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Reference values for railway sidings track geometry

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Abstract

Railway sidings are operated at speeds much lower than those used on national railway lines; a typical speed is 6 km/h. In establishing reference values for maintenance of railway infrastructure in terms of the geometry for such operating conditions, it is noted that both national and European regulations do not provide specific information regarding railway sidings.
The overall objective of the research is, therefore, the definition of possible reference values for track geometry, based on those adopted by European rail networks (European and national standards), which can guarantee the appropriate security level for low speed operation typical of railway sidings connected to the national network.
The basic principle in defining these values is the maximization of technical-economic efficiency and the maintenance of the acceptability of the risk associated to railway operation. The research results can therefore provide useful information about the cost-effective management of maintenance and safe operation for railway sidings.
For this purpose, the approach was inspired to that of Regulation 402/2013, which defines at European level a common safety method for risk analysis. Quantification of probabilities and damages should be based on simulation models because the available statistics do not allow significant results to be inferred. However, the research sector has not yet produced a consolidated modelling. For these reasons, and since it is not possible to quantify probabilities reliably, the proposals resulting from this research are based on the identification of situations where it can be shown that the hazard probability remains unchanged.
The approach used to formulate possible reference values valid outside of national networks (railway sidings) is based on an understanding of the underlying principles of the codes of good practice, on the formulation of hypotheses conform to the same principles, and the proposals about mitigative measures of risk associated to the use of different reference values, such as to keep the risk of the railway within the limits of acceptability, acting conservatively so as to keep unchanged, or reduce, the probability of hazardous events.

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The assessment parameters, object of the first phase of the research referred to in this work and used here as an example, are longitudinal level and alignment of railway track. In the case of vehicles running at low speed, the study was conducted by varying the magnitude of the reference values by using values that belong to external intervals with respect to those in accordance with European and national codes of good practice, examining the corresponding effects on the physical quantities related to safety. The effects of their variations on the wheel-rail interaction forces were studied using a simple dynamic model (with one degree of freedom) and a random generated excitation given by track defectiveness and the corresponding random response in terms of vertical and lateral contact forces (Q and Y).

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Keywords: track; S&C; track geometry quality; sidings; freight

1. Introduction

The track geometry quality concept is related to the irregularities of the track as a source of excitation of the vehicle-track system: the lower the irregularities, the higher the quality. Track gauge, twist, longitudinal and cross-level, alignment are examples of quantities that are used to assess the quality of a track. Free-wheel passage and nose-protection dimensions are examples for switches and crossings (S&C).

Low track geometry quality generally leads to high dynamic vibrations of vehicle and track and to a higher probability of losing geometric compatibility between wheels and track or S&C, and consequently to a higher probability of derailment. That is why track geometry quality is related to running safety, wear of components, noise and vibration.

Therefore the railway sector has developed documents defining reference values for different track geometry parameters, how to measure them and their limit values in order to achieve economically efficient and safe operations.

Limit values were defined at national level first and, in more recent times, in European standards – TSI INF (2014), EN 13848 series for track only -, with the aim of achieving a unified European railway network. The latter values were conceived for interoperable networks that are under the responsibility of national Infrastructure Managers, as defined by European law.

The tracks of railway sidings – i.e. facilities for loading and unloading freight wagons, connected to the main network – are generally not subjected to those regulations. However, compliance with national or European norms is desirable, as it is a straightforward way to guarantee the right level of quality and safety to Railway Undertakings, national Infrastructure Managers and the Public. The problem is that railway sidings are operated at speeds much lower than those used on national railway lines; a typical speed is 6 km/h, and 30 km/h is considered as a relatively high speed.

Sidings are a key element of intermodal facilities, such as sea-rail facilities, as in ports, and road-rail terminals. In such facilities, entire rail yards and rail networks are made of up tracks that may be considered as sidings. Such networks differ from the national railway network not only because of operational speed, but also because of their limited length, operations consisting exclusively of freight wagons shunted by locomotives running on sight, frequent changes in track curvature, high density of switches and crossings and level crossings.

Therefore, in most cases the direct application of track geometry standards to such networks would entail a track that is over-designed with respect to its purpose. This is definitely not desirable in the European context in which a re-launch of rail freight transport is paramount, and depends on the reduction or elimination of operational bottlenecks, among which networks of railway sidings are key players.

