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Effects of geometric track irregularities on vehicle dynamic behaviour when running through a turnout

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ABSTRACT

Railway vehicle dynamics is strongly affected by track irregularities, which can influence the safety and the running behaviour of the vehicle. The EN 13848-5:2017 standard provides the limits of track irregularities for standard track but does not states specific restrictions for switches and crossings. Furthermore, since turnouts have a limited length, their track geometric irregularities cannot be accurately described by stochastic functions usually adopted for railway vehicle dynamics simulations. Nevertheless, irregularities in railway turnouts, related to the non-uniform stiffness of the track support and to the variation of the rail profiles along the longitudinal direction should be considered in dynamic simulations, as they can generate large dynamic loads, strongly affecting the vehicle dynamics and running stability. The aim of the paper is to expand the Switches and Crossing benchmark exercise analysing the effect of several kinds of irregularity with different wavelengths and amplitudes on a complete turnout on the main quantities related to the vehicle dynamics. The influence of each defect on each quantity is estimated through a post-processing sensitivity analysis based on power spectral density calculation. This sensitivity analysis is hence used to combine different types of defects in order to detect irregularity combinations that could compromise running safety.

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Turnout; switch; crossing; track irregularities; track flexibility; running safety

Introduction

Although in many railway vehicle dynamic simulations the railway track is modelled as perfect, i.e. with no irregularities, to speed up the calculations, it indeed does feature irregularities and local defects, which can compromise the vehicle running safety and stability, also possibly leading to failures of the main components of the railway system, i.e. wheelsets, bogies, rails and sleepers. Track irregularities are responsible for the generation of high dynamic vertical contact loads at the wheel-rail interface, and the intensity of these impact loads is strongly related to vehicle speed and axle load, as witnessed by several studies and simulations performed by means of in-house built train-track interaction models, nowadays relying on multibody simulation and finite element methods [1–3]. An

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interesting survey of train-track impact loads due to various irregularities in the wheels, rails and track can be found in the work by Remennikov and Kaewunruen [4].

Therefore, the effect of track irregularities on the vehicle dynamics cannot be neglected when the investigation of operating conditions leading to impact loads is carried out, e.g. when simulating the vehicle dynamics in a turnout section.

Irregularities have a strong impact on vehicle dynamics especially in railway switches and crossings (S&C). In fact, railway turnouts feature a non-uniform stiffness of the track support and non-uniform profiles of the rails in the switch, closure and crossing panels. Due to these reasons, railways turnouts are usually the part of the track requiring the highest number of maintenance operations to restore railhead damages induced by impact loads due to discontinuities in the wheel-rail contact along the running direction. Rail surface damages are worsened by both random irregularities and local damages in the vertical, lateral and longitudinal directions.

Random irregularities in longitudinal level, alignment, cross level and gauge are typically modelled and described by means of PSD functions, obtained by railway research institutes from direct measurements of a huge number of track sections [5–8]. A coupled model of a 30-ton axle-load heavy haul vehicle and track with the main irregularities (alignment, vertical profile, level, twist and composite) was recently developed by Chinese researchers [9], and the vehicle running safety was assessed for different wavelengths and amplitudes checking the maximum values of derailment coefficient, wheel unloading rate, wheel-rail lateral force, axle lateral force, carbody lateral and vertical accelerations. The track irregularities were modelled using a cosine function.

Regarding the simulation of train-track interaction in turnouts, track irregularities cannot be effectively described by means of power spectra, as S&Cs are track sections of limited length, where the vehicle dynamics can be mostly affected by local track defects. In fact, the irregularities in turnouts are mainly related to the unevenness of the track stiffness in the switch, closure and cross panels, which can lead to huge impact loads [10]. Due to these large contact loads, the surfaces of wheels and rails are deteriorated through wear and rolling contact fatigue (RCF), so that the original track irregularity level can worsen, as predicted by refined numerical models described in the railway literature [11,12].

According to Nicklish et al. [13], most of the defects in railway turnouts are due to the lateral displacements in the switch panel, which lead to flange contact, and to the impact loads in the crossing nose, both leading to higher wear rates and RCF damage. In the reference, the authors proposed changes in the gauge widening at the switch panel and in the rail pad stiffness at both switch and crossing panel to reduce wear and RCF damage of the stock and switch rail as well as of the crossing nose and wing rails. In fact, gauge widening proved to give a big contribution in the reduction of flange contact on the switch rail, which could then be realised with a larger thickness, thus guarantying a higher resistance to wear and RCF. At the same time, the results of the simulations presented in the cited paper showed that a reduction of the rail pad stiffness could lead to a reduction of impact loads, especially when the vehicle runs on the crossing panel at high speed.

A deep survey of the possible local defects that can be found in railway turnouts was recently proposed in the context of the CAPACITY4RAIL European project [14], by listing the defects according to the concerned components, namely switch and stock rail assembly, rails, moveable and fixed crossings, check rails, but also plates, fastening material, bearers, driving and locking device and ballast bed. From this survey, it can be discerned that the local defects are due to four main factors, i.e. (i) manufacturing processes (soft spots, progressive transverse cracking, fatigue from weld repair, fatigue from machining stress raisers, corrosion pit, casting defects), (ii) incorrect assemblies, (iii) rolling contact fatigue or RCF (head checks, squats) and (iv) high contact stresses and wear, leading to local plastic deformation and cracks (shelling, sub-surface fatigue, wheel burns, short and long pitch corrugation, abrasive wear, transverse crack on crossing nose).

