Evaluation of the hunting behaviour of a railway vehicle in a curve

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Introduction

Railway vehicles can suffer from a self-excited vibration mechanism known as 'hunting'. Hunting is a combination of lateral and yaw vibrations of the wheelsets and bogies caused by the conversion of energy from the traction system into parasitic oscillation of the vehicle in the horizontal plane.[1] Vehicle hunting occurs at relatively high speed, and the minimum speed at which the vibration onsets, is known as the 'critical speed' of the vehicle. Under certain circumstances, it can be a rather violent vibratory phenomenon, which can impair ride quality and, in extreme cases, generate permanent deformation of the track and affect ride safety. Therefore, appropriate analysis of the problem is required in the vehicle design and acceptance stages to make sure that the vehicle's critical speed falls beyond the maximum service speed.

Lateral and yaw vibrations of railway wheelsets was first noted by Stephenson[2] and received its first comprehensive explanation in the 1960s.[3] At that time, however, the problem was treated as a linear stability problem, which explains why the examination of hunting occurrence is still called 'stability analysis' by railway specialists. More recent investigations initiated by Moelle and Gasch[4] and by True[5,6] clarified the importance of nonlinear effects and hence the need to formulate the problem in the form of a bifurcation analysis. It was shown in particular that, considering a vehicle running on a perfectly straight and aligned track, at low speed only one stationary solution exists which, at a certain speed, known as the 'linear critical speed' v_c loses stability in a Hopf bifurcation. Polach[7] showed that the bifurcation can be either a sub-critical or super-critical one, depending on the actual shape of the wheel/rail profiles. If the bifurcation is of sub-critical type, then a stable periodic solution exists at speeds lower than the linear critical speed v_c, and it is more convenient to assess vehicle stability in terms of the lowest speed for which this periodic solution exists, which is known as the 'nonlinear critical speed' v_n.

The problem is further complicated by the fact that a real vehicle will always run on an uneven track, hence being subjected to random excitation caused by track irregularity. Therefore, in experimental practice the critical speed is defined as the speed at which a given measure of bogie vibration exceeds a threshold.[8] This poses the problem of how the 'operational' definition of the critical speed that is based on line tests, compares to the nonlinear critical speed obtained from a bifurcation analysis, since cases exist in which the stable periodic solutions have small amplitudes and will not produce the overcoming of the vibration thresholds defined by the standards that govern vehicle acceptance.[7,9]

As previously summarised, the question of how a stability analysis can be performed for a railway vehicle running on tangent track can now be considered in a satisfactory manner. However, less research work has been performed to extend stability analysis to the case of a vehicle running through a curve. The few papers that have been published on this topic[10–15] support the conclusion that the critical speed could be lower in a curve than on a tangent track for the same vehicle, but no comprehensive explanation of the mechanism of vehicle hunting in a curve has been provided.

This work originates from experimental observations of lateral vibration of a bogie on a high-speed vehicle running through a large radius curve, which could not be observed in tangent track sections. Despite the level of vibration fortunately being well below the threshold corresponding to the operational definition of the critical speed, this finding supports the conclusion that the vehicle could be 'less stable' in a curve than on a tangent track, a circumstance that needs to be properly taken into account not only in the vehicle design stage, but also in the regulatory acceptance procedure.

It should be noted that the term 'hunting' is used in different ways within the railway engineering community; in some cases, it is used to refer to a growing oscillatory lateral motion, whereas most of the standards try to narrow this definition to cases where the level of a bogie's lateral acceleration exceeds a specified threshold. In this paper, the term 'incipient hunting' will be used to denote a lateral oscillation of the bogie frame that occurs in a narrow and well-specified frequency range and is not justified by the presence of specific wavelengths of track irregularity, although the actual level of lateral acceleration is below the thresholds proposed by the standards.

The aim of this paper is therefore to:

- propose a physical explanation for the occurrence of incipient hunting in a curve at a lower speed than in a tangent track;
- define a numerical model able to reproduce the experimental findings;
- use that model to compute the vehicle's critical speed in curves of different radii and in tangent track.

Until today, a relatively small number of papers have addressed the specific issue of rail vehicle stability in a curve. True and Nielsen[10] and True et al.[11] studied the nonlinear critical speed of Cooperrider's bogie (a well-known model of a single railway bogie with primary and secondary suspensions) in a curve. In the first paper, the study was confined to curve radii between 250 and 450 m, which correspond to short radius curves, whereas in the second paper the analysis was performed for curve radii in the 600–2000 m range. In both studies, the conclusion was that the critical speed in a curve is lower than on a tangent track. Zeng and Wu[12,13] performed a similar study using a model of a complete high-speed railway vehicle with two bogies and one carbody; they considered the effect of traction/compression forces in the couplers for curve radii in the 4000–8000 m range corresponding to high-speed lines. Also, in this case, the conclusion was that the critical speed decreased with track curvature, but only a qualitative explanation was provided for this finding. Zboinski[14] and Zboinski and Dusza[15] examined the stability of a two-axle rail car with linear suspensions, and proposed the use of 'stability maps' consisting of bifurcation plots for different curve radii and for tangent track. They concluded that the nonlinear critical speed is independent of the curve radius, a statement that is not in agreement with other published studies and with the results presented in this paper.

This paper is organised as follows: in the section 'Vehicle stability along a curved track: experimental evidence' experimental evidence of the occurrence of incipient hunting motion in large radius curves for the vehicle under consideration is presented. In the section 'Qualitative analysis of vehicle stability in a curve', a qualitative explanation of this phenomenon is provided. In the section 'The mathematical model of the vehicle and its validation' a multi-body model of the vehicle is introduced and validated and in the section 'Results' the model is used to confirm the qualitative statements made in the section 'Qualitative analysis of vehicle stability in a curve' and to extend the analysis of the possible onset of incipient hunting to curve radius values not covered by line measurements

Vehicle stability along a curved track: Experimental evidence

Line tests performed on Italian high-speed lines using an experimental train have provided experimental evidence of a different behaviour of non-powered bogies running on tangent track and in large radius curves. Some of the coaches in the experimental train were fitted with an accelerometer that measured the vertical and lateral accelerations of the axleboxes, bogie frame and carbodies. In this section, only bogie frame accelerations are presented, to analyse the vehicle's running behaviour. The bogie for which results are shown is equipped with ORE S1002 profile wheels and, at the time when the measurements presented here were taken, all wheels showed a very low amount of wear, so that the actual measured profile was close to the theoretical one. The track was made of UIC60 rails with 1 : 20 inclination and 1435 mm gauge. Curves mostly had a radius $R = 5500$ m and cant $h = 105$ mm or $R = 6000$, $h = 95$ mm, the balance speed being approximately 220 km/h in both cases. In this section, only the first curve geometry was considered.

