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IMPROVEMENT OF METHODS FOR PLANNING RAILWAY SUPERSTRUCTURE REPAIR

Key words*: railway superstructure, repairs, planning, synthetic indicators.*

Introduction

Suitable methods for planning the repair of the railway superstructure should simultaneously meet two basic conditions, i.e. they should:

1. Determine the initial condition of the railway superstructure in need of repair to avoid any hazards.
2. Minimise the costs of the repair and follow-up maintenance of the railway superstructure.

Achieving these goals is not easy given that not only the condition, which can lead to accidents as various sources specify [19], can pose a threat to the railway superstructure, but the process can also lead to an adverse event [5]. Secondly, bringing the railway superstructure to an unrepairable state, due to the delay of the repair, is also a risk.

On European railways, consisting of approximately 300,000 km of tracks, the costs connected with the maintenance and reconditioning of infrastructure amount to EUR 15 – 25 billion a year. Such large expenditures lead to numerous research works, aimed at rationalising this maintenance, to be undertaken [14]. The rationalisation of maintenance includes, for example, improving the planning of railway superstructure repairs, which is the subject of creative research in many countries. Planning methods are considered an opportunity for saving costs, while complying with all the requirements that should be met by the railway superstructure.

The paper includes certain planning methods applied on several railways; it presents synthetic indicators used in the planning of railway superstructure repair, and considerations that led to the development of a new indicator of the structure degradation.

Examples of Planning Repairs and Related Research Work

There are several methods of planning repairs on the US railways, including the fourth version of the Bentley-Optram system, which covers track irregularities and rail damage [12]. There is also a system for planning the replacement of sleepers [27].

An extensive system for planning railway repairs named “T-SPA” is used in England [21]. Regardless of this system, research is conducted there on methods for reducing unexpected repairs. For repairs planned earlier, the Network Rail infrastructure authority spends GBP 850m a year. At the same time, the removal of damage, which is not provided for in the plans, costs approximately GBP 120m. One method to improve these proportions, proposed by the Cranfield University of Technology, is to improve railway superstructure maintenance without increasing employment, thus without increasing the number of employees on the tracks. To better identify places requiring improvement of the track condition, the application of various methods is planned – cameras installed on rail measurement vehicles, track sensors, as well as observations by the drivers running the trains [24].

On the Austrian railways, the NATAS (*New Austrian Track Analyzing System*) is used to assess track condition and make maintenance decisions. It is used, for example, to determine whether increased track settlement results from poor drainage. The system is also characterised by several parameters that assess the wear of rails, which makes it easier to plan their replacement [10]. In Austria, there has also been an increase in the speed limits of trains. This increase has had an impact on the infrastructure maintenance strategy, which takes into account the age, condition and intensity of its use to a greater extent.

The repair planning process involves forecasting, programming and scheduling. An example of a forecast may be a 25-year forecast of replacing sleepers on Mexican railways, based on statistics collected over 17 years [23]. In Denmark, a model used to optimise sleeper tamping with a horizon of up to 4 years [15] was developed. The objective function includes five variables:

1) changes in track degradation expressed by the standard deviation of longitudinal irregularities,

2) horizontal irregularities,

3) deviations allowed at the assumed train speeds,

4) track condition after tamping,

5) tamping machine specifications.

The planning of repairs, especially with limited outlays, should include elements enabling the use of ranking as, for example, introduced in the paper [2]. The criteria for the sequence of repairs are also included in the studies [1].

Types of Plans

A plan is a document that defines the future which the organisation wants to achieve, as well as forming the basis for management. Depending on the goals and deadlines, plans can be strategic, tactical and operational.

A strategic plan can be defined as a set of decisions referring to the basic, directional goals, which the organisation wants to achieve, and the required resources and methods. Strategic plans of the Polish railways include the extensive modernizations of railway lines. Tactical plans include fragments of tasks defined in strategic plans and allocations of necessary resources to perform tasks. Operational plans, usually developed in several scenarios, refer to details. Taking into account the planning deadlines, it can be assumed that strategic plans are long-term ones and span several years, tactical plans are developed for annual periods, and operational plans can even be for one-week periods.

