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Effects of railway track design on the expected degradation: Parametric study on energy dissipation

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A B S T R A C T

This paper studies the effect of railway track design parameters on the expected long-term degradation of track geometry. The study assumes a geometrically perfect and straight track along with spatial invariability, except for the presence of discrete sleepers. A frequency-domain two-layer model is used of a discretely supported rail coupled with a moving unsprung mass. The susceptibility of the track to degradation is objectively quantified by calculating the mechanical energy dissipated in the substructure under a moving train axle for variations of different track parameters. Results show that, apart from the operational train speed, the ballast/substructure stiffness is the most significant parameter influencing energy dissipation. Generally, the degradation increases with the train speed and with softer substructures. However, stiff subgrades appear more sensitive to particular train velocities, in a regime which is mostly relevant for conventional trains (100–200 km/h) and less for high-speed operation, where a stiff subgrade is always favorable and can reduce the sensitivity to degradation substantially, with roughly a factor up to 7. Also railpad stiffness, sleeper distance and rail cross-sectional properties are found to have considerable effect, with higher expected degradation rates for increasing railpad stiffness, increasing sleeper distance and decreasing rail profile bending stiffness. Unsprung vehicle mass and sleeper mass have no significant influence, however, only against the background of the assumption of an idealized (invariant and straight) track. Apart from dissipated mechanical energy, the suitability of the dynamic track stiffness is explored as an engineering parameter to assess the sensitivity to degradation. It is found that this quantity is inappropriate to assess the design of an idealized track.

1. Introduction and scope

Degradation of the railway substructure, in terms of settlements and the development of geometrical deviations of the track, has become a significant issue in recent years. Improving the long-term structural performance avoids the need of frequent inspection and maintenance and leads to an increased availability for railway tracks. In order to achieve such an improved long-term performance, it is essential to understand the relation between track degradation and track parameters. Such an understanding can be particularly relevant during the design stage of the track. Traditionally, railway track (and especially substructure) design is strongly focused on bearing capacity, and therefore on the instantaneous or short-term

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response. This means that the design is mostly purely static or quasistatic, without any proper consideration in the time domain, for example specifying the allowable track deflection under a given axle load [1]. Because degradation is a time-dependent process, induced by a loading process with a time history, such a design can never anticipate on degradation mechanisms and is therefore 'blind' for long-term developments. This can be illustrated also from the variables considered in track design: loading is expressed in terms of forces, and the structural response typically in terms of displacements, stresses and strains. These are variables apt to describe a 'status' in space and time. Degradation is however, in its most elementary form, always a mechanical energy dissipation process, described in terms of variables such as power and energy that account for variation in time.

Earlier studies in this field [2,3] identified as a primary source of track degradation, apart from autonomous soil settlement, the occurrence of a dynamic component of the axle load. This component gives rise to a dynamic - and therefore highly efficient - compaction of the subgrade, leading to irregular track settlement [2]. Such a dynamic component may occur in principle due to three effects:

i. Wheel out-of-roundness (OOR) of the rolling stock, notably lower-order OOR leading to low-frequency dynamic wheel-track interaction [2];
ii. Longitudinal variability of the cross-sectional properties of the track itself - either periodic or non-periodic, leading to transition radiation in the track under moving axle loads [3];
iii. Track irregularity, notably the relatively short-wave defects in the loaded track geometry, which lead to the highest train-track interaction forces.

The existence of a dynamic axle load as a source of degradation has as its point of departure an existing track, at some point during its service life, with given parameters and train loading. The scope of this paper is situated on a different level. It addresses the effects of the track design itself, and more specifically of the elastic and inertial properties of its components and their spatial configuration, on the expected degradation rate. The point of departure in this first study into this subject is a straight and uniform track with no spatial variation except for that periodic one given by the discrete sleeper support, thereby purely considering the effects of track design choices.

The theoretical, qualitative and quantitative modeling of degradation, especially for granular and porous materials such as ballast and soil, is extremely complex and very sensitive to specific material properties [4,5]. This is reflected in the empirical nature of many track degradation models describing long-term behavior of railway track, as found in the literature. Dahlberg [5] provides an overview of such empirical models. Sato [6] observed that track settlement could be divided into two phases and introduced two different mathematical expressions describing the short-term and long-term settlement, on the basis of curve-fitting. Using field data and a multivariable regression analysis, Lyngby [7] developed a model and investigated the effect of axle load and different types of track components (rail, sleeper, soil) on track degradation. Sadeghi and Askarinejad [8] examined the sensitivity of the track deterioration to structural and traffic parameters, by employing a track quality index derived from track geometry data. Varandas et al. [9] have employed an empirical model for the ballast settlement together with a train/track model in order to predict settlement of ballasted track specifically at transition zones. Abadi et al. [10] used measured data from the Southampton railway testing facility (SRTF) in order to evaluate the capability of different empirical ballast settlement models. They indicated that there is a significant difference between the results predicted by different previously-developed empirical models. Soleimanmeigouni et al. [11] reviewed and classified available models for track geometry degradation. Empirical models may help engineers to make a rough maintenance forecast of railway tracks; however, these models do not have a theoretical basis nor provide any fundamental insight. Moreover, only a limited number of parameters or factors have been taken into account for most of these empirical relationships. In order to avoid the difficulties inherent to a proper constitutive modeling of cohesive and non-cohesive granular materials involved in the track substructure, this study uses a different approach to get a grip on the complex issue of degradation. In line with the earlier study [3], it can be stated that dissipation of mechanical energy in a component or system is a precondition for - or even a most elementary representation of - its degradation. In other words, a conservative system is free of degradation. It is therefore sufficient to determine the effect of parametric variation of the properties of a mechanical system under time-dependent loading on localized energy dissipation in order to assess the susceptibility of the system to degradation of specific components.

The first step in the investigation therefore comprises the development of a model for short-term dynamic analysis of the track, capable to describe the mechanical energy flux of relevant individual track components during the loading process. A second step consists in the parametric evaluation of this model with respect to dissipated energy. Energy dissipation, although a very suitable quantity for theoretical analysis, is in itself also a rather abstract quantity which cannot be measured in the field. In practice, often a different engineering parameter is employed: the dynamic track stiffness. This is a measurable quantity for which good results have been obtained in practice and reported in the literature over the past years, in the sense that dynamic track stiffness variations correlate with degradation hotspots. This fact is at the basis of the development of e.g. the Swedish rolling stiffness measurement vehicle. Berggren et al. [12,13] analyzed dynamic track stiffness measured along the track and indicated that variations of track stiffness significantly affect the degradation rate of the track. Variation of track stiffness within a short distance and its effect on track settlement have been discussed in Ref. [14]. Identification of substructure properties using measured dynamic stiffness of the track was carried out in Refs. [15,16]. Using an experimental