Figure 1 shows the time history of the lateral acceleration of the front bogie, measured above the axlebox, when the vehicle was running at 308 km/h along a line section consisting of a tangent track followed by a curve with $R = 5500$ m, $h = 105$ mm: an increase in the amplitude of vibration is apparent when the vehicle negotiates the curve.

This finding was confirmed by the measured band-pass-filtered root-mean square (RMS) value of the lateral acceleration obtained using the method for critical speed assessment defined by EN14363 as the 'simplified measuring method', i.e. based on measuring bogie accelerations instead of wheel/rail contact forces.[8] In Figure 2 the band-pass-filtered RMS value of the lateral acceleration of the bogie frame (evaluated using a 100 m sliding window) is shown for two different vehicle speeds (260 and 308 km/h) as function of the position, with the start and end of the full curve section being marked by vertical dashed lines. In agreement with the data treatment process stated by EN14363, the acceleration signal is band-pass filtered to consider only the harmonic contents in the frequency range of ±2 Hz around the dominating frequency of the signal. The plot shows that at both speeds, the filtered RMS value is approximately three times higher along the full curve section in comparision with that for the tangent section. However, even in the curve, the maximum of the RMS value for the acceleration is well below the limit for stability, which is 5.44 m/s^2 for the bogie under consideration.

Figure 3 compares the Fourier spectra of the lateral acceleration in tangent track and in a curve, both computed on a 12 s basis with an overlap of 3 s, for a vehicle running at 308 km/h. For the tangent track case, the spectrum is representative of a broad-band random signal, showing that the lateral vibration of the bogie is produced by the response of the vehicle to track irregularity. When the curving condition is considered, the shape of the spectrum changes to a narrow-band random signal with prevailing contributions in the frequency range around 7 Hz, which is characteristic of hunting motion for the vehicle considered in this paper.

An analysis of track irregularity measurements, see Alfi et al.[16] for details, allowed the conclusion to be drawn that the observations of higher levels of vibration and the presence of a dominating frequency in the spectrum in the lateral acceleration of the bogie across a curve were not related with the condition of the track, and particularly with specific irregularity wavelengths that only appear in the curve. It was thus concluded that an incipient hunting motion was observed in the 5500 m radius curve, although with levels of vibration well below the limits prescribed by EN14363, whereas in the tangent track no symptom of incipient hunting were observed.

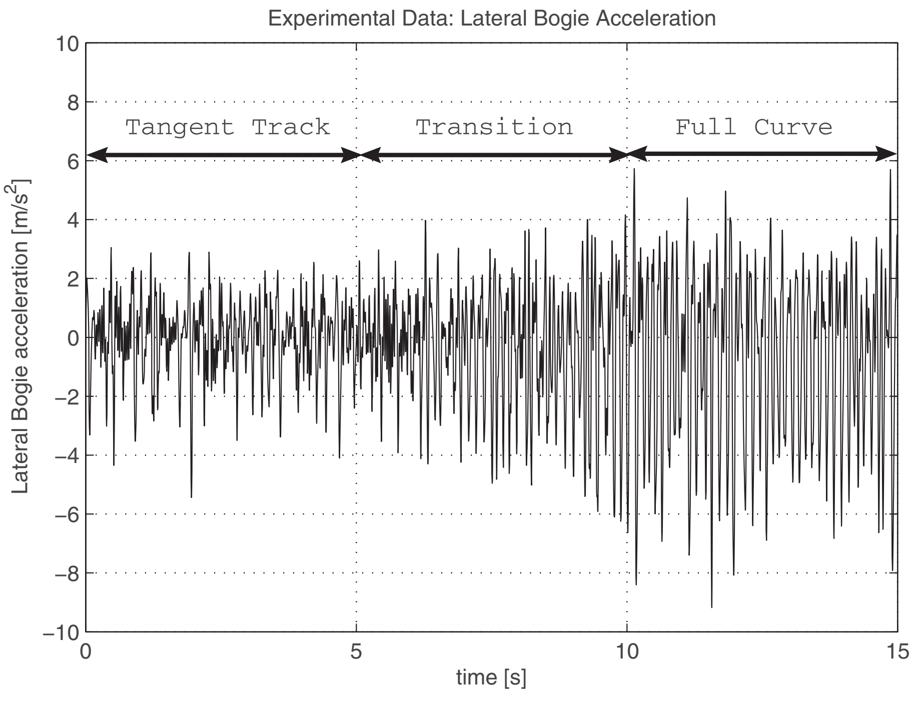

Figure 1. Results from line measurements: time history of the lateral acceleration of the bogie when the vehicle negotiates a curve with a radius of 5000 m at 308 km/h.

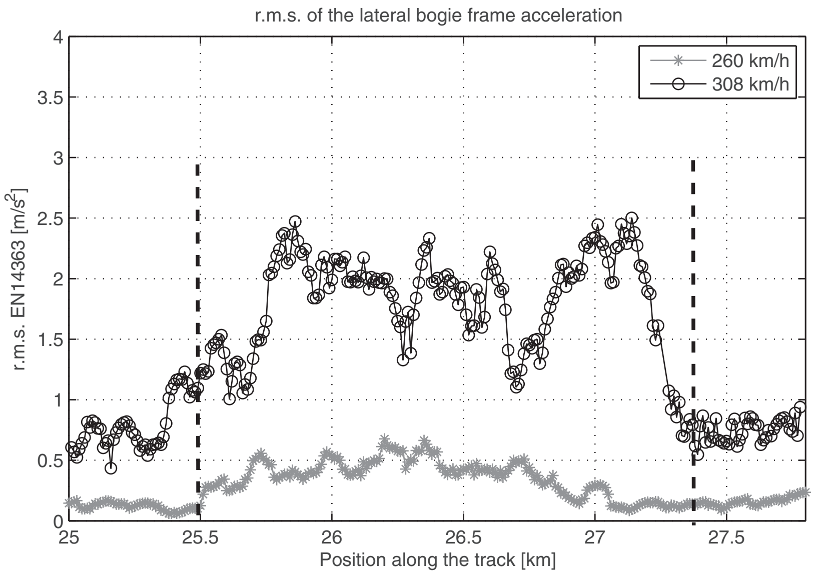

Figure 2. Results from line measurements: RMS value of the lateral acceleration of the bogie over 100 m when the vehicle negotiates a curve with a radius of 5500 m at 260 and 308 km/h.

