FORCE-BASED ASSESSMENT OF WELD GEOMETRY

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Summary: TU Delft developed new geometrical standards for rail welds, for the Dutch Railway administrator ProRail. The current standards were based on the limitation of maximum vertical and horizontal tolerances, as is common practice worldwide. In this approach the geometrical shape of the weld has no significance, thus neglecting the important direct relation to dynamic wheel-rail contact forces and stresses.
In the new approach the influence of the complete geometry is included. A theoretical model is presented to translate the complex dynamic problem of calculating dynamic wheel-rail contact forces into a purely geometrical problem, which is fast to solve and easy to implement in a numerical code for the small processor of a measuring device. Intervention values for the dynamic force have been determined, dependent on the train line speed, by evaluation of a substantial number of weld geometry measurements, and subsequently expressed in terms of the 1st derivative of the weld geometry. The new assessment method asks for new measuring equipment: digital straightedges are necessary to obtain the quality level corresponding to the new standards.

Index Terms: weld geometry, wheel rail forces, weld geometry measurement, rail weld assessment

1. INTRODUCTION

Delft University of Technology has developed new technical standards for the geometrical deviations of metallurgic rail welds in the Netherlands, in cooperation with the Dutch rail infra manager ProRail [1,2]. Like in all norms worldwide, the Dutch standards were based on establishing vertical (and horizontal) tolerances. In this way, only the maximum value of the longitudinal rail surface irregularity played a role, whereas the geometrical shape had no significance. However, this shape has a direct relation to dynamic wheel-rail contact forces, which may not be neglected, as these are the source of many railway component defects and track deterioration mechanisms. Further, in the old standards the train velocity limitation for the line section in question had no influence.
In order to tackle this shortcoming, it was decided to develop a method to evaluate the overall dynamic quality of each individual realized weld geometry, dependent of the line-section speed. This quality can be expressed in terms of dynamic effects occurring for train passage of the weld geometry. The concept is elaborated in the following of this article, and the approach may proof useful for application on a wider scale.

In practice, the above changes have created an incentive to regularly initiate benchmarking, auditing and life cycle costing (LCC) studies (often used in combination). These studies have become inevitable, once performance contracts are introduced. The paper will address two examples in order to show how ProRail used such studies to investigate feasible cost/performance levels and to modify investment and maintenance programs.

2. THEORETICAL BACKGROUNDS

Usually, the rail weld geometry is measured with a straightedge with 1 m base. The sampling of the rail geometry is a discrete process, as will be treated more extensively in section 3. Therefore, there exists some minimum wavelength which can be registered for rail welds, which is described by the minimum of 5 sampled coordinates or 4 sampling intervals. These intervals are taken as 25 mm, as will be explained in section 3. This results into a minimum full wavelength for welding irregularities of 0.1 m. This very well corresponds to the real situation. Smaller wavelengths may exist theoretically, but will have such small amplitudes that they will be deformed plastically immediately after some track use, as they have the same order of magnitude as the geometrical properties of the railhead, and thus play no role of importance in practice. In this way a range for the wavelengths in the weld irregularity is found of 0.1-2 m.
The velocity range for train track generally spoken is 0–300 km/h. The corresponding frequency-range which is of importance now can be found as 0-830 Hz. In train-track-dynamics in this frequency-range several stiffnesses and masses play a role. As most important masses can be mentioned: unsprung wheel mass and equivalent track mass, most important stiffnesses are primary suspension stiffness, wheel-rail Hertzian contact stiffness and the equivalent track stiffness.
However, for each frequency a certain mass in combination with a related stiffness will play a dominating role and determine the magnitude of wheel-rail contact forces. For the lowest part of the frequency range the combination of wheel mass on track stiffness will be dominating; soon the role of the wheel mass as dominating mass will be taken

over by the equivalent track mass, and for the highest part of the frequency range the Hertzian stiffness will replace the track stiffness.

Two different approaches are now possible as a method for estimation of dynamic wheel-rail contact forces and their development in time: an approach relating vertical dynamic forces to the vertical acceleration of the dominant mass and a second one relating forces to its vertical velocity. Both methods are discussed briefly in the following sections. It is mentioned however in advance that both methods include several assumptions, which are justified to some extent from a theoretical point of view but also need both verification and validation by measurements. Main objective is to develop some practical tool for weld geometry assessment, directly relating the geometry to the magnitude of dynamic contact forces occurring for that geometry, without having to perform complex dynamic calculations for each separate geometry.

