

Dynamic Axle Loads as a Main Source of Railway Track Degradation

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Abstract. During train operation, geometrical irregularities develop in soil-supported ballasted railway tracks as a function of born tonnage. This form of degradation is combatted by periodic maintenance in the form of tamping by specially equipped trains in order to guarantee predefined levels of structural performance. The growth of irregular settlements depends on one hand on track properties (such as sleeper spacing, rail bending stiffness, subsoil geotechnical properties) and the intensity of longitudinal stiffness variations (variations in soil profile, switches and crossings, transitions etc.). The latter stiffness variations include both the static and the dynamic, frequency-dependent stiffness. On the other hand also the nature of the loading has an important influence. Running trains exert – depending on their velocity – quasistatic loads on the infrastructure due to the passing axles with a constant loading. Apart from this a dynamic loading component may occur with different frequencies as a result of non-perfect wheels, as a function of the speed. In general, the structural design of a railway line can be optimised with respect to its structural performance for the whole lifecycle. However, for existing lines this is difficult, and the only way to limit degradation and associated costs is to influence the condition of the rolling stock. The present study discusses theoretical backgrounds of track degradation in the form of differential settlements. It then shows results of an analysis of the loading conditions on Dutch railway lines, with both mixed passenger and freight transport and with dedicated freight traffic, based on actual measurements. Conclusions are drawn regarding deterioration and the effects of different loading types. Results show that especially on freight lines huge improvements are possible, with reductions in geometrical degradation up to 52% of actual values. The main driver of excessive degradation appears to be the low-frequency dynamic axle loading component.

Keywords. Track settlement, track degradation, track geometry, dynamic axle load, wheel out-of-roundness

1. Introduction

Railway tracks are subject to degradation under train operation, with two main forms prevailing in practice. A first one is degradation of the running surface of the rail, which degrades in the form of either wear (uniform or periodical in the form of corrugation) or rolling contact fatigue in the form of cracking. A second one is geometrical degradation of ballasted track in the form of irregular settlements along the track. The associated types of periodical maintenance are grinding and tamping.

When a railway track is designed and built, it is important to design it in such a way that life cycle costs (LCC) are minimized. This involves on one hand minimization and on the other hand predictability of maintenance. With respect to deterioration of the running surface of the rail, much optimization work has been done. The second main type of degradation however

receives much less attention in the literature. Two major influencing parameters are: (i) the track geometrical and material parameters and (ii) the track loading by the rolling stock. For existing tracks, the first one can only difficultly be addressed and optimized. Section 2 discusses the associated type of degradation in more detail. The second parameter remains as an option to improve LCC costs of existing infrastructure.

The influence of the rolling stock on geometrical degradation of the track is the central theme of the present paper, with a focus/application on the Dutch network and the corresponding loading regime.

2. Track Design and Degradation, General

Steenbergen (2013) discusses the sources of geometrical degradation of railway tracks; the study addresses explicitly the track side. It

concludes that changes in geometrical configuration and material properties along the track are mainly responsible for – and at the basis of – irregular settlements, as they lead to so-called transition radiation under passing trains.

The concept of ‘transition radiation’, as applies here, can be clarified in an easy way as follows. When a constant axle load moves along a one-dimensional system with uniform properties, the response field, in terms of stresses and strains, is constant and travels along with the load. The mechanical energy associated with this moving field is invariant with respect to time and position. Therefore, considering a given position along the track and under the assumption of elastic material behaviour, the same amount of energy is present with respect to a neighbouring position. This changes as soon as there is a change in the track: in configuration or material. The arriving response field under the moving load must ‘adapt’ itself to the new situation, which causes amplification in stresses and/or strains. The associated amount of mechanical energy becomes therefore variant with respect to time and position. In reality, a railway track never has uniform properties and axles of running trains ‘feel’ continuously changes in dynamic stiffness; only the intensity of the changes may differ. Sleeper bays provide small and bridge abutments significant changes. The energy ‘excesses’ corresponding to the varying response field travelling with the load are locally dissipated in the track. This may happen in the form of irreversible displacement, particle fracture etc., leading to a change in track geometry. This is a cyclic process, for each passing train axle.

In this sense it can be stated that longitudinal variations in track properties and layout are, via transition radiation, at the source of long-term track degradation. Once the geometry is affected, the problem is intensified, as the axle loading gets a dynamic component.

