All the methods proposed can be described as being well-suited; however, the properties of the wheel/rail contact geometry have to be taken into consideration. If the contact geometry is specified by the conicity, those wheel/rail combinations are recommended, at which the equivalent conicity as function of the lateral amplitude increases within a range of 0 to 3 mm or remains relatively constant, and which do not lead to small limit cycles having amplitudes beneath approx. 3 mm. In the presented investigation the combination 04A for conicity 0.4 and 06A for conicity 0.6 applies. If the worst case conditions of the wheel/rail contact geometry are specified by the shape of the wheel and rail profiles, e.g. from measurements, and the limit cycles with small amplitude occur, the critical speed should be judged by the measurement criteria applied in the railway engineering.

## 4. CONCLUSIONS

The stability prediction of a railway vehicle depends significantly – besides other parameters – on the c*ontact geometry wheelset/track* together with the *method* chosen.

The *nonlinear methods* enable a detailed stability analysis, but may lead to significant differences in the results amongst each other. The results are similar if the potentially occurring limit cycles with low amplitude are not considered to be a deviation from the stability limit as applied in railway engineering. Even when the small limit cycle phenomenon does not manifest itself, partially deviating results arise for individual nonlinear methods. These deviations should be taken into consideration during the stability prediction by means of a safety margin.

For the analysis of the worst case situation with regard to bogie stability a *contact geometry* with high equivalent conicity is decisive. The equivalent conicity provides a suitable parameter for the general characterisation of the contact wheelset/track from a stability standpoint. However, an exact specification of the wheel/rail contact geometry is only possible through specification of the wheel and rail profile, rail inclination, and track gauge.

The *linearisation of the wheel/rail contact* and the analysis of the equivalent conicity in function of the wheelset lateral amplitude can enable a better assessment of the nonlinear stability analyses. If the wheel/rail contact geometry is only defined by the specification of the equivalent conicity, it is recommended that in nonlinear analyses profile combinations are applied in which the equivalent conicity as function of the lateral amplitude between 0 to 3 mm increases or remains practically constant, and which do no lead to small limit cycles possessing amplitudes beneath approx. 3 mm.

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