This observation is in agreement with the numerical results reported in the literature.[10–13]

Qualitative analysis of vehicle stability in a curve

In this section, a qualitative discussion is given of the reasons for the running behaviour experimentally observed as reported in the previous section. As previously mentioned, the vehicle under consideration was equipped, at the time when the tests were performed, with very lightly worn wheel profiles; hence, they were very similar to the theoretical values of an ORES1002. Figure 4(a) shows the rolling radius variation diagram computed for the measured wheel profiles coupled with UIC 60 rails with 1 : 20 inclination and 1435 mm gauge. The diagram is slightly non-symmetrical, on account of small differences in the profiles measured on the two wheels. In the central region of the diagram, a very low conicity is expected whereas the extent of conicity considerably increases for a lateral shift of the wheelset with respect to the rail that causes the contact point to move to the flange root of the wheel profile. This is actually the region where contact takes place for both the leading and trailing wheelsets of the bogie when the vehicle negotiates a large radius curve such as the one considered in the experiments with a cant deficiency falling in the range of values covered by the line presented in this paper. Therefore, the wheelsets are expected to experience a very low conicity when running in tangent track, which may inhibit hunting vibration even at very high speeds, and a larger conicity when running through a large radius curve, which will favour the onset of incipient hunting vibration.

In order to confirm this observation, the conicity diagram $\lambda(\Delta y)$ was computed for the considered wheel/rail coupling using the harmonic linearization method:[9]

$$\lambda(\Delta y) = \frac{\int_0^{2\pi} \Delta R(y(\tau)) \sin \tau \mathrm{d}\tau}{2\pi \Delta y} \quad \text{with} \quad y(\tau) = y_0 + \Delta y \sin \tau \tag{1}$$

where y_0 is the steady state lateral position of the wheelset, Δy is the amplitude of the wheelset's lateral movement around the steady state position and $\Delta R(y)$ is the rolling radius difference function shown in Figure 4(a). Figure 4(b) and (c) show, respectively, the conicity diagrams obtained for the centred steady state position $y_0 = 0$ and for the steady state shift $y_0 = -6$ mm, this latter value being consistent with the average position of the leading wheelset in the full curve region for the considered vehicle's running condition. It is confirmed that the equivalent conicity corresponding to the laterally displaced wheelset is much larger than for the centred wheelset, providing a qualitative justification of the different running behaviour of the vehicle observed for tangent track and curves.

However, with an increase in track curvature the steady state longitudinal and lateral creepages are expected to increase on both the inner and outer wheels of the wheelset. This induces a saturation effect in the creep forces and hence a lower value of the creep coefficients describing the linearised creep force–creepage relationship.[1] Again from a qualitative point of view, this is likely to reduce the self-excitation mechanism responsible for hunting, which originates from the creep force–creepage relationship. Hence, it