3. Rolling Stock and Track Degradation, General

As discussed in the introduction, apart from the track design also the rolling stock operating on

the track and loading it has an important role in degradation and irregular settlement growth.

3.1. Track Loading Types

The wheels of passing vehicles transfer the vehicle loading to the track. If these wheels are circular in circumferential direction, this loading is constant for non-zero velocities and called the static axle load. It is normalized in the Netherlands at a level of 225 kN.

If the wheels however suffer from geometrical defects such as wheel flats and out-of-roundness (OOR), this causes, together with a non-zero train speed, an additional, dynamic component of the axle load – even on a perfectly straight track. Geometrical defects on wheels arise to due flange braking and slippage in the wheel-rail contact during braking or curve negotiation, and then develop further due to effects such as non-uniform wear. Geometrical wheel defects are combatted by periodical ‘peeling’ or turning of wheels. In the Netherlands, the average wheel quality of rolling stock for freight and passenger transport is not equal. This has to do with the different maintenance regimes, which on their turn are related to the privatisation (and separate exploitation) of infrastructure and rolling stock companies. Passenger trains operate within the national borders and are subject to a tailored maintenance regime. To that end, the wheel quality is monitored continuously with dedicated monitoring systems (the so-called Gotcha Quo Vadis system) present on key positions in the ProRail network to handle the entire float. Freight trains on the contrary operate – and are often exploited – internationally and are not subject to monitoring and maintenance regimes. As a consequence, the wheel quality of rolling stock for passenger transport is on average better as compared to that for freight transport. Both loading categories and their actual presence on the Dutch railways are discussed in greater detail in paragraphs 4.1 and 4.2.

The dynamic axle load induced by wheel irregularities has some characteristics, related to the wheel circumference and the train speed. The longest possible wavelength of a wheel defect is equal to the wheel circumference, which is between 2.6 and 2.9 m. Considering operational

speeds of 80 km/h and 140 km/h for freight and passenger trains respectively, this leads to lower boundaries of 8 Hz and 14 Hz respectively in the frequency regime of the dynamic component of the axle load that may occur.

3.2. Degradation Laws for Load Components

The preceding paragraph discussed two essentially different types of – both cyclic – loading on railway tracks. The present paragraph discusses the corresponding settlement laws.

According to research summarized by Esveld (2001) the relationship between the cyclic static axle load and the long-term settlement is generally proportional. Increasing the axle load with one percent increases also the settlement with a percent. Denoting the born tonnage as T for the settlement e_{stat} may be written:

$$e_{\text{stat}} \sim T \quad (1)$$

The relationship between the cyclic dynamic axle load and the track settlement is much less uniquely determined. A review is given by Dahlberg (2001). All models have in common that they describe the track settlement under the cyclic total axle load as a superposition of two terms, a first one describing short-term initial consolidation (e_0) and a second one describing long-term accumulating progressive settlement. The ORE-model gives the following relationship between settlement e , tonnage T , dynamic axle load $2Q$ (double wheel load) and line speed v :

$$e = e_0 + hT^\alpha (2Q)^\beta v^\gamma \quad (2)$$

where h is a constant and α , β and γ are validation constants. In general, $\alpha = 1$ and for β empirical values are proposed between 3 and 5.

The exponential contribution of the dynamic axle load component becomes comprehensible against the background of *dynamic consolidation*. This technique is applied in geo and civil engineering both for deep compaction (typically up to 6 times the depth obtained with static consolidation) and for accelerated consolidation. It causes a faster reduction of pore water pressure in clay and peat layers and a denser grain structure in non-cohesive layers. Under dynamic

compaction of a ballast layer in a track body different phenomena occur simultaneously:

- ongoing reduction in volume and height by rearranging granular material;
- grain fracture and refinement;
- abrasive wear of grains, yielding reduced shear resistance of the granular matrix;
- lateral particle transport in the non-confined body, owing to a reduced shear resistance;
- interpenetration of the interfaces ballast – sub-ballast – soil.

Coming back to Eq. (2), the relationship between the long-term settlement and the cyclic dynamic loading can be expressed, in a conservative approach with $\beta = 3$, as follows:

$$e_{\text{dyn}} \sim Q^3 \quad (3)$$

It should be finally remarked that the ‘dynamic’ long-term settlement (according to Eq. (3)) has, apart from the magnitude, a more detrimental nature as compared to the ‘static’ one (according to Eq. (1)). For a perfectly straight track with uniform properties, the latter one would lead to a uniform settlement whereas the first one yields a spatially variant settlement.