The investigation of the effects of turnout track irregularities on the vehicle dynamics and on the generation of dynamic loads is fundamental to reduce surface damages and rolling contact noise and vibrations. In 2000, Andersson and Dahlberg [15] implemented a computer programme modelling a turnout and a half-bogie, and they also simulated the case of an irregular transition at the crossing from the wing rail to the nose. Alfi and Bruni [16] developed a model of train-turnout interaction considering the variation of the rail profile and of the track stiffness in the running direction and simulated the effects of wheel and rail worn profiles and of the low track misalignment irregularity on the train-track coupled dynamics. Li et al. [17] developed a method based on a combination of multibody simulations, run in GENSYS, and FEM analysis in NASTRAN to simulate the track settlement in railway turnout. Xu et al. [18] used a similar solution, based on Simpack and ANSYS, to evaluate the impact of switch and stock rail profile wear on the generation of dynamic loads in vertical and lateral directions and on the contact stresses at the wheel-rail interface. Boiko et al. [19] ran several simulations of a vehicle running on an underground railway considering vertical irregularities on the switch frog and found an expression for the calculation of the dynamic load as a function of the irregularity main parameters and of the vehicle operating conditions.

Track irregularities in turnouts can also be generated by the non-constant value of the track stiffness in the switch and crossing panels. Several works can be found in the literature dealing with the optimisation of the rail pad and under sleeper pad stiffness to reduce the impact loads in crossing and switch panels [9,20–22]. However, modelling of the track flexibility with a variable stiffness along the running direction is extremely demanding from the computational point of view.

Therefore, the investigation of the effects of the main track irregularities in switches and crossings performed in this paper neglects the variability of the track flexibility in the travelling direction. In the author's opinion, this is not a major limitation, since the variable track flexibility can be globally seen as a track irregularity.

The present work aims at overcoming some simplifications adopted in the Switch & Crossing benchmark [23] to guarantee an easier comparison of the results obtained by participants using different simulation software packages, which included (i) separate simulations for switch and crossing panels and (ii) absence of track irregularities throughout the whole length of the track. However, considering the whole turnout, i.e. switch panel, closure panel and crossing panel, track stiffness could assume different values, increasing the dynamic loads and generating geometric irregularities. The work investigates the effects of track geometric irregularities on the running performance of the passenger vehicle from the Manchester Benchmarks running through a turnout. For this purpose, a complete turnout model is created starting from the data available in the benchmark for the GB 56E1-R245-1:9.25, comparing the results of two different software packages (VI-Rail and Simpack). Then, the effect of the main track irregularities (gauge, alignment, longitudinal level, cross level and twist) is analysed separately. To take significant values into account, irregularities corresponding to the three limit levels of EN13848-5 are considered in the D1 wavelength range, i.e. $3 < \lambda \leq 25$ m. Starting from the switch toe, the irregularities are modelled varying the wavelength in the D1 range, i.e. the peak position, and the amplitude, using a cosine function. Experimental values of measured track irregularities are not used in the paper since the aim of the proposed work is a relative comparison of the effect of different track irregularities, localised in turnout sections, on vehicle dynamics. Simulations are then performed to evaluate the effect of these irregularities and finally a track with combined irregularities is defined by weighing the amplitude of each defect according to the corresponding effect on the vehicle dynamics. Tests are hence repeated on this track to highlight any non-linear behaviour of the superposition effects. The results of this work allow to identify location and type of the irregularities which have the greatest influence on the dynamic behaviour of the selected vehicle running through a turnout. The main contribution of the paper is thus the comparison of the effects of different types of track local geometric irregularity in turnout sections, generally related to a nonuniform track stiffness in the running direction, which have a major impact on the vehicle running behaviour and safety.

Description of track and vehicle numerical models

Vehicle model

The vehicle model is the same used in the benchmark exercise, i.e. the Manchester Benchmark vehicle 1. As the complete set of information about its characteristics can be found in [24], here only a comparison of the main natural frequencies of the vehicle is presented. Table 1 shows the carbody and bogie modes for both Vi-Rail and Simpack vehicle models.

The effect of track irregularity on the vehicle behaviour is often evaluated by means of the typical safety parameters for running dynamics, i.e. the sum of guiding forces ΣY, the wheel unloading $\Delta Q/Q$ and the derailment quotient (Y/Q). In addition, vertical and lateral accelerations of the bogie, $\ddot{z}^+$ and $\ddot{y}^+$, and the carbody, $\ddot{z}^*$ and $\ddot{y}^*$, can be evaluated. Track sections including switches and crossings are often discarded from the statistical evaluation of the runs performed during vehicle acceptance testing according to EN14363. The effects

Table 1. Main natural frequencies for Vi-Rail and Simpack vehicle models.

Mode	Frequencies of the Vi-Rail model [Hz]	Frequencies of the Simpack model [Hz]
Carbody		
Lower Sway	0.52	0.54
Yaw	0.75	0.75
Bounce	1.07	1.07
Upper sway	1.23	1.23
Pitch	1.28	1.29
Bogie		
Bounce out of phase	7.51	7.48
Bounce in phase	7.53	7.49
Roll out of phase	9.76	9.57
Roll in phase	9.79	9.60
Pitch out of phase	11.90	11.86
Pitch in phase	11.90	11.86

on vehicle behaviour of these track peculiar components is not investigated and remains unknown.

In this paper, some safety parameters are first evaluated for the vehicle passing over the turnout without irregularities and then re-computed adding isolated and repeated defect as described in the next paragraphs. Axle and bogie accelerations are measured by sensors at the front-right axlebox position in order to include roll movements of the running gear while passing over the irregularities. Carbody accelerations are instead evaluated at centre of mass height above the front bogie.

Track model

The track modelling strategy both for VI-Rail and Simpack software packages was chosen to be as simple as reasonably possible, using a 'co-running', or 'moving' track model. Both commercial codes give the possibility for a more detailed flexible track system model, in order to include rail flexibility and variable conditions of the track supports, i.e. both the connections between the rails and the sleepers (rail fasteners and railpads) and between the sleepers and the ground (ballast). A thorough comparison of this modelling and standard 'co-running' modelling can be found in [20]. Moreover, a detailed flexible modelling increases the solving time and the analysis of the mid-high frequency phenomena are out of the scope of this paper. In fact, running safety of railway vehicles is mainly evaluated for low frequencies ranges and the irregularities chosen for the analysis are such that only the frequency range of $0 \div 20$ Hz is affected.