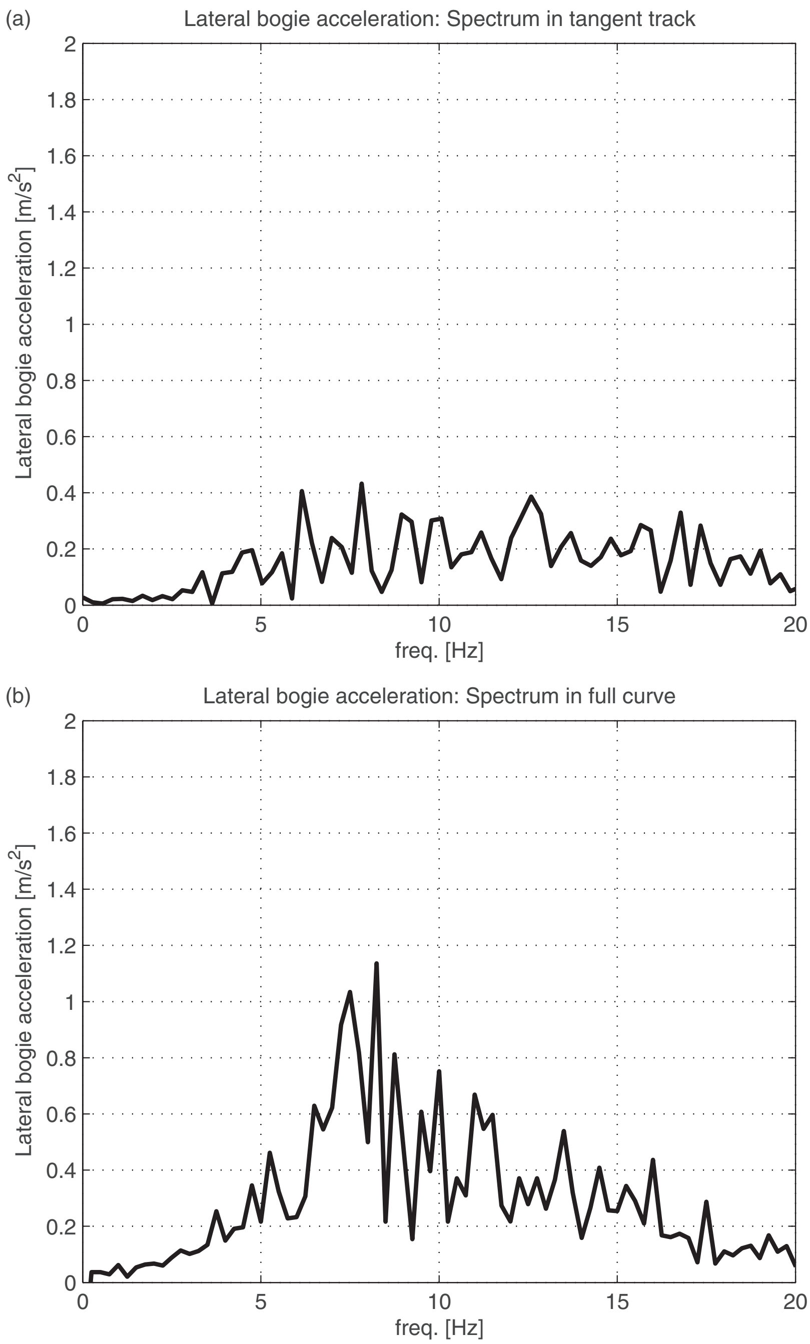

Figure 3. Results from line measurements: (a) spectrum of the lateral acceleration of the bogie over 5 s on tangent track and (b) spectrum of the lateral acceleration of the bogie over 5 s on a full curve. Vehicle speed 308 km/h.

is expected that for relatively large track curvature, incipient hunting is suppressed by this saturation effect.

To represent this situation, a saturation coefficient S_c is defined as:

$$S_c = 1 - \left(\frac{T}{\mu N}\right) \tag{2}$$

where T is the magnitude of the resulting steady state creep force (vector sum of the longitudinal and transverse components), μ is the friction coefficient and N is the normal load. The saturation coefficient will reach its maximum value ($S_c = 1$) for a zero steady state creep force, which leads to the maximum value of the linear coefficients of the creep force, and will go down to zero in full saturation condition, corresponding to a zero value of the linear coefficients of the creep force with no possibility for incipient hunting to occur.

With increasing curvature of the curve, the equivalent conicity λ increases, as shown above, promoting incipient hunting, whereas the saturation coefficient S_c decreases, eventually inhibiting incipient hunting

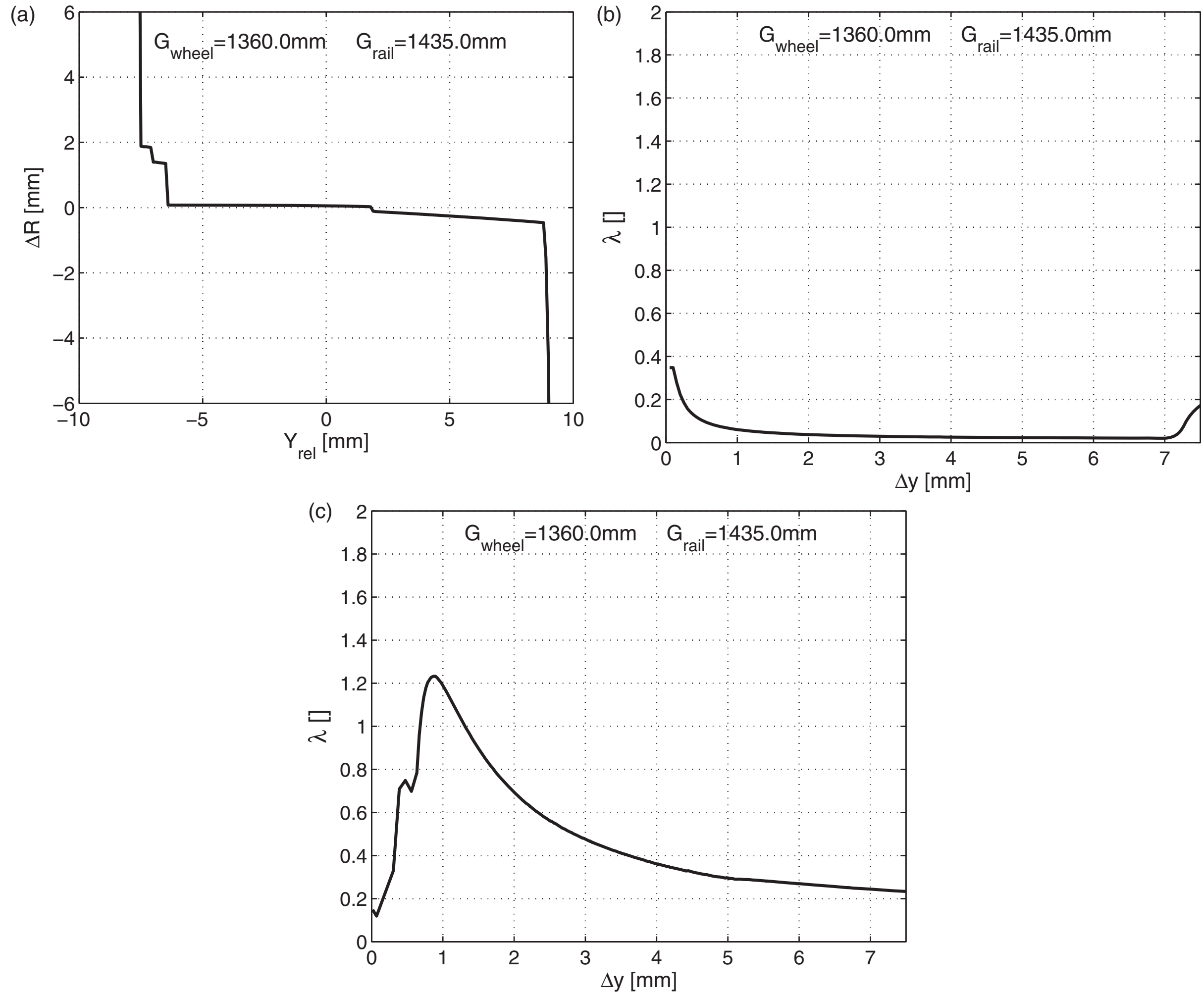

Figure 4. (a) Rolling radius variation diagram; (b) equivalent conicity for the wheelset in the centred position; and (c) equivalent conicity for a wheelset with a steady state lateral shift of -6 mm.

for tighter curves. Therefore, it is qualitatively expected that incipient hunting as identified from line measurements takes place only for an intermediate region of curvature values.