This characteristic shows that the planning of repairs for the next year, in which the type of repair is determined on a particular section of the railway line, the dates of its commencement and completion, details of track closures, and rules for train operations during this period, are tactical plans. As already stated, a necessary component of railway superstructure repair planning is forecasting its changes. The purpose of the forecasts is to specify when and how these repairs should be performed interesting data on the necessary times of track closures (windows) and planning horizons are provided in a comprehensive report developed for the Swedish railway authority [13]. Table 1 shows some of its content.

Table 1 – Examples of Possession Closure Time and Planning Horizons on Swedish Railways

Closure Time	Activity	Planning Horizon
8 h	Track/ turnout replacement	2+ years
every 4 – 8 h	Tamping of track	1 – 2 years/1 month
	Grinding	every 1 – 2 years
	Railway switch replacement	every 1 – 2 years
1 – 4 h	turnouts tamping	1 – 2 years/1 month
	Repairs of fastenings/rails	1 – 2 months
0 – 1 h	Track measurements (inspection)	0 – 2 months
1 h – x days	Emergency repairs	—

Synthetic Indicators in Assessing Railway Superstructure Condition and Planning its Repair

On many railways, synthetic measures are used to determine the condition of the railway superstructure, mainly in terms of its geometry. A very simple indicator was used by Japanese railways. It expressed the ratio of the track length, on which the deviations of vertical irregularities exceeded ± 3 mm $l_{\pm 3}$, to the total length of the assessed track l [17]

$$P = \frac{l_{\pm 3}}{l}. \tag{1}$$

This indicator, being, in fact, the defectiveness of only one irregularity of the track, has recently been supplemented by the standard deviation of this irregularity and its maximum amplitude. In the repair planning support system, these three measures are used, assuming that they provide a more complete picture of the track condition. The value of the synthetic indicator is not enough to determine the need for repair on the Japanese railways.

Measurements of the track, in addition to the measuring car, have been carried out in Japan since 2013 by devices installed on a normal passenger car included in regular trains [16]. As a result, a large number of measurements are obtained, performed in short intervals (130 measurements over two months), facilitating the prediction of the development of railway superstructure degradation. Knowing, for example, that the increase in irregularity of the track after track renewal is 0.36 mm/100 days, it is possible to predict when they will reach the limit. The new system of measurements and planning on the basis of railway superstructure repair is being gradually developed and is treated not as a finished work but as a constantly evolving system.

On English railways, the role of the synthetic indicator, to a certain extent, played by the standard deviation of vertical irregularities referred to the wavelength of 35 m. At train speeds between 115 and 125 mph (185 – 201 km/h), the limit value of this deviation is 4.7 mm. If it is exceeded, the speed has to be limited [20].

On the Malmbanan railway line in Sweden, which is used to transport ore and where the maintenance of the railway superstructure is particularly difficult [18], the basic parameters for assessing the railway superstructure condition are the standard deviation of vertical irregularities and the amplitude of these irregularities. A standard deviation exceeding 2.5 mm or an amplitude exceeding 10 mm qualifies the track for repair.

In Poland, for almost 30 years, the *J* synthetic indicator of the track condition has been used [8] as the basic parameter of the geometrical condition of the railway superstructure. It is based on the standard deviations of four geometrical values

$$J = \frac{S_z + S_y + S_w + 0{,}5S_e}{3{,}5}, \tag{2}$$

where: S_z, S_y, S_w, S_e – are the standard deviations of vertical and horizontal irregularities, twist and track gauge, respectively.

This indicator is calculated and printed on the charts of track geometry cars, charts of electronic gauges, and used in programs supporting the making of diagnostic decisions, such as SOHRON, SOKON, DIMO and UNIP [6]. It has also been used in foreign papers. Thus, it showed a very good railway superstructure condition on the Lisbon-Porto line, where it amounted to approx. 0.5 mm [9]. In Poland, after the track renewal it is higher and fluctuates between 0.7 and 1.2 mm [4].

There is a clear correlation between the *J* indicator and the standard deviation of vertical irregularities (Fig. 1).