The chosen track model has therefore three degrees of freedom for each rail (vertical, lateral and roll, with respect to the sleeper) and three degrees of freedom for the sleeper (vertical, lateral and roll, with respect to the ground). Stiffness properties are considered by adding linear springs and dampers, while the roll degree of freedom of the rails was blocked using a high stiffness. This strategy was adopted in both Simpack and VI-Rail models. The main advantage of Simpack over VI-Rail is the possibility to introduce different track components with different properties inside the 'co-running' track model. The Simpack users have defined individual masses, moment of inertia and stiffness values for the stock rail, the switch rail and the crossing, resulting in a more realistic modelling. The VI-Rail users have instead considered average and constant values for masses, moment of inertia and stiffness properties along the whole running section. The constant values chosen for the VI-Rail model are shown in Table 2.

The Simpack model considers different rail sleeper mass and stiffness properties for the switch and crossing panel. This is obtained by defining separate sets of wheel-rail pairs for the two panels. Variable rail profiles on the right rail are used to model the switch and

Table 2. Stiffness and damping properties used in VI-Rail.

	Sleeper to ground connection	Left rail to sleeper connection	Right rail to sleeper connection
Lateral Stiffness [kN/mm]	70	30	30
Lateral Damping [kNs/mm]	0.35	0.15	0.15
Vertical Stiffness [kN/mm]	280	150	500
Vertical Damping [kNs/mm]	2.8	0.1	0.35
Rolling Stiffness [MNm/rad]	157.5	1000	1000
Rolling Damping [MNms/rad]	1.575	10	10

the crossing panels. Considering the switch panel, the switch and the stock rail are modelled as two separate bodies. About the crossing panel, the left stock rail and the check rail are considered as two separate bodies, while the crossing and the wing rails are modelled as a single body. The elastic and damping properties are modelled by means of bushing elements. Inertia and stiffness properties are the same provided by the S&C benchmark exercise [23].

In VI-Rail, to further simplify the track model implementation, the geometry of the switch panel and the crossing panel are considered using variable rail profiles of the right rail as shown in Figure 1. The switch rail, the stock rail and the crossing are therefore modelled as one body. In the real case the switch rail is laterally positioned close to the stock rail by the point machines, and the correct modelling of the switch rail in vertical direction should include the flexibility and the supports, made by several slide chairs or rollers, whose behaviour is different with respect to standard sleeper-rail connections and often asymmetrical or not regular. However, the lack of the degree of freedom between the stock rail and the switch rail is not considered an issue for the aim of the paper in which greater track irregularities are considered with respect to the possible movements of the switch rail. However, this modelling strategy is not recommended if the local conditions of the wheel-rail contact must be evaluated, such as wear analysis. In Figure 2 a detail of the vertical and lateral contact forces at the switch toe is shown for the Vi-Rail model and the Simpack model.

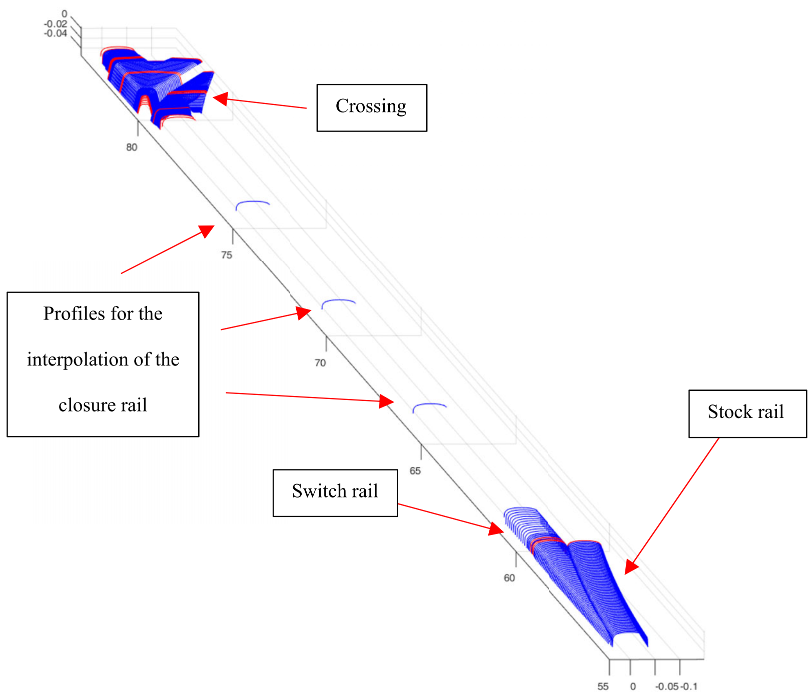

Figure 1. View of the variable profiles used to simulate the whole turnout in VI-Rail. Red profiles show the points where the interpolation was stopped to improve the track definition.

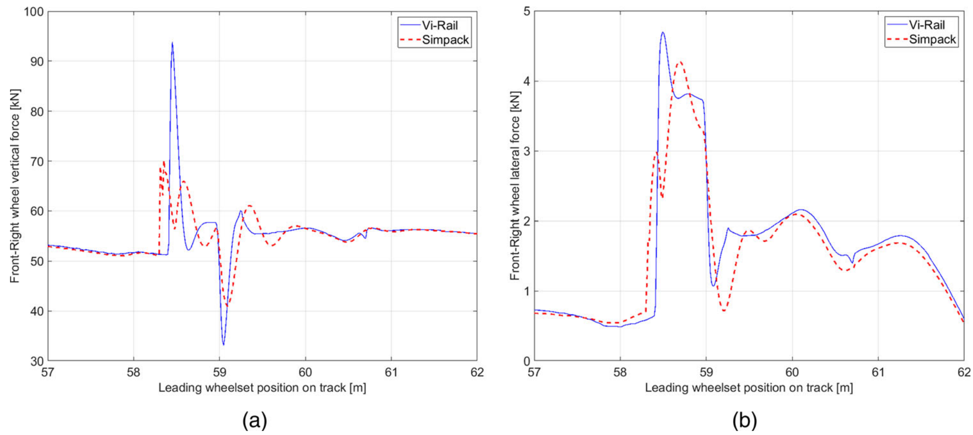

Figure 2. Vertical (a) and lateral (b) contact forces of the right wheel passing over the switch toe for Vi-Rail model, in which the switch rail and the stock rail are modelled as one body, and the Simpack model, in which the switch rail and the stock rail are modelled as two bodies.