2.1 Acceleration approach

Assuming a quasi-static response for the dominating mass-stiffness combination, disturbed by the weld irregularity as a function from the longitudinal coordinate $z(x)$ moving at train speed *v*, the dynamic component of the wheel-rail contact force is equal to the inertia force originating from the mass *M* which follows the vertical irregularity (Fig. 1), or, according to Newton:

$$F_{dyn}(t) = M\ddot{z}(t) \qquad (1)$$

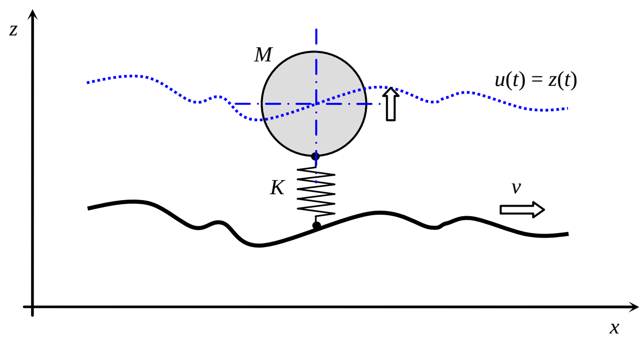

Fig. 1 Mass-spring system disturbed by rail irregularity

At a train velocity v and e.g. the minimum wavelength *L* of 10 cm the excitation frequency equals:

$$f = \frac{v}{L} = 10v \ \text{[Hz]} \qquad (2)$$

from which the requirement for f can be read directly. A quasi-static response occurs for $f < 0.5 f_0$ approximately, where f_0 denotes the natural frequency of the mass-spring system under consideration, to be determined from mass *M* and stiffness *K*.
In terms of track and train parameters, the requirement for quasi-static response reads:

$$\frac{v}{L} < 0.5\sqrt{\frac{K}{M}} \qquad (3)$$

Whether (and to which extent) this requirement is satisfied depends heavily on the specific track properties and must be verified by measurements. The train velocity *v* herein is given by the line-section speed in question.
In order to translate the complex dynamic contact-force problem into a geometrical problem, the quasi-static approach proofs to be very useful, as the curvature of the geometry is a direct measure for dynamic contact forces. In the dynamic formulation a 2nd order differential equation (or a system of them) must be solved, whereas in the geometrical problem only an algebraic equation must be solved to determine the contact force.
In terms of the vertical rail geometry, for (1) can be written:

$$F_{dyn} = \alpha M v^2 \frac{d^2 z}{dx^2} \qquad (4)$$

In (4), a validation factor α is added to account for dynamic influences which were not modeled, inaccuracies introduced by assumptions on the response and non-linearities. Its value can be chosen different per line-section speed and should be determined from validation measurements.

2.2 Velocity approach

The vertical rail geometry in longitudinal direction is a function $z(x)$ which can be transformed to the frequency domain (its discrete sampling via FFT).
When, in analogy to (1), a contact force is assumed coupled to the second time derivative of the geometry, but now with an equivalent mass m_e of the dominating mass-stiffness combination inversely proportional to the frequency f or proportional to the wavelength *L*, can be written:

$$F_{dyn}(t) = m_e \ddot{z}(t) \qquad (5)$$

where

$$m_e = \frac{1}{L_0} ML = \frac{1}{L_0} M \frac{v}{f} \qquad (6)$$

with L_0 some reference wavelength. Starting from a harmonic signal $z = z_0 \sin\left(2\pi vt / L\right)$, after some elaboration follows:

$$F_{dyn} = M \frac{2\pi v}{L_0} \dot{z} \qquad (7)$$

Due to the initial assumption (which is no more than an assumption, but may fit measurement data better than the assumption of a force being totally uncorrelated to the wavelengths in the signal or a fully quasi-static response) of a linear relation between wavelength and effective mass, this expression is independent of L and holds for any arbitrary function z. Via $dx = v \cdot dt$ follows, directly in terms of the rail geometry (slope):

$$F_{dyn} = \beta \frac{M}{L_0} v^2 \frac{dz}{dx} \qquad (8)$$

For qualitative comparisons, the reference wavelength L_0 can be taken as 2 m, measuring the weld with a 1 m straightedge then yields for the longest wavelength in the signal $m_e = M$. In (8) again a constant validation factor β is added. Its value again may be chosen different per line section velocity and should be determined from measurements.