The overall objective of this research is thus the definition of possible reference values for track geometry, based on those adopted by European rail networks (European and national standards), which can guarantee the appropriate safety level for the low speed operation typical of railway sidings connected to the national network.

2. Analysis of regulatory documents

For this purpose, the research approach was inspired to that of Regulation 402/2013, which defines at the European level a common safety method for risk analysis, with risk defined as frequency of occurrence of accidents and incidents resulting in harm and the degree of severity of that harm. In a case such as ours, it would be desirable for frequency and harm (often obtained by multiplying the probability of an accident occuring and the related damage) to be quantified explicitly on the basis of simulation models. Unfortunately the available statistics do not allow significant results to be achieved, since the research sector has not yet produced a consolidated modelling approach. It is thus not possible to quantify probabilities reliably, so the key challenge of this research was to identify ways in which to demonstrate that the system change represented by the application of different track geometry limits to a railway siding network does not increase the probability of derailment. The challenge is being met by understanding the underlying principles of the codes of good practice and seeking similar reference systems to the system constituted by the network of railway sidings addressed in this research. In fact, these are two of the three "risk acceptance principles" identified by Reg. 402/2013, along with explicit risk estimation, which as mentioned is not currently applicable. In fact, demonstration of conformity to a code of good practice can be taken as demonstration of acceptability of risk, and the same applies if similarity to a reference system with acceptable risk is demonstrated. Since in our case the existing codes of practice do not regulate in detail the speed range of interest, we seek to demonstrate the next best thing to literal conformity: that is conformity with the underlying principles.

This approach is facilitated by referring to the IAL (Immediate Action Limit) concept which is promoted by European legislation (TSI and EN). With this concept, a limit is no longer strictly prescriptive. An exceedance of the limit requires, on the part of the inframanager in our case, an immediate action to re-establish an acceptable risk level. Exactly which action is not specified.

To translate this approach into practice, the following steps are being systematically performed:

1. analysis of applicable regulatory documents, both inside and outside Europe;
2. identification and analysis of assessment quantities and limit values for geometry of track and S&C, with the purpose of understanding underlying principles, correlated hazards and vehicle reactions, correlated quantities that are more directly related to risk;
3. sensitivity analysis of the risk-related quantities to variations of the regulated assessment quantities in ranges comprising the limit values.

The above steps are described in this paper with reference to a simple case, with two well-understood track geometry assessment quantities: longitudinal level and alignment.

3. Analysis of regulatory documents

In Licciardello et al. (2015) we presented (step 1. above) an overview of the regulatory documents analysed during the research and listed the relevant assessment quantities for both the geometry of track and S&C (see Fig. 1 for a graphical overview related to track only). We also described the underlying physical principles and listed the corresponding quantities that are more risk-related than simply the geometric assessment quantities.

The analysis took into account European regulatory documents – TSI Infrastructure (2014) CR and EN 13848 – national norms of EU Member States (Italy, Sweden, Denmark, UK), and norms of non-EU countries (essentially Australia).

The most important assessment quantities for track are: longitudinal level, alignment, gauge, twist (correlated with cross-level). For S&C there are numerous geometric quantities, broadly classifiable as free-wheel passage dimensions and nose-protection dimensions.

The analysis showed a good degree of consistency between EU and national Member States values, with the former being the less restrictive and describing a "safe envelope" within which the latter values are contained. It also underlined the almost complete transition to risk-based safety limits, such as IAL, as opposed to prescriptive limits.

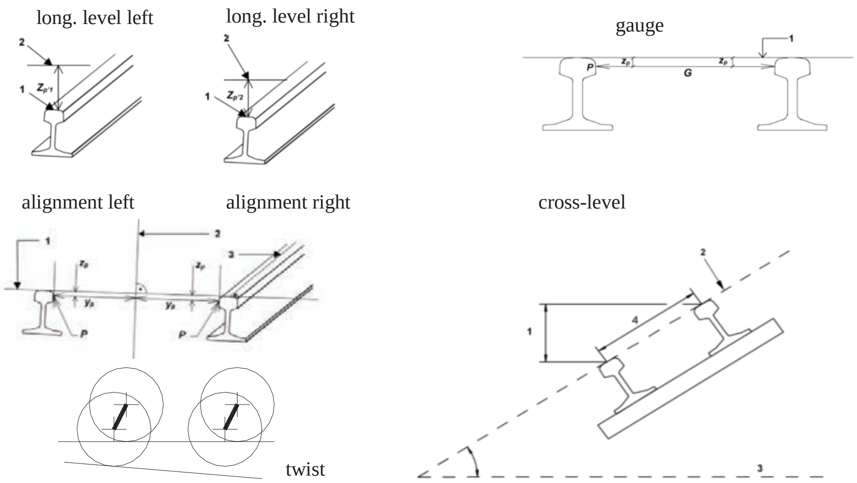


Fig. 1. Graphical representation of main assessment quantities for track, according to EN 13848 and TSI Infrastructure.