Simulation of track irregularities

The European standards about track geometry quality are drafted by the Working Group 28 of the Technical Committee 256. In particular, the standard EN 13848-5:2017 deals with geometric quality levels on plain lines and switches and crossings, defining the safety limits for the main parameters defined in the EN 13848-1:2017. The standard defines three safety levels: the alert limit (AL), the intervention limit (IL), and the immediate action limit (IAL). If the last limit is reached, measures to reduce the risk of derailment and actions to correct the track geometry have to be taken immediately. Limit values for each level are given for isolated defects identified after filtering recorded track geometry data in three wavelength λ ranges. The most relevant range for the evaluation of the track-vehicle interaction at conventional speeds ($D1$ range, $3\,\text{m} < \lambda \leq 25\,\text{m}$) is considered in the present work. However, the standard recommends paying attention not only to the amplitude of a single irregularity but also to its shape, its combination to other defects or its cyclic nature, as unsafe situations can be reached even if the IAL is not exceeded. In fact, according to the informative Annex A of the EN 13848-5, the complete track geometry quality must be defined considering all the track parameters and determining the thresholds for their significant combinations with respect to track-vehicle safety issues. However, the standard only gives some examples of combined irregularities and the vehicle parameters affected. These proposed combinations and the related vehicle parameters are shown in Table 3.

Table 3. Running parameters influenced by different combinations of track irregularities according to EN13848-5:2017.

Running parameter	Track gauge	Longitudinal level	Cross level	Alignment
ΣY	x		x	x
Q		x	x	x
Y	x		x	x
$\ddot{y}^*$			x	x
$\ddot{z}^*$		x		
(Y/Q)	x	x	x	x

Cyclic irregularities are important for vertical irregularities, i.e. longitudinal level defects, which could activate the resonances in the vertical behaviour of the vehicles, thus generating higher wheel unloading and derailment risks. Freight vehicles are very sensitive to this kind of irregularities, also known as *cyclic top*, and infrastructure managers have adopted specific procedures to monitor their evolution [25].

To investigate the effects on switches and crossing, in which high dynamic loads are generated by the change of the profiles along the running direction, several kinds of irregularity are modelled and superimposed to the track geometrical layout, varying the wavelength, the amplitude and the position of the defects. Both isolated and repeated irregularities are modelled, and then the combined effect is investigated. The shape of the irregularities was defined according to Equation (1), in which A is the amplitude and L is the wavelength of the irregularities, as described in [9].

$$z(x) = A/2(1 - \cos 2\pi x/L) \tag{1}$$

Several simulations were performed as shown in Table 4 considering the through route and a speed of 100 km/h, with irregularities sketched in Figure 3. A first simulation is performed without irregularities in order to compare the results of the two software packages without any additional input, and therefore two simulated scenarios (separated in the benchmark) of the switch and the crossing are combined. The first group of irregularities (T21, T22 and T23 in Table 3) describe longitudinal level defects with three wavelengths and three limit values, i.e. *AL*, *IL* and *IAL*. The maximum wavelength, i.e. $\lambda = 25$ m, covers the whole length between the switch toe and the crossing nose, simulating a fault of the switch panel and the closure panel. A shorter wavelength defect ($\lambda = 10$ m) is related to a switch panel with the peak corresponding to the switch toe, while the $\lambda = 3$ m defect is positioned just before entering the turnout. The same wavelengths are adopted for track alignment irregularities (T31, T32 and T33 in Table 3) with the corresponding limit values. Cross Level defects (T41, T42 and T43 in Table 3) are implemented adding a vertical dip only on the left rail with three different amplitudes, resulting in twist levels of 4, 5 and 7 ‰, at the switch toe. Then, three repeated irregularities in the vertical direction (T51,

Table 4. List of simulations.

Code	Kind of irregularities	Rails	Start [m]	Wavelength [m]	Frequency at 100 km/h [Hz]	Cycles [-]	Amplitude [mm]	Twist [‰]
T11	Without irregularities							
T21	LL	L/R	52	3	9.3	1	16 (AL)	0
T22	LL	L/R	50	10	2.8	1	19 (IL)	0
T23	LL	L/R	55	25	1.1	1	26 (IAL)	0
T31	AL	L/R	52	3	9.3	1	11 (AL)	0
T32	AL	L/R	50	10	2.8	1	13 (IL)	0
T33	AL	L/R	55	25	1.1	1	17 (IAL)	0
T41	CL	L	51	8	3.5	1	16	4 (AL)
T42	CL	L	51	8	3.5	1	20	5 (IL)
T43	CL	L	51	8	3.5	1	28	7 (IAL)
T51	CT	L/R	50	5	5.6	4	16 (AL)	0
T52	CT	L/R	50	10	2.8	2	19 (IL)	0
T53	CCL	L/R	51	8	3.5	1 - alt	16 (AL)	4
T61	TG	L/R	55	3	9.3	1	−11 (IAL)	0
T62	TG	L/R	55	3	9.3	1	+35 (IAL)	0

Note: LL = Longitudinal Level; AL = Alignment; CL = Cross Level; CT = Cyclic Top; CCL = Cyclic Cross Level.