The mathematical model of the vehicle and its validation

With the aim of providing a quantitative confirmation of the arguments presented in the previous section, a multi-body model of the railway car under consideration was defined and validated. The considered vehicle was a non-powered car with four axles and two bogies. The model was defined using the software ADTreS, a code for the simulation of the non-stationary running behaviour of rail vehicles in tangent track, in curves and on switches that has been developed by the Department of Mechanical Engineering, Politecnico di Milano.[17,18]

The multi-body model used in the analysis presented in this paper is based on the modelling of a single vehicle, using a rigid-body representation of all bodies except the wheelsets. Each rigid body was assigned with five degrees of freedom, the forward speed at the centre of mass of the body being set to a constant value.

The modelling of wheel/rail contact is a critical issue that determines the accuracy of the results provided by a train/track interaction model. In order to provide a reliable evaluation of a vehicle's stability at high speed and of train/track forces during curve negotiation, it is essential to use the actual shape of the wheel and rail profile, which on account of wear effects, may be quite different from their theoretical values. The computation of the normal contact forces as a function of the elastic penetration of the two bodies at each wheel/rail contact point was performed by means of a multi-Hertzian algorithm,[19] and the creepage forces belonging to the tangential contact plane were obtained using the Shen–Hedrick–Elkins heuristic formulation.[20] The wheel/rail geometry, that is related to the transversal profiles of the two bodies in contact, was taken into account for the calculation of both kinematics and contact forces as a function of the wheel/rail relative instantaneous position.

A validation of the mathematical model was performed to demonstrate the capability of reproducing the running behaviour of the vehicle, with a special focus on curve negotiation at high speed. For this aim, measurements gathered in line tests at speeds ranging from 200 to 360 km/h were used. Some results of the model validation procedure are now presented. Figure 5(a) compares the measured and simulated trend in the RMS value with speed for the band-pass-filtered lateral acceleration of the bogie frame over the axlebox of the leading axle. Measurements are shown as a black solid line and the simulation results as a grey dashed line. The horizontal dashed line shows the limit value according to EN14363. The experimental results show an increasing trend with speed, but the values are always well below the stability limit. This behaviour is well-reproduced on a qualitative and quantitative basis by the simulation results. Figure 5(b) compares the measured and simulated lateral accelerations of the bogie frame in terms of a Fourier spectrum of the signal for a running

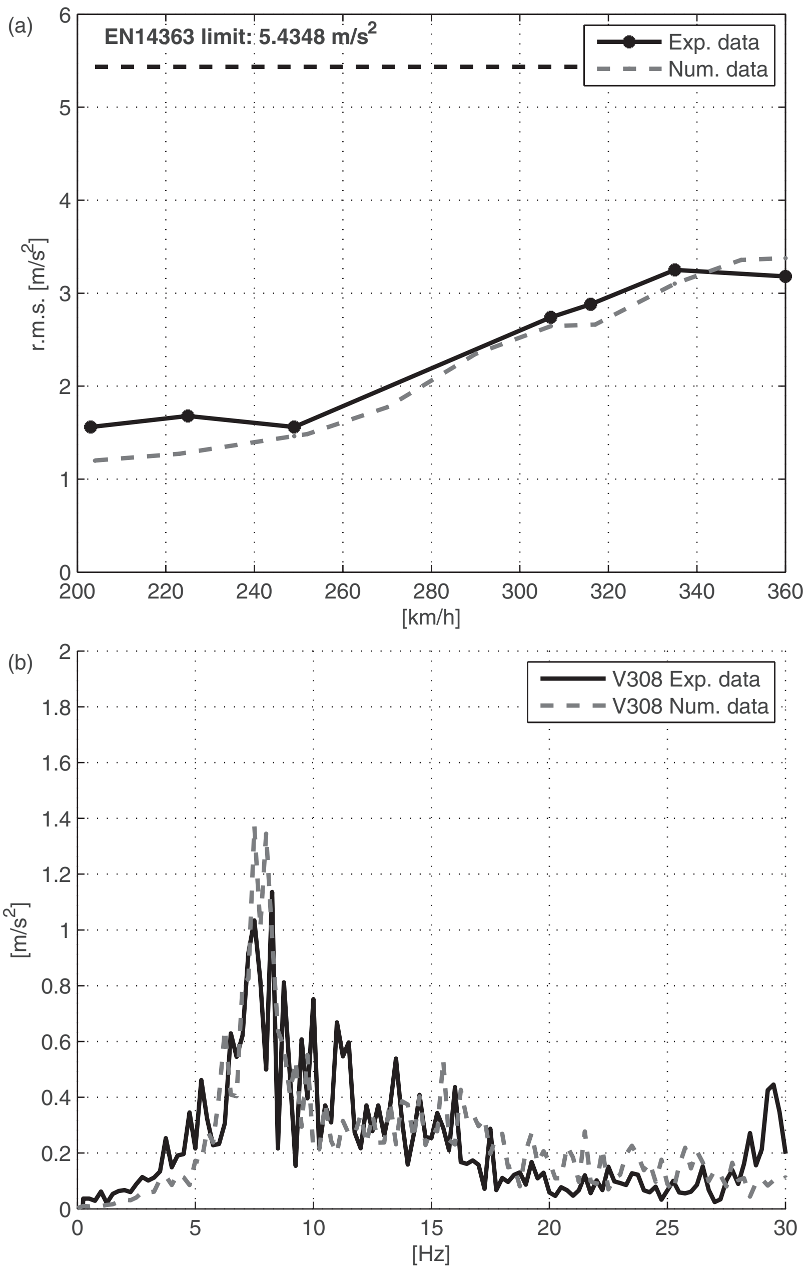

Figure 5. Comparison of measurements and numerical simulations: lateral acceleration of the bogie frame measured above the leading wheelset: (a) trend of the RMS value with speed and (b) Fourier spectrum. Solid line: experimental, dashed line: numerical simulation.

speed of 300 km/h. Dominating harmonic contents are observed in the frequency range around 7 Hz, this is the frequency of the hunting motion for the considered bogie.