4. Loading Conditions on the Dutch Network

As discussed in 3.1, axle loads on the ProRail network are being monitored on a daily basis with the help of Gotcha systems. With gathered data on dynamic load components, maintenance actions for passenger trains are planned. For the present study, relevant Gotcha measurements over the Prorail network in the half-yearly period 1-10-2013 to 1-04-2014 have been used, corresponding to 36.6 million axle passages (24.9 passenger – 11.7 freight); statistics are discussed in more detail in paragraphs 4.1 and 4.2. Gotcha systems make a distinction between:

- a) *static* wheel/axle loading;
- b) *low-frequency* dynamic axle loading, filtered in the area 20 – 220 Hz and meant to detect lower-order OOR or wheel eccentricity;
- c) *high-frequency* dynamic axle loading, filtered in the area 180 – 1200 Hz and meant to detect wheel flats and polygonisation.

In the current situation, exclusively the information under c) is translated into periodical maintenance actions for rolling stock, as high-frequency loads (impact) are considered detrimental for components.

It is stressed in this context that the currently available registrations, designed for maintenance planning of rolling stock, do not account for the complete frequency regime: the spectral content between 8 – 20 Hz is missing. They can therefore give only preliminary results when interpreting them quantitatively with respect to degradation. However, being aware of this, these results can very well indicate trends and orders of magnitude, which is the aim of this study.

The frequency limits for the low- and high-frequency dynamic axle load components can be translated, via the train speed, to corresponding wavelengths of their track ‘projections’. With operational speeds for freight and passengers of 80 km/h and 140 km/h respectively, it follows that a maximum possible wavelength for the high-frequency part occurs of 0.2 m; all other track forces have shorter wavelengths. The rail height is, for the 54E1 rail profile applied in the Netherlands, 0.16 m and the sleeper distance is 0.6 m. It can therefore be concluded that the high-frequency part (c) is born predominantly by the rail structure itself (rail mass, bending and shear stiffness) and less transferred to the subsoil and –structure. The opposite is true for the low-frequency part (b), which is, along with the associated mechanical energy, transferred almost directly to the track sublayers and subsoil.

As mentioned, in the current regime there is only ‘feedback’ from the high-frequency loading part to the wheel condition for passenger trains. This is reflected in a significantly lower share of high-frequency dynamic forces as compared to the low-frequency ones (see Fig. 3); magnitudes are an order 5 lower. This is remarkably also true for freight trains; likely due to the fact that untreated short wheel defects develop gradually into longer defects (see Snyder et al. (2003)).

Both discussed aspects give rise to an approach in which, from both parts, only the registration of the low-frequency component of the axle load (b) is taken into account in the following of this study when addressing the effect on track degradation.

4.1. Static Axle Loads, Measurement Results

Fig. 1 shows the axle load distribution of both passenger and freight trains over the entire network. For the latter category, the difference between ‘empty’ and ‘loaded’ is clearly observable. Of all passed axles, for freight traffic 3.5% exceed an axle load of 22 tonnes; 1.1% that of 23 tonnes. For passenger traffic overloading is not an issue under the current regime.

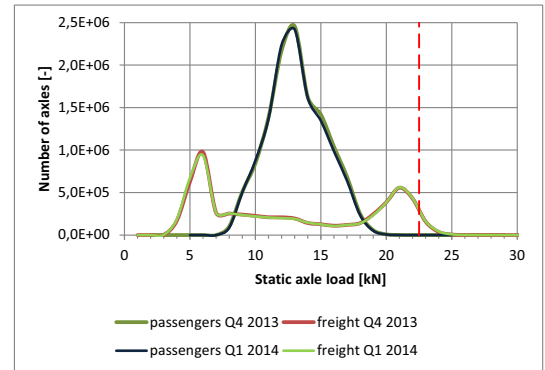


Figure 1. Distribution of the axle load; passenger and freight traffic for two 3-month periods (network level).