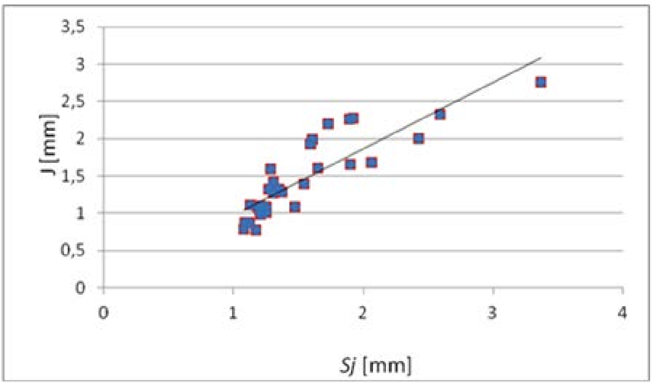

Fig. 1 - Regression-Correlation Dependency between J Indicator and Standard Deviation of Vertical Irregularities S_j

In a specific case, this dependency is represented by the following formula [7]

$$\overline{J} = 0{,}89S_J + 0{,}08, \tag{3}$$

with the correlation coefficient $r = 0.86$.

It is worth mentioning that, in some studies, the values of the standard deviation S_z [mm] are assigned the names of the track condition. Thus, according to [22, 25], these conditions are, as follows:

$S_z \leq 1$ – perfect
$1 < S_z \leq 2$ – good
$2 < S_z \leq 4$ – satisfactory
$S_z > 4$ unsatisfactory.

The information value of the *J* indicator can be increased by adding two subscripts, the first of which is the maximum speed [km/h] on the track characterised by this indicator, divided by 10, and the second one is Tg/year, rounded to 1. The full notation of the extended indicator is, therefore, as follows

$$J_{(V/10)\,[km/h],q\,[Tg/year]}\ [mm]$$

On the track where the maximum speed is 200 km/h, and the transport intensity is 15.7 Tg/year, the extended form of the *J* indicator, presented so far as 0.8 mm, is $0.8_{20,16}$.

The values of the *J* indicators at the speeds V = 20 – 200 km/h are given in the table of permissible railway superstructure deviations [26]. This dependence was determined assuming that, at a given speed, all tolerances of the values *i* and a_{id} reached their limit values. Adopting this assumption and applying the *3 sigma* principle, the standard deviations of the values of formula (2) from the below formula were calculated

$$S_i = \frac{a_{id}}{3} \tag{4}$$

In the case of a track gauge with asymmetrical deviations, half of the upper and lower deviation ranges were added to formula (4). Figure 2 shows the dependency calculated using this method. The calculated values are marked with points and the curve connecting them describes the empirical formula

$$J=19.148-0.2695V+0.0015V^2+2.95\cdot10^{-6}V^3 \tag{5}$$

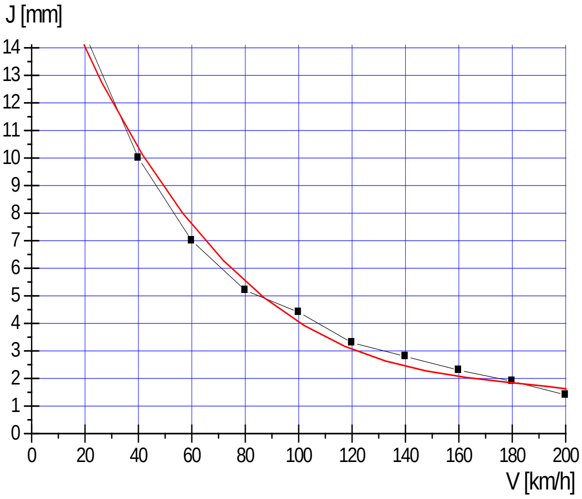

Fig. 2 - J Indicator Values in Speed Function according to conditions [26]

Structure Degradation Indicator

The usefulness of the *J* indicator in studies related to the maintenance of the railway superstructure, confirmed by many years of practice, is the reason behind the search for a similar synthetic indicator, however, concerning the condition of railway superstructure construction and, therefore, the degradation indicator. It was assumed that this new indicator should, in numerical terms, contain information as close as possible to the *J* indicator. It means that the same values of both indicators should indicate the approximate condition of the track in terms of geometry and construction.

Looking for the appropriate measure of the structure degradation, it was assumed that it should be in a similar numerical range as the *J* indicator, where low values would mean a very good condition of the structure, and high values would be interpreted as a high level of degradation. The upper limit of the *J* indicator range, i.e. 14.5 mm [26], should be reduced in the calibration of the degradation measure – it should not be assumed that all deviations at a given speed will reach acceptable limits every time. Starting from this assumption, it was assumed that the upper limit of the standard *J* indicator should be equal to 10.