Another comparison of line measurements and simulation results was performed to determine the shape of the incipient hunting vibration cycle for the bogie. For this aim, the dominating harmonic components of the Fourier spectrum were extracted for the lateral acceleration of the bogie's centre of mass $\ddot{y}_b$ and for the yaw acceleration of the bogie frame $\ddot{\sigma}_b$, and the non-dimensional parameter r was defined as:

$$r = \frac{p}{2}\frac{\ddot{\sigma}_b}{\ddot{y}_b} \quad (3)$$

where p is the wheelbase of the bogie. For line measurements, the lateral acceleration $\ddot{y}_b$ was approximated by taking the average of the lateral accelerations measured above the leading and trailing axles, and the yaw acceleration $\ddot{\sigma}_b$ was evaluated by taking the difference of the two accelerations measured above the two axles, divided by the bogie's wheelbase.

Since the coefficients of the Fourier spectrum are complex-valued, the quantity r defined by equation (3) is also complex-valued, with the magnitude being proportional to the ratio of the amplitudes of the lateral and yaw motion components of the bogie frame and with the phase being proportional to the time delay between the lateral and yaw oscillations of the body. Figure 6 compares the magnitude and phase of the r coefficient obtained from measurements and simulation: a reasonably good agreement is observed both in terms of amplitude and phase. Especially noteworthy is that the phase value is close to -90°, which is typical of the mechanism of hunting oscillation.[1]

It can thus be concluded from the presented comparisons, that the multi-body model of the railway vehicle presented in this section shows the ability to replicate the incipient hunting phenomenon in terms of acceleration level (RMS trend as a function of speed), value of the dominating frequency and complex shape r of the bogie's vibration.

Results

In this section the occurrence of incipient hunting motion in large radius curves is investigated based on nonlinear simulation of the vehicle's running behaviour, using the multi-body model introduced in the previous section. For this aim, a sequence of numerical simulations were performed, considering the vehicle negotiating curves with radii in the range 2500–7500 m and additionally the tangent track running condition. In all simulations, the vehicle speed was set to 250 km/h, and the curve's cant was adjusted to produce the same cant deficiency value, which was set to 90 mm.

Figure 7 shows the trend with track curvature of the RMS value of the band-pass-filtered lateral acceleration of the bogie frame evaluated above the primary suspension of the leading axle (black solid line) and above the trailing axle (grey dashed line). The horizontal dashed line shows the limit value of this quantity as stated by EN14363 to evaluate vehicle stability based on the simplified measuring method.[8]

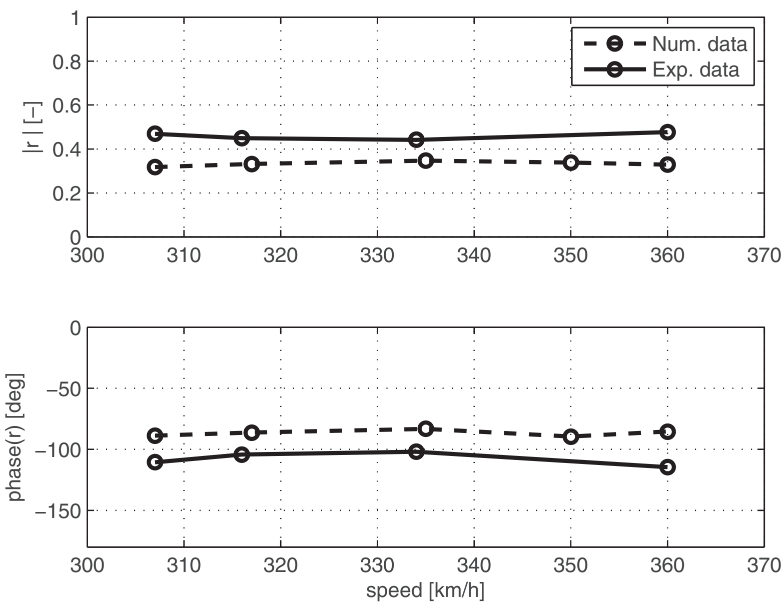

Figure 6. Comparison of measurements and numerical simulations, magnitude and phase of the non-dimensional ratio r describing the shape of the lateral and yaw vibrations of the bogie.

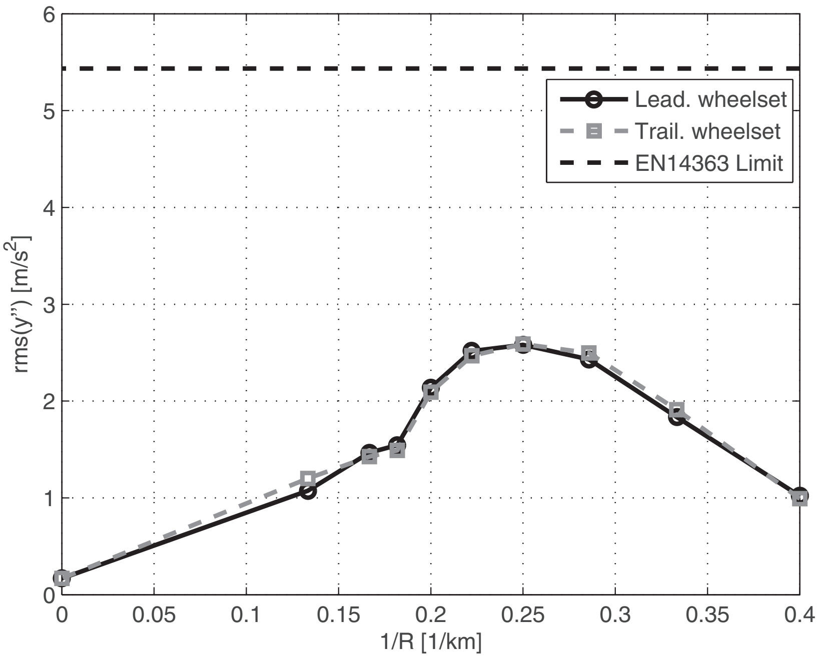

Figure 7. Results of numerical simulations: trend with track curvature of the RMS value of the lateral acceleration of the bogie after band-pass filtering based on the EN14363 standard. Cant deficiency 90 mm.