2.3 Comparison

In both approaches the dynamic contact force problem was translated into a purely geometrical problem. This is important, as an evaluation of each individual weld geometry asks for a simple procedure to estimate occurring dynamic effects. A geometrical approach is easy to implement in a numerical code for the small processor of a measuring device, and much faster than a dynamic approach. Further, both approaches allow a *qualitative* comparison between different rail geometries. To obtain quantitative results, the model parameters as well as the factors α and β should be obtained via measurements. Which of both approaches is closest to reality should be found from measurements.

3. DERIVATION OF WELD GEOMETRY STANDARDS

The intervention levels for the force, according to (4) and (8) respectively, have been derived in both cases by evaluation of a large sample of weld geometries, and are different per line-section speed. The measuring devices in use in the Netherlands sample the vertical rail geometry each 5 mm. Before determining the derivatives of the discrete signal, it is averaged over a distance of 25 mm (5 data points), and a data point each 25 mm is used (Fig. 2). This is done to avoid very grassy signals for both derivatives due to very short-length micro-irregularities, which in reality will deform plastifically after a certain number of train passages.

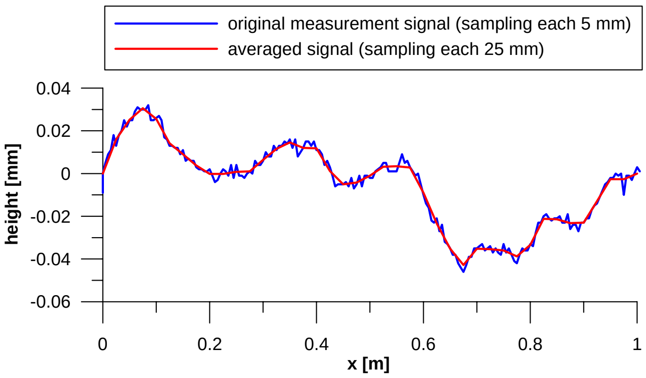

Fig. 2 Example of a measured and averaged weld geometry

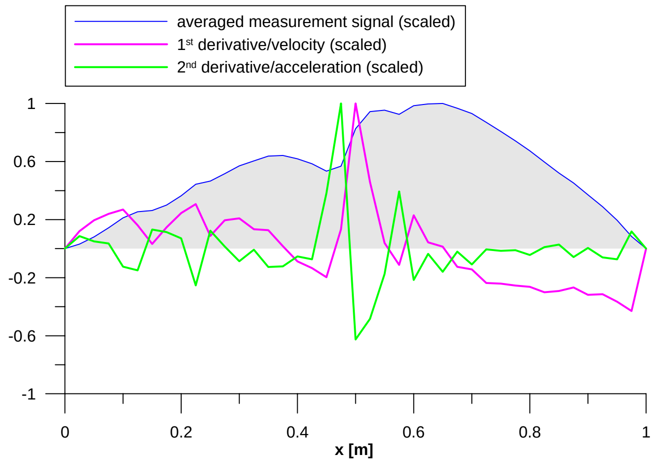

Fig. 3 Non-dimensional weld geometry, first and second derivatives

In Fig. 3 an example is shown of an averaged measurement signal of a weld geometry with both its first and second derivatives. All quantities have been scaled with their respective maxima. It is obvious that both derivatives provide a good estimation of the 'smoothness' of the longitudinal weld geometry. Both discussed approaches will be evaluated separately in the following.

3.1 Acceleration approach

Evaluation of a large number of weld measurements from practice, according to expression (4), where the dominating mass is taken as the wheel-mass as a reference case (taken is half the un-sprung mass, 2000 kg and $\alpha = 1$), leads to the following intervention levels in terms of the maximum force, per train velocity range:

- $v \leq 40$ km/h: 50 kN
- $40 < v \leq 80$ km/h: 100 kN
- $80 < v \leq 140$ km/h: 250 kN
- $140 < v \leq 200$ km/h: 500 kN

It is stressed that the values given above only have *relative* meaning. The level of acceptation per velocity range has been determined subjectively, on the basis of experience. One would expect the same admissible force level for all velocity ranges, however, due to the quadratic velocity influence in (4), this turns out to be not feasible. For example, the force corresponding to the maximum accuracy obtainable in welding for high-speed-lines would lead to tolerances in the order of centimeters for railway yards, which is unacceptable.