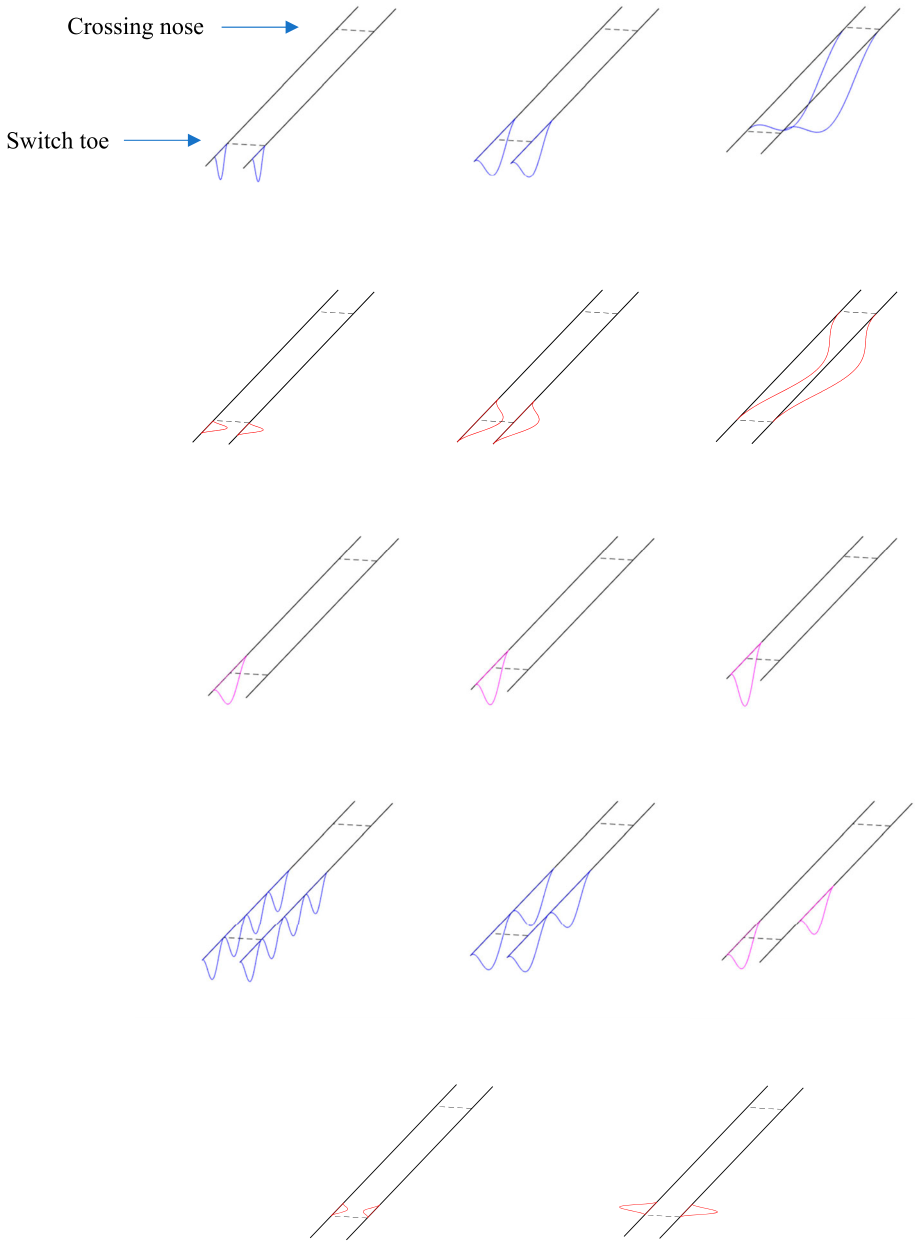

Figure 3. Schematic representation of the irregularities.

T52 and T23 in Table 3) are simulated, in order to evaluate the differences with respect to isolated defects. Two of the previously described scenarios simulate a cyclic top over 20 m with different wavelengths, while the third one simulates a cyclic cross level defect applied sequentially on the left and on the right rail. Finally, the last two simulations (T61 and T62 in Table 3) regard track gauge shrinking and widening, only considering the *IAL* limit values.

Results and discussion

Preliminary comparison

The results of the two software packages are first compared in the four track cases T11 (no irregularities), T23 (longitudinal level defect), T33 (alignment defect) and T41 (twist defect). The comparison of vehicle's parameters with and without irregularities are shown in Figure 4 (lateral and vertical wheel displacement), Figure 5 (lateral and vertical bogie acceleration) and Figure 6 (lateral and vertical carbody acceleration).

In the complete turnout model, the switch toe is positioned at 55 m while the crossing IP is positioned at 80 m. As shown Figure 3(a), even without irregularities, the presence of the switch gives a non-zero lateral displacement of the wheelset while entering the crossing, but this un-stationary condition has a limited effect on the running dynamics over the crossing. The results of the two commercial codes are in good agreement, even though some differences can be found in the vertical displacement of the right wheel of the leading axle of the leading bogie, see Figure 3(b) and (c). This can be explained by the differences in track geometry definitions between the VI-Rail and the Simpack model, especially for the different stiffness properties and preloads issue, as explained in the main paper of the benchmark [26]. These discrepancies disappear considering the results related to the bogie

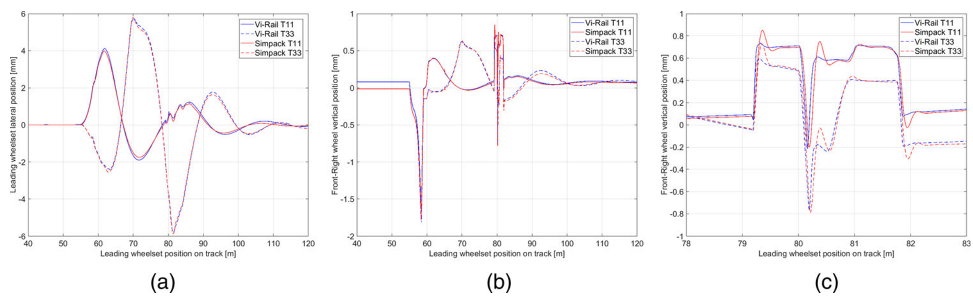

Figure 4. Software comparison for T11 and T33 simulations. (a) Lateral wheelset displacement; (b) Right wheel vertical displacement; (c) Right wheel vertical displacement over the crossing.