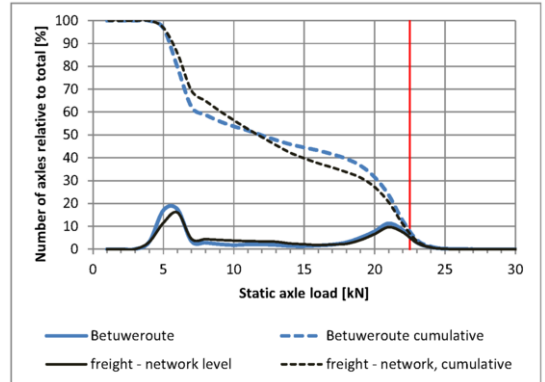


Figure 2. Distribution of the axle load on the Betuweroute and comparison to the network level (freight only).

The presented data look at a global network level and do not provide information on the variation and extremes that may occur on a local level. Fig. 2 zooms therefore in at a dedicated freight line, for which the Betuweroute is chosen, from the port of Rotterdam to Germany. On this line, 4.1% of all axles have an axle load of 23 tonnes or higher, which is comparable to the network average – when freight traffic is concerned.

4.2. Dynamic Axle Loads, Measurement Results

As has been discussed, only the low-frequency part of the dynamic axle loading registered by Gotcha is taken into account. Fig. 3 shows the distribution of its magnitude.

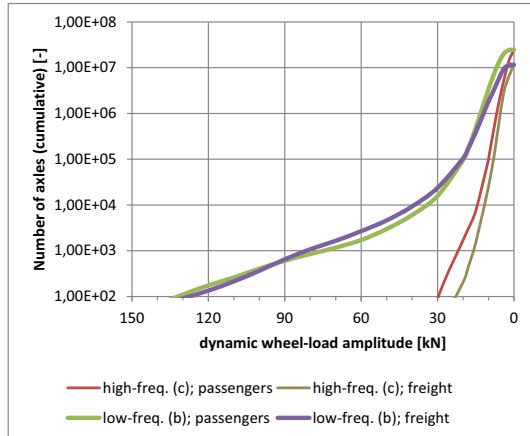


Figure 3. Cumulative distribution of the dynamic load level; low- and high-frequency components (network level).

There is no substantial difference between passenger and freight traffic. To gain insight into differences between results on an average, global level and a local level also here the Betuweroute is examined. Results are shown in Fig. 4, showing a relative very significant presence of dynamic loads over the whole spectrum.

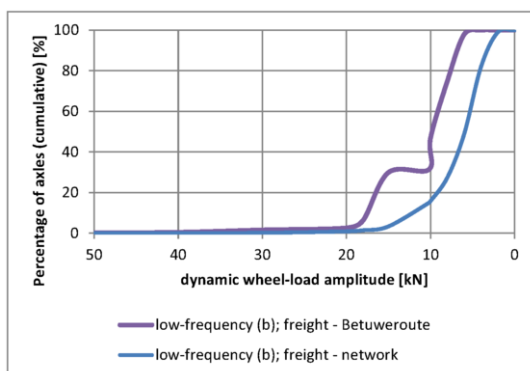


Figure 4. Cumulative distribution (% of total axle population) of dynamic load magnitude; dedicated freight line versus network level.

5. Interpretation: Degradation on the Dutch Network and Improvement Potential

The loading results can now be interpreted in terms of track degradation. Again, static and low-frequency dynamic loading components are addressed individually. As no absolute settlement values are available, evaluations are performed relatively, with respect to actually occurring values.

5.1. Static Axle Loads and Track Degradation

According to Eq. [1] the relationship between born tonnage and settlement is proportional. Therefore, each ton of axle load increase with respect to the norm of 22.5 tonnes yields an increase Δe_{stat} of 4.4%. With the help of this, for each additional ton of overloading and the corresponding number of axles (#) the settlement increase is computed and then added to obtain the total settlement increase in Table 1.

Table 1. Relative settlement increase due to static overloading of axles (network level)

axle load [ton]	# axles	% of total # axles	Δe_{stat} [%]	weighted Δe_{stat} [%]
22 – 23	863877	2.36	0.0 – 4.4	0.0 – 0.1
23 – 24	320343	0.88	4.4 – 8.9	0.04 – 0.08
24 – 25	79934	0.22	8.9 – 13.3	0.02 – 0.03
25 – 26	14616	0.04	13.3 – 17.8	0.005 – 0.007
				Σ 0.1%

The relative increase in track degradation due to overloading is 0.1%, or very limited. In other words: the way the actual norm is enforced and complied with on a network level is satisfactory from a LCC point of view.