For the used sample of weld geometries (72), the percentage of rejected welds according to the old standards was 76%. According to the new system 33%, 64%, 93% and 94% are rejected respectively for the four velocity ranges.

3.2 Velocity approach

Following the same procedure as described in the previous section, but now applying expression (8) (with $\beta = 1$), leads to the following intervention levels for the force:

- $v \leq 40$ km/h: 2.5 kN
- $40 < v \leq 80$ km/h: 7.5 kN
- $80 < v \leq 140$ km/h: 17.5 kN
- $140 < v \leq 200$ km/h: 32.5 kN

As both methods are not comparable, not the same factor between the different force values (which, as discussed before, have only relative meaning) exists in both approaches. For the used sample of weld geometries, the percentage of rejected welds according to the new system is 33%, 53%, 81% and 86% respectively for the four velocity ranges.

3.3 Evaluation of both methods and choice for standardization

To enable a comparison between both methods, a so-called quality index per weld is introduced. The calculated maximum force per weld is divided by the intervention level for certain velocity range. This way a non-dimensional number is obtained; a quality index smaller or equal to 1 means acceptance of the weld. Comparison between both approaches shows that in general the velocity approach leads to less extreme values than the acceleration approach. This conclusion can also be drawn from the average scores for the analyzed weld population. According to the acceleration approach, average quality indices were 1.2, 1.8, 3 and 3 for the four considered velocity ranges, and 1.2, 1.6, 2 and 2.2 according to the velocity approach, which is much more moderate.
In addition, the acceleration method turns out to be very sensitive for very small and short-length irregularities (with length-scale centimeters) and not very sensitive for longer irregularities (with length-scale say 0.5 m), which is not the case for the velocity approach. Very small, short-length irregularities (indentations) often occur in welding of rails at both sides of the weld material, due to shrinkage after cooling down. In Fig. 4 two examples are given of almost perfectly straight welds, but both with these indentations. The weld in Fig. 4a has quality indices 1.3, 1.7, 3.3 and 3.3 according to the acceleration approach and indices 0.5, 0.7, 0.9 and 1 according to the velocity approach. For the weld in Fig. 4b this is 1.3, 1.7, 3.3, 3.3 and 0.6, 0.8, 1, 1.1 respectively.

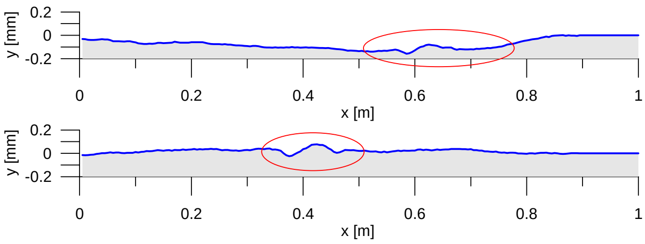

Fig. 4 a and b Measurement examples of welds with indentations due to shrinkage after welding

In Fig. 5, an example is shown of a weld geometry with irregularity with a longer length-scale (the weld is of bad quality, with maximum height 0.8 mm). The weld has quality indices 0.6, 0.9, 1.4 and 1.4 according to the acceleration approach and 1.1, 1.4, 2 and 2 according to the velocity approach.

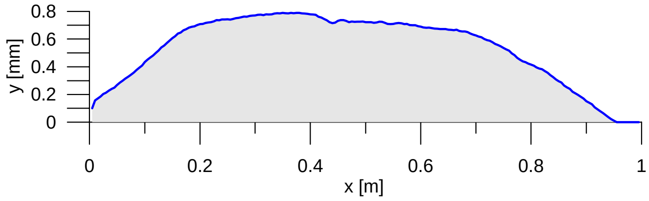

Fig. 5 Example of a weld with irregularity with longer length-scale

On the basis of the above comparisons and the comprehensive analyses described in [1] it was decided to adopt the velocity – or 1st derivative approach as the standard for vertical weld geometry assessment.
In Fig. 6, a clear example is shown of the difference between the old and the newly developed standards. The weld geometry, which shows an aggressive step, is accepted according to the old standards (before grinding, tolerance +0.3 mm). However, according to the new standards the weld has indices 1.1, 1.7, 2 and 2.5 for the four velocity ranges and is rejected.