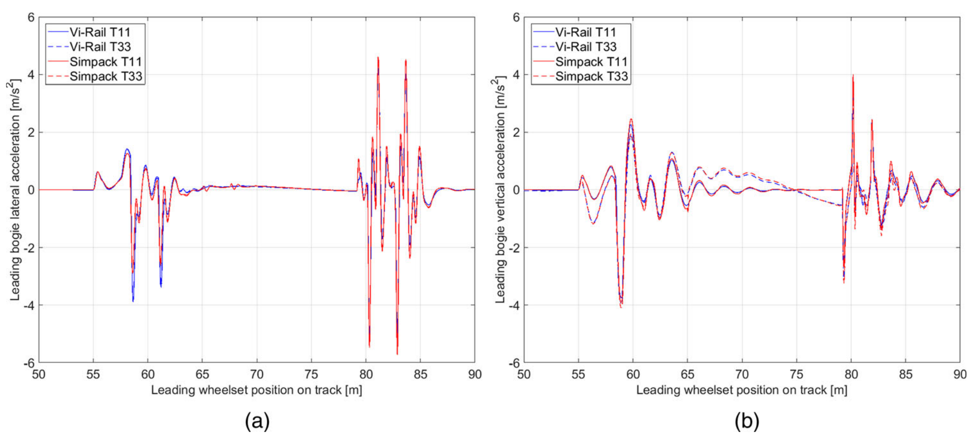

Figure 5. Bogie accelerations measured above the front-right axlebox for T11, T23 and T33 simulations. (a) lateral acceleration; (b) vertical acceleration.

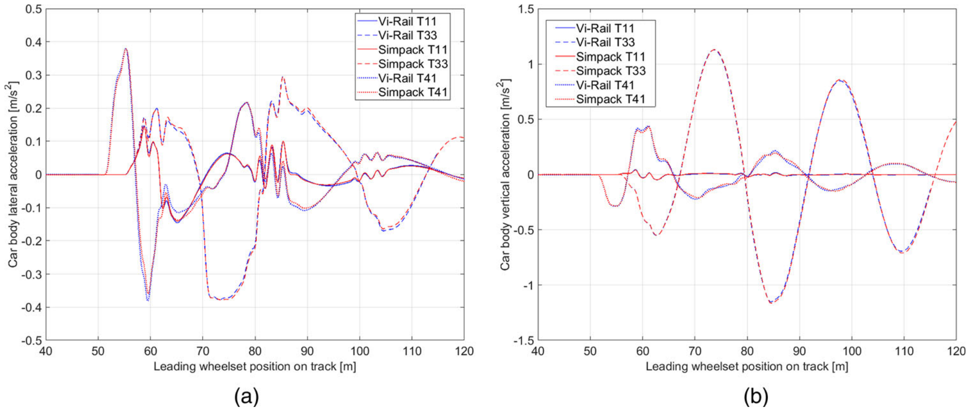

Figure 6. Carbody acceleration measured above the front bogie for T11, T23, T33 and T41 simulations. (a) lateral acceleration; (b) vertical acceleration.

and the carbody due to the filtering effect of the suspensions, as shown in Figures 4 and 5. This behaviour demonstrates that the differences in Figure 3 are caused by the different modelling of the track flexibility.

It is worth highlighting that bogie frame acceleration values while passing over the switch and the crossing are clearly visible, especially for lateral accelerations which reach values up to 5 m/s^2. Secondary suspensions filter out most of these accelerations, but a residual lateral acceleration is still present on the carbody.

Safety parameters, such as Y/Q and $\Delta Q/Q$, are not critically affected by the turnout. Wheel unloading only reaches high values while passing over the crossing, due to high-frequency dynamics, not usually considered during running safety evaluations.

Influence of irregularities on vehicle dynamics

After the comparison previously described, simulations with other kinds of irregularities are performed separately with either the Simpack model or the VI-Rail model. This allows to speed up the simulation process and to consider all the cases shown in Table 4. To compare the effect of different track irregularities on the vehicle running behaviour a specific data analysis process is implemented. The method is based on the analysis of the power spectral density (PSD) of the quantities which are more affected by track irregularities. The quantities considered are the following:

- Lateral and vertical accelerations of leading bogie measured above the front-right axlebox ($\ddot{y}^+$,$\ddot{z}^+$).
- Lateral and vertical carbody accelerations measured above leading bogie ($\ddot{y}^*$,$\ddot{z}^*$).
- Leading wheelset of leading bogie lateral force ΣY
- Derailment quotient of right wheel of leading wheelset of leading bogie Y/Q
- Wheel unloading of right wheel of leading wheelset of leading bogie $\Delta Q/Q$

The power of each quantity is calculated performing a Hamming window and using a periodogram, of the same length as the time signal, to estimate the power spectral density. The power P_{PB} is calculated in the frequency range 0-20 Hz since this range is the one that more affects the vehicle running behaviour. The contribute of upper frequencies does not affect the quantities analysed in this work. For each simulation case of Table 4, the power $(P_{BP,i})_j$ relative to the i-th quantity and j-th simulation case is compared to the power calculated for the same i-th quantity, but considering the track without irregularities $(P_{BP0,i})_{T11}$ (T11 case). The influence factor $(IF_i)_j$ of the i-th parameter and j-th simulation case is defined according to Equation (2).

$$(IF_i)_j = \frac{(P_{BP,i})_j}{(P_{BP0,i})_{T11}} \tag{2}$$

The influence factor measures the effect of a specific track irregularity (j) on a specific quantity (i). It allows to measure the single effect of the specific irregularity since the effect of the geometric discontinuity due to the switch is already taken into account by the parameter $(P_{BP0,i})_{T11}$.

Figure 7 shows the PSD of the wheel unloading factor relative to the track without irregularities T11 (blue line) and the track with cyclic level irregularities T51 (red line). The red curve shows a PSD peak at f$\cong$5.5 Hz, which corresponds to the exciting frequency at 100 km/h of a $\lambda = 5$ m cyclic irregularity.