For all the performed simulations, the RMS value is much lower than the EN14363 limit, leading to the conclusion that the vehicle's running conditions should be classified as being stable. However, the RMS values obtained for curved conditions are much larger than for tangent track running for all curvature values, and reaches a maximum value for track curvatures in the range 0.22–0.3 km^{-1}, corresponding to curve radii in the range 3000–4500 m. Hence, the experimental observations reported in the section 'Vehicle stability along a curved track: experimental evidence' can be generalised by stating that the level of lateral vibration of the bogie obtained for the considered vehicle and wheel/rail contact couple, is highly dependent on track curvature and shows a maximum for curve radii in a range slightly shorter than those considered in the line test measurements. Unfortunately, the available experimental results do not allow this conclusion to be fully validated, due to the lack of measurements for curves with a radius below 5500 m. However, incipient hunting was not experimentally observed when the vehicle was running in curves with much larger radius values (e.g. 8000 m), which is in agreement with the results shown in Figure 7.

Figure 8 shows the trend with track curvature of the conicity λ (circle-shaped points) evaluated for the leading wheelset of the vehicle around the steady state position of the wheelset in full curve conditions and considering the actual amplitude of the lateral displacement obtained from each simulation. This figure also shows, in a different scale, the values of the saturation coefficient S_c for the same wheelset, obtained from simulation results obtained using equation (2) (star-shaped points). As expected, the conicity monotonically increases with track curvature, but larger curvature values lead to increased saturation effects in the wheel/rail contact as shown by the decreasing trend of the saturation coefficient. The 0.22–0.3 km^{-1} curvature range is the one in which significantly high conicity values are obtained ($\lambda = 0.55$–0.7) while saturation effects are still small, which justifies the maximum level of lateral vibration of the bogie found for these running conditions.

Figure 9 shows the band-pass-filtered track shift force on the leading and trailing axles of the first bogie plotted as a function of track curvature. This is the assessment value prescribed by EN14363 for the verification of stability according to the 'complete measuring method'. Also, for this quantity a non-monotone trend with track curvature is observed, with maximum values occurring in the 0.2–0.3 km^{-1} range, in the same way as for the lateral acceleration of the bogie. The maximum value is much lower than the limit value defined according to EN14363, confirming that the vehicle is far from an unstable condition as defined by the standard. The Y/Q quotient of the guiding force versus wheel force, not shown here for the sake of brevity, does not show any meaningful trend with curvature and in all considered running conditions the values obtained from simulation are below 0.25, i.e. far below the limit value of 0.8.

Finally, multi-body simulation was used to consider the effect of cant deficiency on incipient hunting in a curve. For this aim, the running behaviour of the

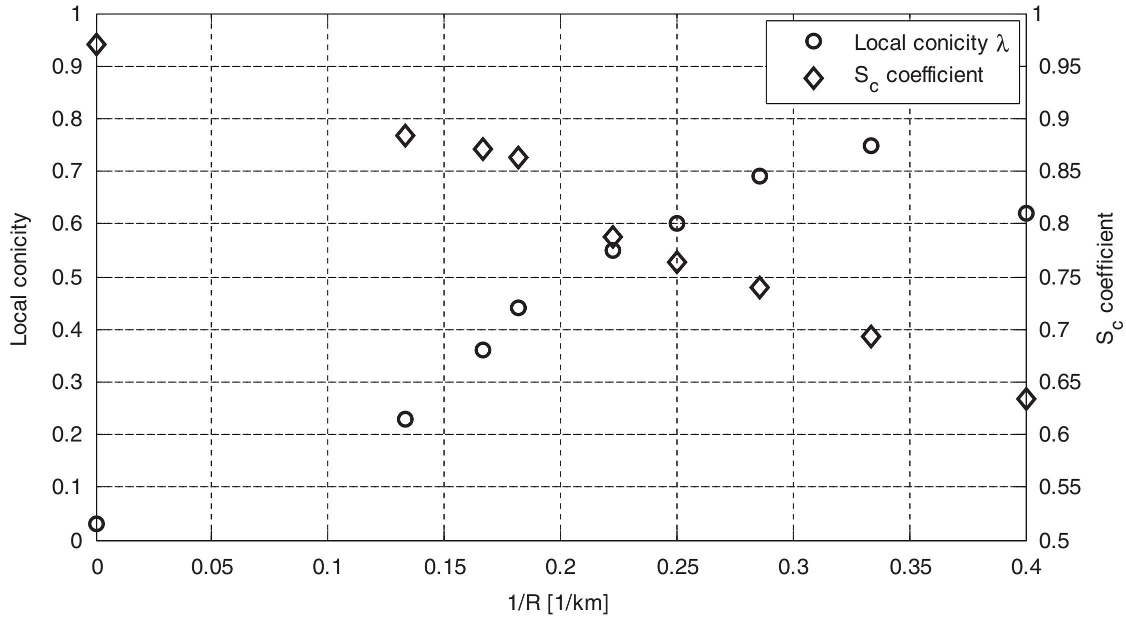

Figure 8. Results of numerical simulations: trend with track curvature of the conicity λ and of the saturation index S_c.

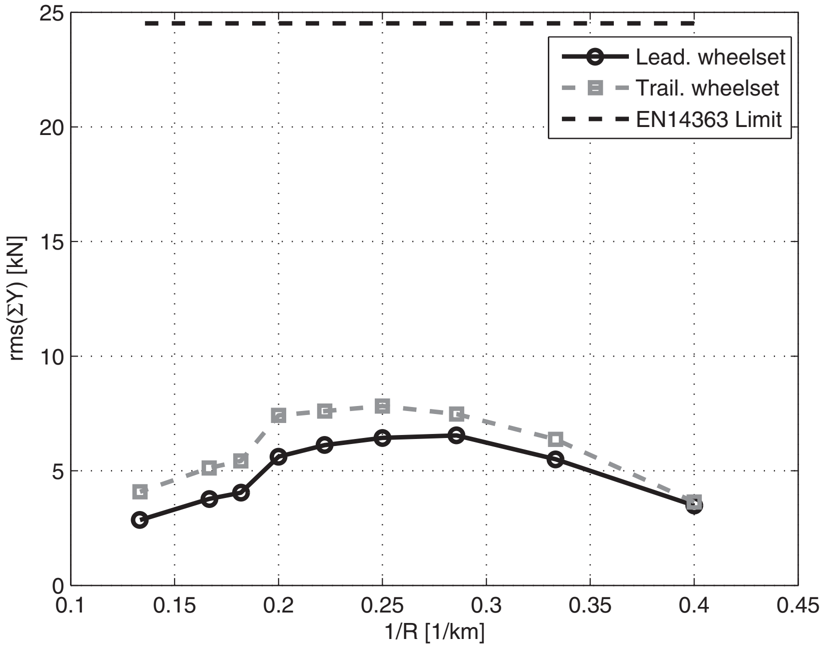

Figure 9. Results of numerical simulations: trend with track curvature of the RMS value of the track's shift force after band-pass filtering based on the EN14363 standard. Cant deficiency 90 mm.