The level of degradation of each part of the railway superstructure can be assessed on the basis of observations, statistics or calculations, with different criteria being used for the assessment of wooden sleepers, different ones for ballast and still different ones for rails. In the synthetic assessment which should be included in the forecasting, the degradation criterion should be common and additionally provide information on how the specific section of the railway superstructure deviates from its limit of exploitation incapacity. This criterion should also be independent of the value used to express this limit (time or load). These assumptions are met by the ratio of the lifetime of a given section of the railway superstructure w_t or the load it transfers w_Q to the probable life limit of a given section w_{pt} or w_{pQ}

$$k_t = \frac{w_t}{w_{pt}} \quad , \tag{6}$$

$$k_Q = \frac{w_Q}{w_{pQ}} \quad . \tag{7}$$

The introduction of the “probable life” concept was justified in the monograph [5], providing many examples of different times and loads transferred by rails on different railways. This probability is well described by sigmoidal functions.

Adapting the range of the structure degradation indicator D_k to the range of the *J* indicator required the development of an appropriate function depending on the ratio w/w_p (in general). The function expressing this dependence has the following form (see Fig. 3)

$$D_k = 5\left(\frac{w}{w_p}\right) + 2\left(\frac{w}{w_p}\right)^2 , \qquad (8)$$

or shorter $D_k = 5k + 2k^2$ (9)

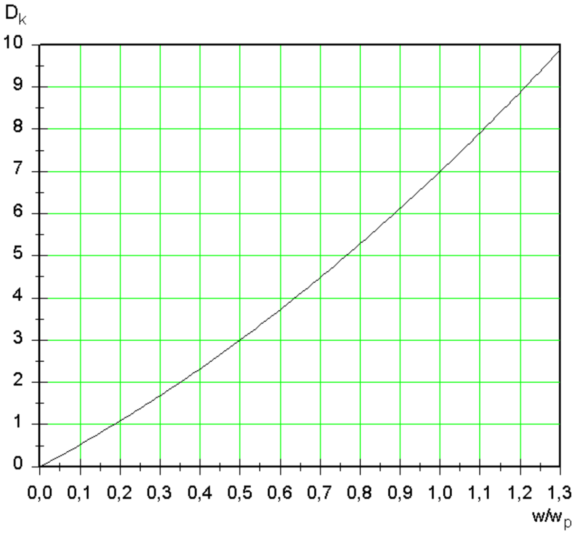

Fig. 3 - Shape of Structural Degradation Indicator Function

The value of the D_k = 10 indicator corresponds to the probable life w_p being exceeded by 30%, which often happens. Therefore, it is a condition of the structure that corresponds (conventionally, not physically) to a geometrical condition, which allows driving at a speed of 20 km/h. On the other hand, D_k = 0.1, i.e. characterising the structure in the initial period of its operation and, therefore, usually after removing defects under warranty, is the equivalent of very good geometrical quality. The use of half of the probable life corresponds to D = 3, and the achievement of this limit corresponds to D = 7. The choice of the shape of the function describing the degradation factor was preceded by the analysis of the rail degradation function according to the conditions [26] expressed by the following formula

$$G_s = e^{2\left(\frac{Q}{Q_{gr}} - 1\right)} . \qquad (10)$$

The shape of this function (Fig. 4) did not prove to be a good standard for the D indicator, because it has a value other than zero at the beginning of its operation.

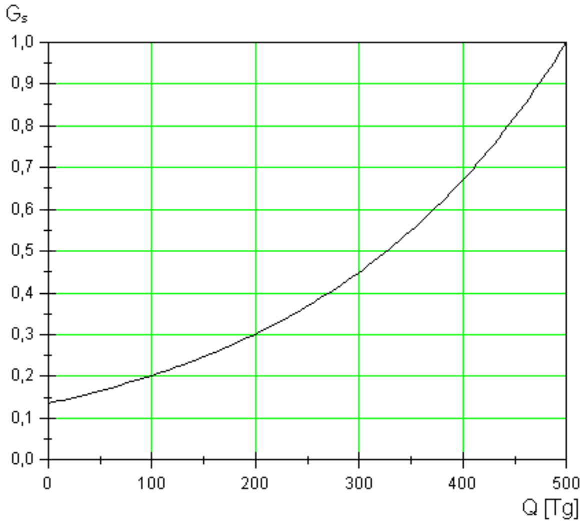

Fig. 4 - Function Describing Rail Degradation according to conditions [26]