Since the task is to compare the effect of different types of irregularities (simulation cases in Table 4) on a specific quantity i, the influence factors are normalised by the maximum absolute value as shown in Equation (3).

$$(IF_i)_{j,norm} = \frac{(IF_i)_j}{\max((IF_i)_j)} \tag{3}$$

The computed normalised influence factors are shown in Table 5. Considering for example the lateral bogie acceleration $\ddot{y}^+$(i-th quantity), it is more influenced by the T31

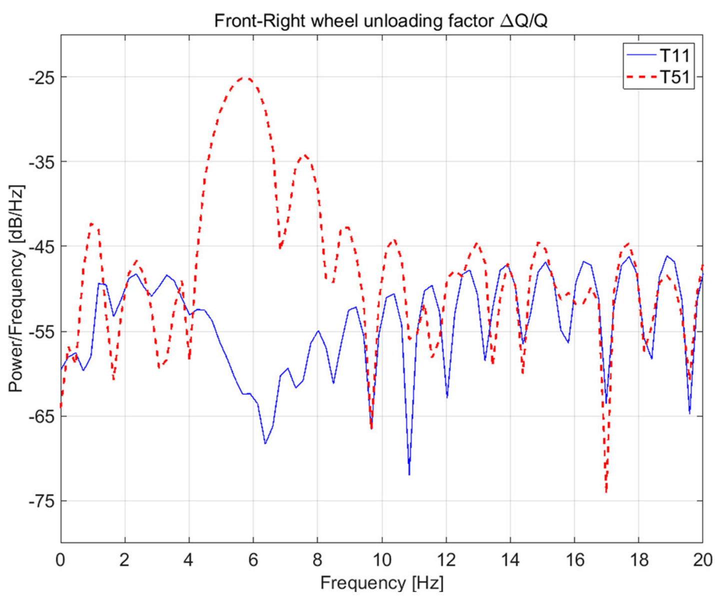

Figure 7. PSD of the wheel unloading factor relative to the T11 and T51 track irregularities.

Table 5. Matrix of Influence Factors (IF) considering different track irregularities and different vehicle's parameters.

	Sim	$\ddot{y}^+$	$\ddot{z}^+$	$\ddot{y}^*$	$\ddot{z}^*$	ΣY	(Y/Q)	ΔQ/Q
Longitudinal Level	T21	0.14	1.00	-	0.12	0.19	0.11	0.46
	T22	0.13	-	-	0.44	0.19	0.11	0.11
	T23	0.14	-	-	1.00	0.19	0.11	0.17
Alignment	T31	1.00	-	0.27	-	0.88	0.83	-
	T32	0.91	-	0.67	-	0.95	1.00	-
	T33	0.24	-	0.86	-	0.54	0.48	-
Twist	T41	0.17	-	0.34	-	0.35	0.14	0.19
	T42	0.21	-	0.52	-	0.48	0.17	0.28
	T43	0.33	-	1.00	0.18	0.84	0.56	0.52
Cyclic	T51	0.13	0.94	-	0.14	0.17	0.43	1.00
	T52	0.14	-	-	0.37	0.16	0.23	-
	T53	0.51	-	0.84	-	1.00	0.32	0.60
Gauge	T61	0.15	-	0.10	-	0.28	0.13	-
	T62	0.11	-	-	-	0.14	0.10	-

Note: IF $=$ 1 means that the influence of one irregularity is the highest for the considered parameter. IF $<$ 0.1 values were discarded.

track irregularity (j-th simulation) since the corresponding normalised influence factor $(IF_i)_{j,norm}$ has a unitary value.

Track gauge has very little effect on all vehicle parameters and therefore it was discarded for further analysis. Lateral bogie acceleration $\ddot{y}^+$ increases for all irregularities, with attention to alignment defects. However, the effect decreases with increasing wavelength defect (from T31 to T33), while the effect on derailment quotient (Y/Q) is greater for the middle wavelength defect (T32). Twist (from T41 to T43 and T53) irregularities have also an important effect on lateral acceleration especially on the carbody $\ddot{y}^*$, see also Figure 6(a), as high twist values (T43) have a greater IF with respect to long wavelength alignment irregularities (T33). Moreover, they strongly affect also wheel unloading $\Delta Q/Q$ and the derailment quotient (Y/Q). Bogie vertical acceleration $\ddot{z}^+$ is only affected by short wavelength longitudinal level irregularities, both single (T21) and cyclic (T51), while the carbody $\ddot{z}^*$ seems to be mainly affected by long wavelength defects (T23), see also Figure 6(b). However, a cyclic longitudinal level irregularity (T51) gives the greatest effect on wheel unloading $\Delta Q/Q$, even if it has a lower amplitude with respect to other cases such as T52. This can be explained considering the first vertical natural frequency of the bogie, which is 7.5 Hz, as shown in Table 1. Considering a vehicle speed of 100 km/h, the T51 defect has a frequency of about 5.6 Hz, while the T52 defect has a frequency of about 2.8 Hz. Being the frequency of the first defect closer to the bogie natural frequency, it produces a greater effect in vertical direction reducing the vertical load on the wheel.

Short wavelength irregularities have different effects considering the starting position. A sensitivity analysis was performed for T21, T31 and T43 simulations, with starting positions of 50, 55 m, i.e. coincident with the switch toe, and 60 m. The greatest effect on (Y/Q) is produced when alignment and track twist defects start from 55 m, mainly because in that case the position of the irregularities is closer to the track position where the contact point changes from stock rail to switch rail.