In Table 1 we present an extract of a larger table that lists the quantities addressed in this paper, along with reference values and other information.

Table 1. Assessment quantities addressed in this paper and European reference values.

Assessment parameter	Symbol	Reference value (IAL)	Reference
Longitudinal level (left rail, right rail)	LL	31 mm (V≤40 km/h, isolated defect)	EN 13848-5
alignment (left rail, right rail)	A	25 mm (V≤40 km/h)	EN 13848-5

4. Analysis of assessment quantities and limit values

Step 2. of the process requires understanding underlying principles, correlated hazards and vehicle reactions, and correlated quantities that are more directly related to risk.

Table 2 represents an extract of a larger table in which we associate the assessment quantities with hypotheses about related hazardous events and potential damage.

A potential damage always resulting from the exceedance of the limits values is the possibility of derailment,. However longitudinal level and alignment excess generally does not lead directly to a derailment if not via excess track twist or gauge. For this reason we distinguish between type A (limit that needs to be exceed only once to create damage) and type B (limit that needs to be exceeded many times to create damage). At certain speeds a large alignment fault could potentially cause a derailment without having to be run over many times, hence the “type A” entry. However this case is not considered to be important at the low speeds we are addressing.

Both assessment quantities are characterized by the fact that a reduction in speed leads to reductions of the actions exerted on the rolling stock and associated with the possibility of derailment. For both of them the lower the vehicle speed, the lower the damage.

Moreover, in case of derailment of a freight wagon carrying dangerous goods, additional damage could be associated with the possible loss of cargo. This occurrence is clearly influenced by the vehicle speed; in fact the lower the speed is, the smaller the probability that loss of cargo is associated with the derailment.

Table 2. Hazardous events and damages related to exceeding limit values for longitudinal level and track alignment.

Assessment quantities	**Symbol**	**Hypothetical hazardous events related to an exceedance of limit values**	**Potential damage** (A type: just one exceedance could create damage; B type: more exceedances are needed to create damage)
Longitudinal level	LL	- excessive dynamic wheel loads (Q)	- B type: derailment
Track alignment	A	- excessive dynamic lateral forces (Y)	- B type: derailment - A type: derailment due to track misalignment

Table 3 shows the correlation between the assessment quantities and the characteristic parameters of the vehicle response typically used for the acceptance of running characteristics of railway vehicles.

Table 3. Relationship between track geometry parameters and the vehicle response (EN 13848-5:2008).

Vehicle response (forces and accelerations)	**Track geometry assessment quantities**	
	Longitudinal level	**Alignment**
ΣY	—	✓
Q	✓	✓
y''	—	✓
z''	✓	—
Y/Q	✓	✓

We note that longitudinal level is correlated with “vertical” forces (Q) – i.e. wheel loads – and accelerations (z''), as is intuitive, whereas alignment is mainly correlated with lateral wheel forces/accelerations (ΣY, i.e. sum of the lateral forces acting on a wheelset, y'' lateral wheel acceleration), but also with vertical forces Q, since alignment defects tend to excite vehicle swaying motion inducing variations of wheel load. Both quantities are thus related to the well-known derailment ratio Y/Q.

Vertical and lateral accelerations tend to gain importance at high vehicle speed so they have quite low effects in case of low vehicle speed as those examined in this research.

We may conclude that the quantities, associated with the geometric quantities longitudinal level and alignment, which are more directly related to risk are vertical and lateral forces, in terms of their dynamic variations.

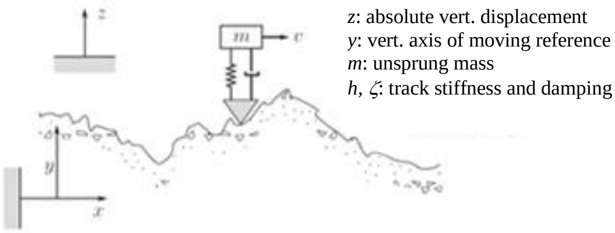
5. Sensitivity analysis

Dynamic vertical and lateral loads have been identified as the quantities most directly related to the risk that is counteracted via the limits on longitudinal level and alignment.