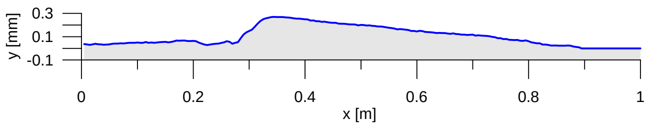

Fig. 6 Measurement of a weld with a step

In Fig. 7, an example is shown of an almost perfect weld. However, as it has some negative height coordinates, it is rejected according to the old standards. According to the new standards, the weld has indices 0.5, 0.7, 0.9 and 1 and is accepted for all velocity ranges.

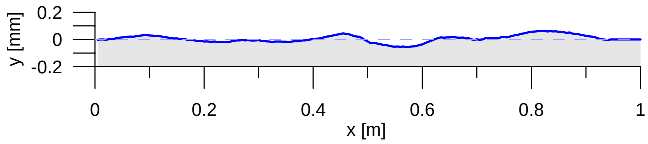

Fig. 7 Measurement of a weld with negative height coordinates

Via expression (8), the intervention levels for the force can be expressed directly in terms of the first spatial derivative of the vertical rail geometry (in milliradians):

- $v \leq 40$ km/h: 3.2 mrad
- $40 < v \leq 80$ km/h: 2.4 mrad
- $80 < v \leq 140$ km/h: 1.8 mrad (9)
- $140 < v \leq 200$ km/h: 0.9 mrad

The above given values for the spatial first derivative of the vertical rail geometry are the final standards for the vertical weld geometry adopted by ProRail (Fig. 8).

For the horizontal weld geometry an empirical approach based on common practice was followed. In the lateral direction dynamics do not play an important role; the wheel-flange has only a real elastic contact with the railhead in curves, where in addition the rotating wheel-flanges grind off small imperfections. The following practical values were adopted in terms of the versine on a 1 m base:

- $v \leq 40$ km/h: +/- 1.0 mm
- $40 < v \leq 80$ km/h: +/- 0.7 mm
- $80 < v \leq 300$ km/h: +/- 0.5 mm

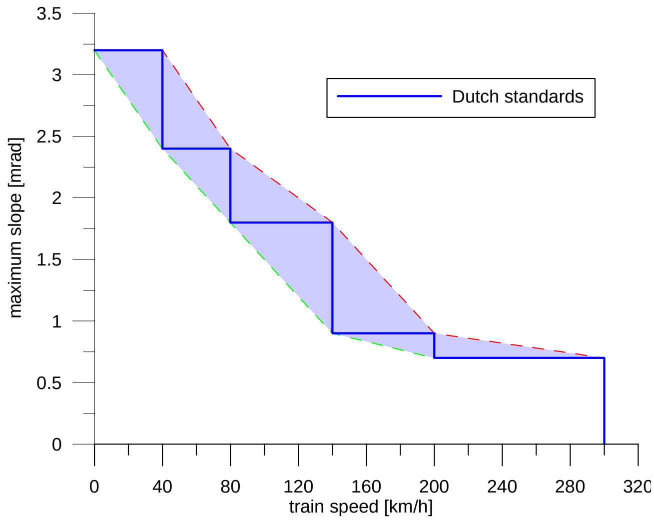

Fig. 8 New Dutch standards for vertical rail weld geometry

4. PRACTICAL IMPLEMENTATION

In practice, the new assessment of a weld (in vertical direction) is made according to the following steps:

1. The weld is measured with a 1 m digital straightedge (Fig. 9). The sampling interval of the vertical rail geometry equals 5 mm.
2. The software of the straightedge filters out irregularities with length-scale smaller than 25 mm, calculates the 1st derivative of the filtered geometry, and divides the discrete values of the first derivative by the speed dependent norm given in (9), after which the maximum is determined. In this way the dimensionless quality index (QI) of the weld is obtained.
3. The geometry itself is scaled with a value of 1 mm and is plotted together with the absolute value of the normalized first derivative on the graphical display so that the welding crew can immediately see the result of their work. If the above quality index is larger than 1 the weld is rejected and if smaller than 1 accepted.
4. In practice the welding crew will try to achieve a weld geometry which is complying to the standards and thus will grind additionally until the standards are met. This is often not so easy and so it is often more effective to apply a grinding train, especially if long possession times are available.
5. To check weld geometry according to the previously discussed standards, high accuracy measuring equipment (like the RAILPROF [4]) is necessary. For the mentioned instrument the absolute accuracy is about +/- 0.03 mm and the repeatability is in the order of 0.005 mm. A steel straightedge is inadequate, as its accuracy is insufficient. Further, errors are introduced e.g. in the case of new rails, where rust and mill scale are taken wrongly as the rail surface, whereas a digital straightedge [4] works according to an eddy current principle and measures the real rail surface.