For a consideration on local level the freight transport data from the Betuweroute are used. In a similar way as calculated above values of 3.3% settlement increase are found in eastern direction (loaded) and 0.4% in western direction (unloaded). These values are higher but still not very significant.

5.2. Dynamic Axle Loads and Track Degradation

The total settlement under a non-perfect wheel consists of a contribution of both the static and the dynamic load component. On the basis of

Eqs. [1-3] may be written for the relative settlement increase δ due to a wheel defect:

$$\delta = \frac{e_{\text{total}}}{e_{\text{stat}}} = 1 + \frac{e_{\text{dyn}}}{e_{\text{stat}}} = 1 + \frac{Q_{\text{dyn}}^3}{Q_{\text{stat}}} \quad (4)$$

As it is unknown for each wheel inducing a dynamic load component what is the corresponding static load, the average wheel-load $\bar{Q}_{\text{stat}}$ of the concerned dataset is used, which is 63.8 kN on network level. Then, for each dynamic loading magnitude or category i , the relative settlement increase δ_i can be computed. Multiplication with the number of axles in this category (denoted as $\#_i$) yields a relative contribution to the track settlement. In this sense, Fig. 5 shows the relative contribution of different load categories to the total track settlement (100%) on a network level. On this level, the contribution of passenger transport is the highest (about 60% of 100%), which is due to its higher representation on the network.

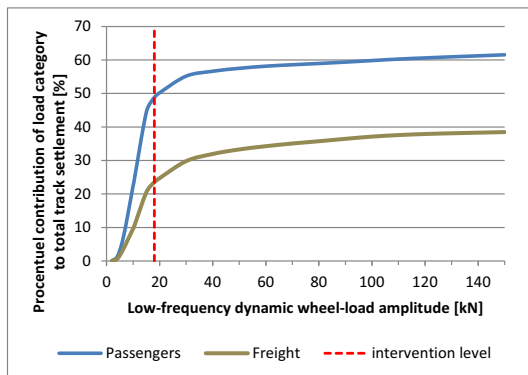


Figure 5. Cumulative distribution of the contribution of dynamic load categories to track settlement (network level).

In order to estimate the potential relative improvement it is necessary to introduce an ‘intervention level’ for the low-frequency dynamic force; imposing a zero dynamic force level over the whole life-cycle of rolling stock is attractive from a theoretical viewpoint but unrealistic. Therefore, quite arbitrarily the intervention level of 18 kN is chosen (see Fig. 5), which is currently in use as a ‘category 1 wheel defect level’ in Gotcha for the high-frequency part and seems therefore well feasible in practice.

In this case, the relative reduction of degradation Δ can be calculated as follows:

$$\Delta = \left[1 - \frac{\sum_{i=1}^{18 \text{ kN}} \#_i \cdot \delta_i + \sum_{i=18 \text{ kN}}^{150 \text{ kN}} \#_i \cdot \delta_{i=18 \text{ kN}}}{\sum_{i=1}^{150 \text{ kN}} \#_i \cdot \delta_i} \right] \cdot 100\% \quad (5)$$

Evaluation of Eq. [5] for the dataset yields a potential improvement with respect to degradation of 23% on a network level (differentiation into passengers and freight yields shares of 10% and 13% respectively).

The same exercise can be performed on a local level. Evaluation of measurement data for the Betuwelijn yields very significant values for potential reduction of 52% in western direction ($\bar{Q}_{\text{stat}} = 35$ kN for the dataset) and 36% in eastern direction ($\bar{Q}_{\text{stat}} = 95$ kN).

As has been stressed in sections 3 and 4, the obtained values should not be taken as exact values. On the other hand, found magnitudes are very significant, and accounting for the facts that the low-frequency regime has been disregarded partly in the load measurements and the exponent β has been taken most conservatively as 3, it may be expected that real percentages are even higher.

6. Conclusions

Most important conclusions from this study are:

- rolling stock (axle loading and wheel condition) plays a significant role in degradation of track geometry;
- the low-frequency dynamic axle load component is most damaging;
- for the Dutch network, potential reductions of 23% on a network level and 52% on a local level (freight line) are established. These values are representative for the associated infrastructural life cycle/maintenance costs.

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