Therefore, we investigate the effects of geometric assessment quantities and vehicle speed on dynamic loads acting on a single wheel of a wheelset, for a given track quality expressed in terms of power spectral density.

A train running on a track sees its components subjected to vertical, lateral and angular accelerations due to the presence of track irregularities. In order to simplify the problem we consider just the vertical accelerations caused by the presence of longitudinal level defects (Fig. 2) and we consider the vibrational behaviour of suspended masses as uncoupled from that of the single unsprung mass (i.e. the wheel) in the range of wavelengths addressed (e.g. the 3–25 m range which corresponds to the lowest frequency range addressed in EU regulatory documents). This simplifies the problem with no significant loss of accuracy.

Irregularities impose a vertical displacement on the mass running over them. As the longitudinal speed of the mass increases, such movements must take place in shorter time spans with a consequent increase of vertical velocities and vertical accelerations. Load Q must then increase and decrease with respect to its static value (variation that is indicated here as ΔQ, the dynamic component), in order to achieve the vertical motion of the mass.



z: absolute vert. displacement
y: vert. axis of moving reference
m: unsprung mass
h, *ζ*: track stiffness and damping

Fig. 2. Scheme of the dynamic model of an unsprung mass (half a wheelset + vibrating track section) excited by longitudinal level irregularities.

The calculation of the dynamic component on the basis of the magnitude of longitudinal level irregularities is carried out in the frequency domain, according to an approach widely used in vibration theory. Defects are taken into account through their Power Spectral Density (PSD) $s_d(\Omega)$ [m^3] (or [mm^3]), where Ω is the spatial frequency [rad/m]. The PSD assumes a typical shape for a railway track (Fig. 3, in which four different track qualities are represented) – this shape reflects the fact that the rail is constructed so as to admit defect amplitudes (and thus PSD of defects) higher at low spatial frequencies (long wavelengths) than at high spatial frequencies (short wavelengths).

In this paper we are not interested in any specific track, so we used the following simple analytical expression to represent the PSD in Fig. 3. This formula interpolates PSDs measured on real track (Proud'homme, 1970). Constants A and B define the shape of the spectrum:

$$s_d(\Omega) = \frac{A}{(B+\Omega)^3} \tag{1}$$

In order to examine how “track quality” affects dynamic loads at varying speed, we decided to represent variations of track quality by keeping constant B and varying A in such a way as to obtain different values of standard deviation of the longitudinal level σ_d. The standard deviation of defects over a certain length of track – typically 200 m – is obtainable from the PSD by means of integration (it is related to the area subtended by the curves) and is a frequently used indicator of track quality (e.g. EN 13848).

The PSD of track defects is transformed from a function of spatial frequency $s_d(\Omega)$ to a function of (time) frequency $s_d(\omega)$- simply by multiplying by vehicle speed. Displacements of the unsprung mass are obtained from the displacements corresponding to the track defects by multiplying by the square of the modulus of the system's transfer function $|H(\omega)|^2$ which accounts for track stiffness/damping and mass. These displacements are then derived twice in order to obtain accelerations – this corresponds to multiplication by ω^2 in the frequency domain. Accelerations are finally multiplied by the unsprung mass to obtain the dynamic forces that must act on such mass.

Concisely:

$$s_{\Delta Q}(\omega) = m \cdot |H(\omega)|^2 \cdot \omega^2 s_d(\omega) \tag{2}$$

Integration of this PSD gives us the standard deviation $\sigma_{\Delta Q}$ of dynamic loads acting on the unsprung mass. In order to understand the relationships between input and output of this model, Fig. 4 shows how the dynamic loads change when the main influence quantities are changed – track stiffness and damping, unsprung mass. For this example speed is kept constant (80 km/h), as is track geometry quality (standard deviation of the longitudinal level of 2 mm).

It can be observed that for input variations within reasonable operational ranges the standard deviation of the dynamic wheel loads range from about 8 to 12 kN (80 km/h, σ_d = 2 mm). Considering that static loads per wheel vary between 50 kN and 110 kN, this means that we have oscillations of about 10÷30% in relative terms. These are already quite high fluctuations since 3 times the standard deviation, for low static axle load, is close to 100% of the load. Note also that the magnitude of the dynamic load depends only on the unsprung mass and not on the static load.