Fig. 9 RAILPROF with PDA

In Fig. 10 an example is given of the graphical output of a measuring device.

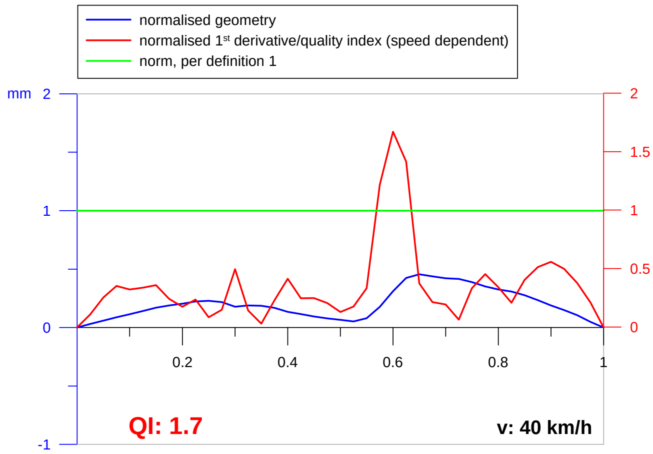

Fig. 10 Screen output of a measuring device for the new assessment of rail welds

5. EXTENSION TO HEAVY HAUL AND HIGH SPEED LINES

The assessment of rail welds on the basis of the maximum slope as proposed for conventional track may proof also useful for heavy haul applications and high-speed lines.

The most important difference for the welds between conventional track, high-speed lines, and heavy haul tracks is the difference in axle loads. Further, the velocity range is different. For heavy haul this means that in terms of the wheel-rail contact force the static component of the wheel-rail contact force is much higher as compared to the normal case. Assuming that the values (9), determined on the basis of experience for the situation in the Netherlands, lead to maximum allowable wheel-rail contact stresses (not only to avoid plastification of wheels and rails, but also to avoid rapid deterioration of the track, one think of damage to the ballast bed), the values for the dynamic force component or

the standardized values for the 1st derivative can be adjusted for both heavy haul track and high-speed lines.
In Fig. 11 the influence of the static axle loads is shown for different track types in the total wheel-rail force versus speed diagram. For heavy haul tracks the initial offset is much larger as compared to conventional track, which poses restrictions on the allowable maximum dynamic component which is allowable, and which is much smaller than in the case of conventional tracks. For high-speed lines holds the opposite.

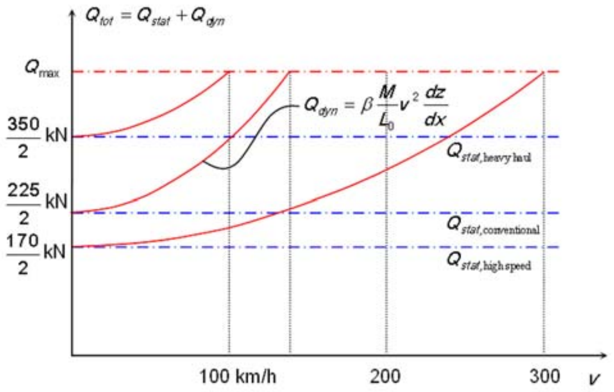

Fig. 11 Total wheel-load versus speed diagram for different axle loads

For the total wheel-load Q can be written:

$$Q_{tot} = Q_{stat} + Q_{dyn} \tag{10}$$

or, according to (8):

$$Q_{tot} = Q_{stat} + \beta \frac{M}{L_0} v^2 \frac{dz}{dx} \Rightarrow \frac{dz}{dx} < \Delta Q \frac{1}{\beta} \frac{L_0}{M} \frac{1}{v^2} \tag{11}$$

where the maximum total wheel load follows from the maximum axle load, which can be taken as about 450 kN. Above this value heavy problems can be expected as regards track damage and deterioration.
On the basis of (11) and starting from (9) the norm for heavy haul and high speed lines now can be derived easily; compare Table 1.