vehicle was simulated for the same curve radii considered in Figure 7 and for cant deficiency values in the range 0–135 mm. Results are shown in Figure 10; in order to maintain the same running speed of 250 km/h, the track's super-elevation was adjusted and, for some combination of curve radius and cant deficiency, the super-elevation considered in the numerical simulation was either below zero or above 180 mm which is assumed here to be a realistic maximum value in real lines. These running conditions are shown in Figure 10 using a dashed line whereas running conditions corresponding to a super-elevation in the range 0–180 mm are displayed by a solid line. It is observed that the vehicle's running behaviour is strongly dependent on the cant deficiency condition: when the vehicle runs at balance speed, the level of the

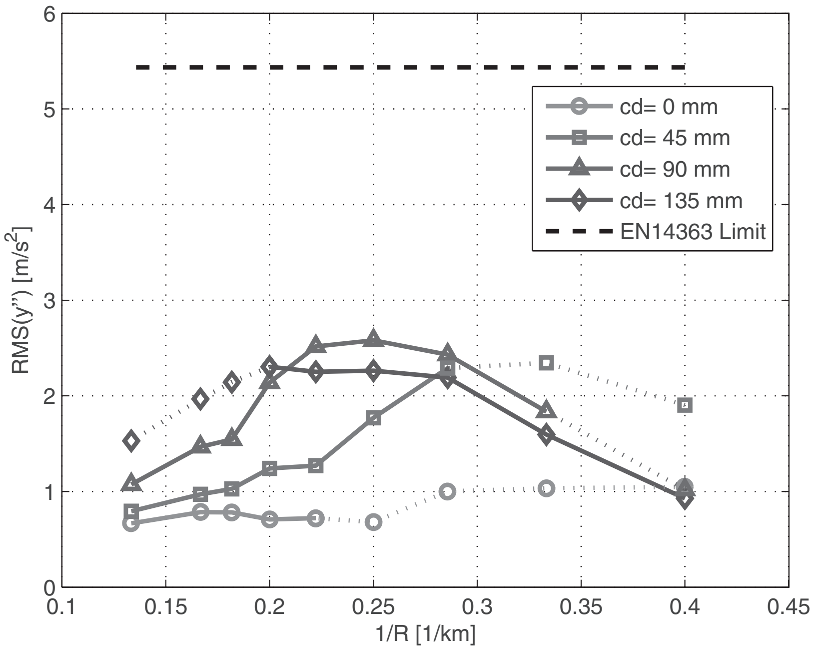

Figure 10. Results of numerical simulations: trend with track curvature and with cant deficiency of the RMS value of the lateral acceleration of the bogie after band-pass filtering based on the EN14363 standard.

RMS value of the lateral acceleration is modest, showing the absence of incipient hunting. This is due to the fact that lateral displacements of the wheelset towards the outside curve are less significant and hence the equivalent conicity is lower than for a higher value of the cant deficiency. When the cant deficiency is raised to 45 mm, larger acceleration levels are found in the region of the larger curvatures (shorter curve radius) covered by the analysis. For a 90 mm cant deficiency (same results as already shown in Figure 7), the region of larger vibration of the bogie moves to an intermediate range of curvatures and finally for a cant deficiency of 135 mm the region of larger RMS values of the acceleration moves further to the low curvature region. Overall, the occurrence of incipient hunting in a curve appears to be a complex phenomenon which is highly affected by both track curvature and cant deficiency.

Conclusions

Line tests performed on Italian high-speed lines highlighted a different behaviour between non-powered bogies in tangent track and in large radius curved track. The evaluation of lateral accelerations of a bogie in terms of Fourier spectra showed that the phenomenon is related to the onset of incipient hunting when the vehicle negotiates large radius curves. In order to provide a scientific explanation of such a phenomenon, in the present study, a qualitative and quantitative analysis was performed, supported by numerical experiments replicating the real running condition of the train on the track and then extending the results to consider different track curvature conditions.

The numerical results demonstrated that the phenomenon is governed by the combined effect of the equivalent conicity occurring during curve negotiation and of the saturation of the creepage–creep force relationship. When a high-speed vehicle with an almost new wheel profile negotiates a curve with a large radius, the conicity experienced by the wheel is higher compared to the one that occurs when the vehicle runs in tangent track; therefore, incipient hunting is more likely to take place. However, creep force saturation effects increase with increasing track curvature, until a point where incipient hunting is inhibited. Furthermore, the vehicle's running behaviour is strongly affected by the cant deficiency condition. For a low cant deficiency, very low levels of lateral vibration of the bogie are obtained. When the vehicle negotiates a curve with a sufficient level of cant deficiency, a range of curve radii for which incipient hunting motion is more evident is found, and this range changes with cant deficiency. Clearly, the above summarised results depend on many factors such as vehicle parameters, wheel profiles and adhesion condition.

More generally, this study clearly shows that curve negotiation may affect the stability of a railway vehicle. Generally, this fact is not taken into account in the design and verification stage of a railway vehicle, nor is it acknowledged by the European standards that govern vehicle testing for acceptance, although the AAR Chapter XI standards that cover freight car performance in North America prescribe hunting tests to be performed in curves. It is suggested as a final conclusion of this study that more research should be devoted to fully understand the mechanism of hunting in a curve, e.g. in terms of the effect of wheel/rail profiles, bogie design and cant deficiency.

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