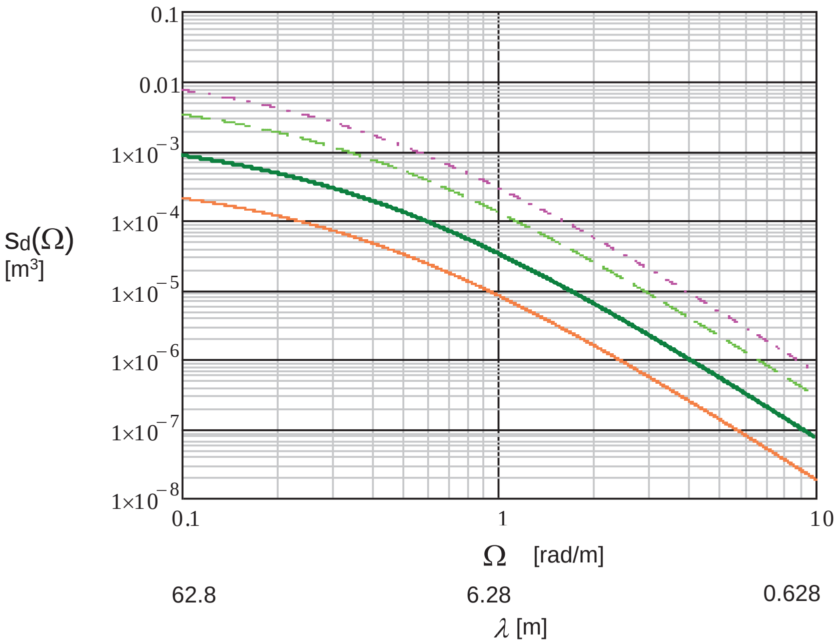


Fig. 3. PSD of longitudinal level for 4 values of constant A = $k\cdot\sigma_d^2$ corresponding to σ_d = 5, 10, 20, 30 mm.

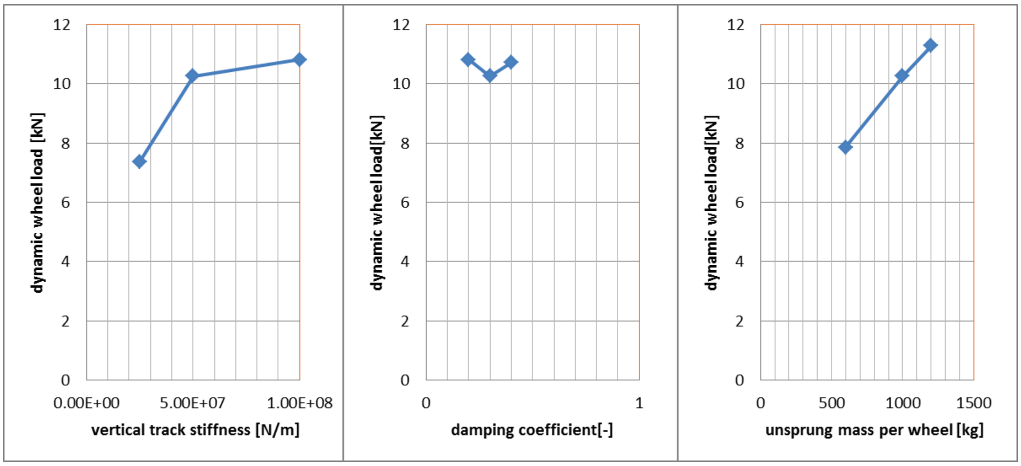


Fig. 4. Sensitivity analysis of the dynamic wheel load to the input data, kept constant in this research. The analysis is performed using $V = 80$ km/h, $\sigma_d = 2$ mm.

Starting from the reference condition defined above, we are interested in understanding how speed and track quality variations influence the dynamic loads. The following simplified formula was found to approximate the exact theory described above with reasonable approximation (<10% error in the range 0–40 km/h):

$$\sigma_{\Delta Q} = C \cdot V \cdot \sigma_d \qquad (3)$$

$$C = \frac{4}{\pi} \cdot \sqrt{k \cdot m \cdot h} \tag{4}$$

in which:
$k = 8.14 \cdot 10^{-7}$ constant value dependent on the analytical form chosen for the spectrum (eq. (1))
h track stiffness

Using values of *m* e *h* equal to those used for Fig.3 we obtain:

$C = 0.04 \div 0.11$ (central value about 0.07), V [km/h], σ_d [mm], $\sigma_{\Delta Q}$ [kN].