Table 1 Derivation of standards for heavy haul and high-speed lines

	ΔQ [kN]	v [m/s]	$\frac{dz}{dx}(\cdot\frac{\beta M}{L_0})$	**norm value [mrad]**
Conventional	225/2	40	0.070	**1.8**
Heavy Haul	100/2	30	0.056	**1.4**
High-Speed	280/2	85	0.019	**0.5**

From Table 1 follows the value 1.4 mrad as maximum for the 1st derivative of the vertical rail weld geometry as a first proposal for heavy haul tracks. For high-speed lines the value 0.5 mrad is found. However, as will turn out in the next section, here the value 0.7 is a better value, as this is close to the maximum accuracy obtainable in grinding. Also the rails themselves satisfy the requirement of a maximum discretized 1st derivative of 0.7 mrad (Fig. 12), and there is no need for stronger requirements for the welds than for the rails. In addition, in Table 1 all β-factors were taken the same, whereas they may be quite different for the different velocity-ranges. This however has to be found from measurements.

6. EVALUATION OF STANDARDIZED VALUES

The algorithm for the weld assessment looks at the first derivative or inclination of the weld geometry. High quality rails should fulfill the requirement that the peak to peak value over 3 m (which is the circumference of the straightening rolls) should be less than 0.3 mm, i.e. an amplitude less than 0.15 mm. Theoretically this corresponds to a first derivative of about 0.3 mrad. Recent measurements [3] on the HSL-South in the Netherlands have shown that actual values for new high-speed rails are better than 0.7 mrad. Fig. 12 shows the distribution of maximum 1st derivative of vertical rail geometry for 100 segments of 1 m rail, measured with a RAILPROF. The horizontal axis displays the quality index QI for 300 km/h. The value of 1 corresponds to a first derivative of 0.7 mrad. These measurements confirm the chosen values for the intervention levels.

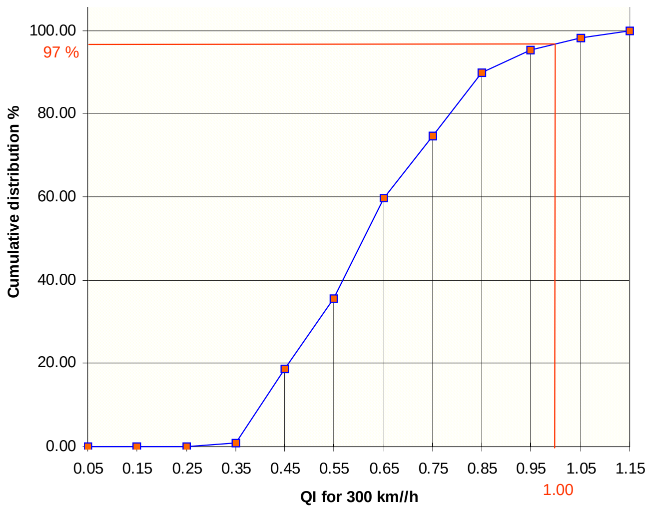

Fig. 12 Cumulative distribution of QI for vertical rail geometry pertaining to 300 km/h. QI=1 corresponds to a 1st derivative of 0.7 mrad.

In the same campaign also a series of welds were measured which were just lightly ground. The deviations were substantially larger, globally speaking with a first derivative between 1 and 3 mrad and obviously the weld geometry had to be improved by grinding. In [3] it was concluded that for high precision weld geometry manual grinding is not very effective and consequently it was decided to use mechanical grinding machines to achieve the required quality level.

7. CONCLUSIONS

From the previous discussion the following conclusions can be drawn, important for railway engineering praxis:

1. The theory developed on the basis of the first derivative provides a practical tool to assess weld geometry quality from a point of view of dynamic wheel-rail contact forces.
2. Measurements have shown that new high quality rails have a first derivative which is better than 0.7 mrad
3. Only with powerful grinding, or machining tools similar standards for welds could be achieved
4. Steel straightedges are absolutely inadequate for an accurate assessment of rail weld geometry.
5. Instead accurate electronic straightedges should be introduced as a standard to measure and document weld geometry in terms of displacement (versine) and the first derivative of the displacement.
6. The presented concept is very well applicable to heavy haul tracks.

To proof the theoretical foundations of the new assessment concept verification and validation measurements are inevitable. These measurements will be carried out on the ProRail network in the near future.

8. REFERENCES

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