In order to investigate the effect of different types of defects at the same time the irregularities are combined. For example, longitudinal irregularity T21 is combined with

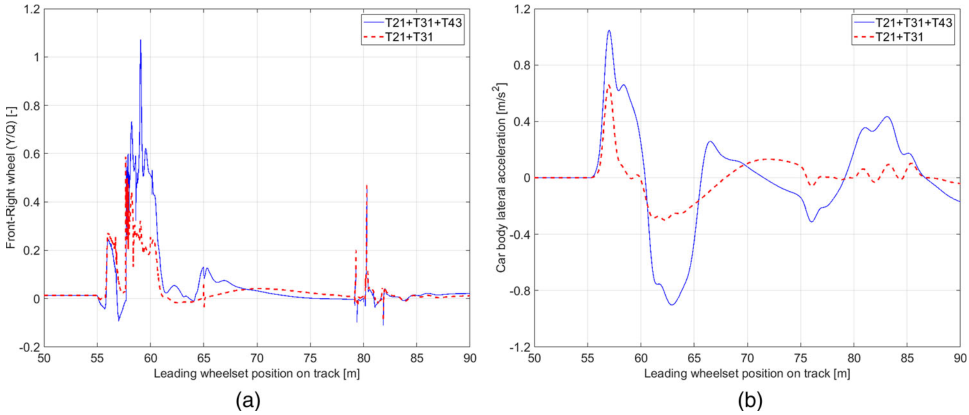

Figure 8. Results with combined alignment, longitudinal level and cross level irregularities. (a) derailment quotient (Y/Q); (b) lateral carbody acceleration.

alignment irregularity T31 since the first one affects the bogie lateral acceleration and the wheel unloading, while the second one affects the bogie vertical acceleration and the derailment coefficient. Then the cross-level irregularity T43 is combined to the longitudinal and alignment irregularity. In Figure 8 (left) the red line shows the derailment quotient when considering the combination of the first two irregularities, while the blue line shows the same quantity when three irregularities are combined. The same is shown in Figure 8 (right) for the lateral acceleration of the carbody.

It is evident that the cross-level irregularity has a strong influence on the vehicle lateral behaviour increasing the derailment coefficient. As already shown in previous cases the irregularities located close to the switch panel, also when combined, do not produce a significative effect in the crossing panel. The contribution of the cross level is evident also considering the carbody lateral acceleration.

The greater effect on lateral force, and therefore on the derailment coefficient, is confirmed for the middle wavelength alignment irregularity T32. This is evident also when

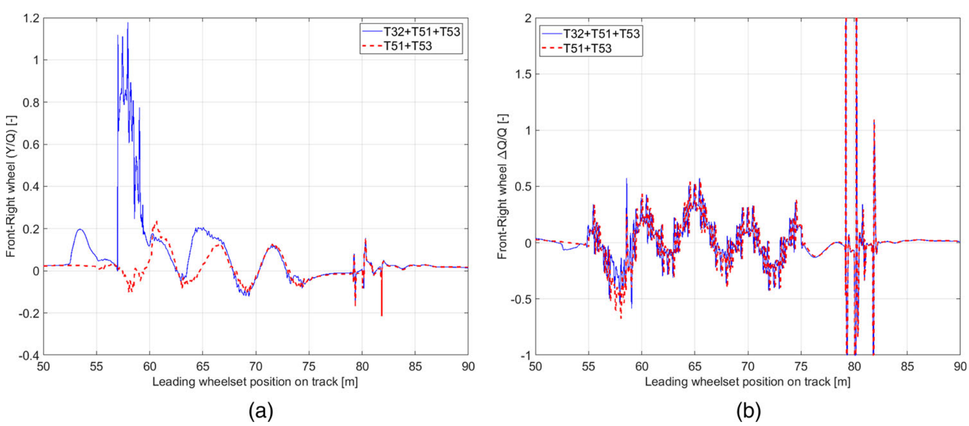

Figure 9. Results with combined alignment and cyclic longitudinal irregularities and cyclic cross level irregularities. (a) derailment quotient (Y/Q); (b) wheel unloading.

combined to a cyclic longitudinal level (T51) and cross level defect (T53), as shown in Figure 9, when a wheel unloading equal to 0.5 at 58 m is produced.

Conclusions

The work deals with the effects of geometric track irregularities on vehicle dynamic behaviour when running through a turnout. Different types of irregularities were analysed considering different wavelengths and the three limit values, i.e. *AL (alert limit)*, *IL (intervention limit)* and *IAL (immediate action limit)* proposed by the EN 13848-5:2017 standard. After an analysis of single irregularities, the work analysed the effect of combined and cyclic irregularities, whose limit values are not defined in the EN 13848-5:2017, although the standard suggests paying attention to these cases. The simulations were performed using the VI-Rail and Simpack multibody dynamics codes.

Differently from the S&C benchmark, this work also considered the complete turnout including the switch and the crossing panel in the same simulation. This allowed to consider the effect of the switch on the vehicle dynamics during the negotiation of the crossing, performing a further comparison between the Simpack and VI-Rail multibody code. However, the results have shown that the dynamic behaviour of the vehicle in the switch panel and in the crossing panel is not cross-related. This confirms that the strategy adopted in the S&C benchmark of separately simulating the switch and the crossing panel is the correct approach for this kind of turnout. The numerical models were also compared considering the effect of track irregularities showing very good agreement although some simplifications on track modelling were implemented.

Starting from the hypothesis that the cross-section in the crossing panel provides an higher stability to the track, due to longer and heavier crossing bearers than the standard sleepers and heavier monobloc crossing rail which contributes to increase the stiffness of the crossing panel, track irregularities were considered only in the switch panel and closure panel, which are more similar to plain line track section. Also, in this case the results show that irregularities placed on the switch panel have little influence on the vehicle dynamic behaviour during crossing negotiation.

Another interesting aspect, which is highlighted by the results, is that, when combined, irregularities featuring amplitudes lower than the *IAL* limit can have a significant impact on vehicle running behaviour and safety. These combinations might generate dangerous conditions in some cases. For example, alignment irregularities which have the peak value where the contact point moves from the stock to the switch rail produce a huge increase of the derailment quotient and of the carbody lateral acceleration. Also, cyclic top irregularities with amplitude values lower than the *IAL* limit can produce dangerous wheel unloading when the combination of vehicle speed and irregularity wavelength produces an excitation close to the bogie vertical natural frequency.

The paper also showed a purposely built data analysis process to compare the effect of different track irregularities. The method is based on the analysis of the power spectral density (PSD) of the quantities which are more affected by track irregularities.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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