Conversely, if we wish to understand which track quality corresponds to a given maximum admissible level of dynamic loads (for example the level that is presumably acceptable as implied in the regulation)

$$\sigma_{dmax} = C^{-1} \cdot \frac{\sigma_{\Delta Qmax}}{V} \tag{5}$$

with the constant being the inverse of the previous one:

$C^{-1} = 9 \div 25$ (central value about 14), V [km/h], σ_d [mm], $\sigma_{\Delta Q}$ [kN].

This way of proceeding was used, with the exact formulas, to achieve the results of Fig. 5 for the longitudinal level (left panel in the graph) which shows values of the standard deviation as a function of running speed calculated on the basis of the spectrum used as a reference (eq. (1)). For comparison the indicative standard deviation values of European norm EN 13848 are shown, as well as the corresponding IAL values (on a different y-axis).

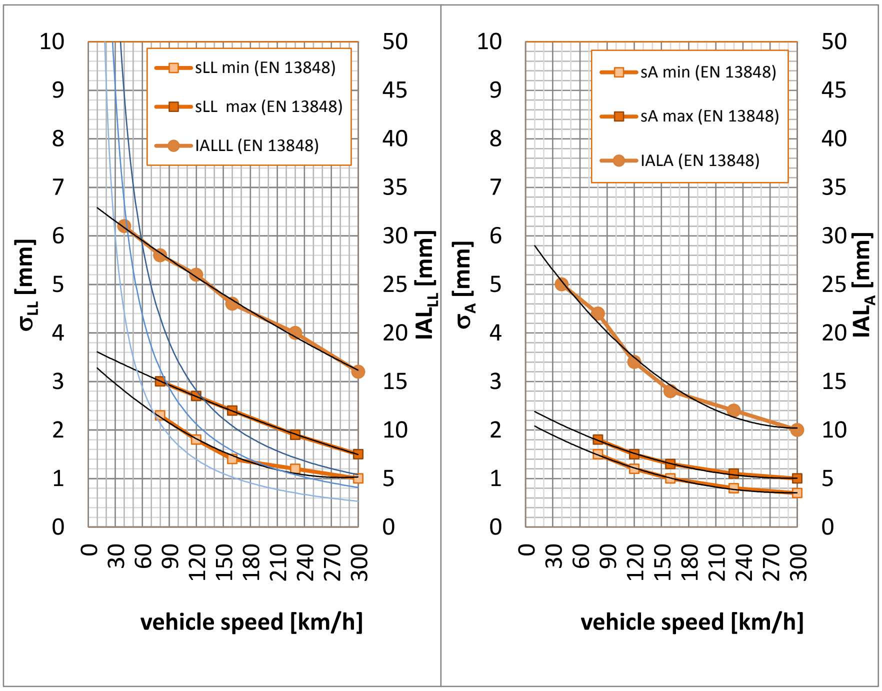


Fig. 5. Left. Longitudinal level. Calculated values of admissible longitudinal level standard deviation for given admissible dynamic load (11 kN; 16.5 kN; 22 kN, thin continuous lines) compared with the ones given as an indication in EN 13848 and with the mandatory IAL values. Right. EN 13848 values for alignment: indicative values for standard deviation and mandatory values for IAL. N.B. σ is indicated as s.

The three continuous lines on the left panel are calculated according to the model described above. They represent permissible σ_{LL} values corresponding to three values for increasing $\sigma_{\Delta Qmax}$ (11 kN; 16.5 kN; 22 kN), as in eq. (5) but with the exact model.

In the right panel the standard deviation of the alignment and the corresponding IAL values are shown for comparison.

We observe how, given a value of admissible dynamic load $\sigma_{\Delta Qmax}$, the corresponding admissible standard deviation of the longitudinal level increases significantly at low speed. We also observe, however, that the EN 13848 values correspond to values of permissible dynamic loads $\sigma_{\Delta Qmax}$ which decrease with speed: over 22 kN are implicitly allowed for speeds greater than 120 km/h, whereas less than 16.5 kN are allowed for speeds lower than 80 km/h.