Having the two indicators, i.e. J and D, it is possible to consider whether they should form one measure, for example, by proposing an arithmetic or geometric mean value, or if both indicators should be provided separately without combining them. The answer to this question is given by the paper [3], which shows no dependence of the J indicator on the degree of using the rail lives and poor dependence on the sleeper ages. Between the degree of the use of rail life and the J indicator, the correlation coefficient is negative and r = -0.23. With a relatively low value of J (approx. 2 mm), the rail life is used to approx. 75%, and vice versa – there are cases where the J indicator exceeds 5 mm on a track with rails that have not been used for a long time.

A weak correlation dependence exists between the age of concrete sleepers and the J indicator (r = 0.54), but in this case there are many cases indicating no regularity and, for example, with an advanced age of sleepers of ca. 40 years, there can be tracks with $J \approx$ 2 mm and > 8 mm. The correlation coefficient between the J indicator and the age of wooden sleepers is even smaller (r = 0.17).

These results show that there are situations in which, even after a long period of operation of the basic parts of the railway superstructure, i.e. rails and sleepers, the track is in good geometrical condition. The good condition of the ground has a large influence on such an arrangement. More frequent, however, are the cases where, with little use of life, especially rail life, the geometrical condition of the track is bad. The reasons for such anomalies are numerous – no track drainage, delayed repairs, poor quality of work during track renewal or their incomplete execution.

The presented results prove the purposefulness of using both indicators. The complete synthetic notation of the geometrical structural condition of the track would, therefore, have the following general form

$$G = J_{V,q} / D_k \,. \qquad (11)$$

The degradation indicator D_k of the entire structure would be calculated as the mean of the degradation indicator of rails (D_r), sleepers (D_s) and ballast (D_b)

$$D_k = \frac{D_r + D_s + D_b}{3} \,. \qquad (12)$$

Role of the *J* and *D* indicators and Rules of their Projection

Both indicators should be used in forecasting the condition of the railway superstructure and planning its repair. The synthetic indicators of the track condition *J* in the periods *i*, *i*+1, *i*+2, …, *i* + *n*, will be determined on the basis of time series recorded in the periods *i* –1, *i* – 2,…., *i* – *n*, including repairs. The *J* indicators will be important in the planning of current repairs.

It is seemingly easier to estimate the *D* structure degradation indicators, which are very important in planning track renewal. The increment of time determining their replacement is obvious, and the accumulation of load, with the known *q* transport intensity [Tg/year], should not be a problem, either. The difficulty here, however, is with the on-going changes in the limits of probable life, which in the course of railway superstructure use may be different from those assumed at the beginning. These limits must, therefore, be analysed and, if necessary, adjusted, especially in the second half of the railway superstructure's operation period. Failure to perform such a correction may cause errors in forecasting the replacement track renewal. The basis for the correction of probable limits should be damage statistics and observation results.

Conclusions

People with experience of analysing the railway superstructure condition using the synthetic indicator of track condition *J* can, on the basis of its value, form a quick idea of the need to repair or even the approximate speed of trains allowable on a specific section of the track. This skill is acquired by looking at charts presenting measurements from hundreds of kilometres of track, on which the values of *J* are always given.

However, though the conclusions regarding the relationship between *J* and the geometrical condition have solid grounds, referring them to the structure condition is based on an incomplete induction, i.e. reasoning that *in good geometrical condition, the structure condition is usually good, and poor geometrical condition often entails considerable degradation of the structure*. However, such reasoning does not always lead to valid conclusions.

The introduction of the proposed degradation indicator *D* will remove this uncertainty and let us know when or with what load the railway superstructure achieves the limit of its life. The use of the *J* and *D* indicators will also facilitate the ranking of selected sections of the track to be repaired, and thus the identification of those to be repaired first. Consequently, it should facilitate the maintenance of the railway superstructure and, to a certain extent, reduce its expenditures. However, it should not be forgotten that the cost of this maintenance is also influenced by the right choice of structures, such as the fastenings of rails to sleepers [11].

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