Another interesting observation is that the ratio between IAL and maximum indicative standard deviation is approximately constant – actually slightly increasing with speed for longitudinal level and slightly decreasing for alignment. The ratio is between 9 and 12 (about 10).

6. Formulation of hypotheses for reference values

The graphs of Fig. 5 allow some interesting possibilities for new reference values to be formulated for speeds lower than the 40 km/h regulated in the EN norm. The mere application of the EN would require isolated longitudinal level defects to remain within 31 mm for any line speed below 40 km/h. Even a simple extrapolation of the EN values (see extrapolation lines in Fig. 5) could reduce the over-design that would stem from this application. Such an approach (see Table 4) is, in our opinion, quite cautious. It can be shown not to increase the probability of derailment due to excessive dynamic loads, since these loads tend to decrease rapidly. It respects the rationale of the current regulations.

A similar reasoning may be applied to alignment, for which however it is more difficult – but not impossible – to derive the inputs for the model of §5. With the same reasoning, different IAL can be identified for temporary speed restrictions.

Table 4. Current limit values and proposed limit values.

Assessment parameter	**Parameter linked to safety**	**General criteria**	**Specific criteria**	**EN13848-5 /TSI reference values (IAL)**	**Proposed values**
Longitudinal Level	Dynamic component of Q force	Maintaining probability of hazardous event unchanged. Respect of the rationale of the EN norm.	Identification of the limits implicitly allowed for the dynamic components of the force Q with a theoretical model. Extrapolation of the values mentioned into EN 13848 up to the low speed range. Verification of not exceeding the limits implied above (verification largely satisfied). Speed restriction to 20 km/h and 10 km/h with the same criteria in the case of exceedance of the proposed values.	31 mm (V≤40 km/h, isolated defect)	31.5 mm (V≤30 km/h) 32.0 mm (V≤20 km/h) 33.0 mm (V≤10 km/h)
Alignment	Dynamic component of Y force	Maintaining probability of hazardous event unchanged. Respect of the rationale of the EN norm.	Extrapolation of the values mentioned in EN 13848 up to the low speed range. Analogy with longitudinal level for acceptability of the extrapolated values. Speed restriction to 20 km/h and 10 km/h with the same criteria in the case of exceedance of the proposed values.	25 mm (V≤40 km/h)	26.5 mm (V≤30 km/h) 27.5 mm (V≤20 km/h) 29.0 mm (V≤10 km/h)

Given the steep rise at low speeds in the curves of Fig. 5 providing the admissible defect levels for given admissible dynamic loads, it is not illogical to consider the possibility of excluding altogether both longitudinal level and alignment from the assessment of track geometry quality at low speeds. In fact, such assessment quantities are strongly linked to other quantities that are of much greater interest at low speeds, namely track twist and gauge.

7. Conclusions

In this paper we present an approach to arrive at proposals of revised limit values for railway sidings. Such facilities are characterised mainly by the low speed of operations, and by a high density of switches and crossings.

The approach is inspired to the criteria of the Common Safety Method for risk assessment of Reg. 402/2013. Since explicit risk estimation not possible as a risk acceptance principle, reference to codes of practice and similar systems is chosen.

We focused here on two important track geometry assessment quantities: longitudinal level and alignment. Both the TSI Infrastructure and European Standard EN 13848 are taken as reference codes of practice. Since the mere application of the IAL (Immediate Action Limits) of such codes of practice to railway sidings could represent a case of overdesign (i.e. track quality too high for actual needs), we sought to propose a revision of such limits by respecting the underlying principle of the codes of practice: longitudinal level and alignment must not be so high as to create excessive dynamic loads on wheels.

We thus used the simplest possible model to link the safety-related quantities (dynamic loads) to the regulated assessment quantities (longitudinal level and alignment), and showed that the former decrease significantly at the low speeds typical of operations at sidings.

We finally made a cautious proposal for revised IAL, showing indirectly that it does not increase probability of derailment. In turn this target (non-increase of probability) introduces an element of caution, since damage generally also decreases at low speeds, so in theory higher probability of derailment would be allowable without necessarily increasing risk.

This paper hopes to pave the way for further research aiming at reducing overdesign in rail freight facilities, with consequent positive effects for the tax-payer, whilst maintaining if not improving the high levels of safety achieved by the rail sector.

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