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Adaptive Multipoint Method for Predicting Geometric Parameters of the Railway Track Based on Convergence Theory

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Abstract: The article describes the properties and application of the original adaptive multipoint (for each irregularity size) method for predicting the values of track geometric parameters and their changes over time, based on the use of convergence theory. Prediction results are presented in the form of irregularity size distribution function (ISDF). ISDF shows the cumulative length of specific-size track irregularity within an arbitrary length track segment at the end of the prediction interval. The method is based on three main principles: using the ISDF function to describe track condition and changes therein, using only the results of previous measurements for calculations as input information about the condition of the track, using the ISDF convergence process analysis to calculate future values of the track geometric parameters. The method is invariant to the length of the time interval between past measurements. The method also allows to identify a tendency to sudden spontaneous deterioration of the track, which does not follow from a regular trend. For longitudinal level defects, the average prediction error for defect sizes s>|3|mm and prediction intervals of 2 and 6 months does not exceed 0.35%.

Keywords: Rail Track, Degradation, Track Condition Prediction, Convergence

1. Introduction

Track degradation has a significant impact on traffic safety; therefore, prediction of track degradation is very important in order to guarantee the high level of track technical condition, optimize maintenance plans and reduce maintenance costs.

There are a large number of publications that consider various methods of predicting track quality. A very informative work by Australian scientists [1] contains 61 references to such publications. In this paper, the authors provide a detailed analysis of known methods and models used to predict the technical condition of the track. According to the authors, when solving the prediction problem, it is necessary to take into account "condition of assets (i. e. sleepers, fastening and ballast), age of rails, axle load, speed, traffic density, traffic type, rail-wheel interaction, track curvature, rail profile and rail track construction, rail track superelevation, rail welding, rail lubrication". A consequence of the multiplicity of factors affecting the track characteristics is the assignment, for example, by the [2], of track segments to 17 different categories based on the above parameters, which, naturally, considerably limits or even makes impossible the use of their method for practical purposes.

When calculating the degree of track degradation, as a rule, the exponential law is used a priori to describe changes in the characteristics of defects, and based on it, the input information is smoothed, which changes its structure and automatically leads to distortion of the results.

Common features of prediction methods described Elkhoury et. al [1] are that they predict just a single parameter - the value of the standard deviation (SD) or quality characteristics derived from it (for example, KPI), and that they use deterministic models with a priori specified properties (pre-written equations or distribution functions).

It should be noted that all prediction models described in well-known publications describe behavior of the track with some inaccuracy, the magnitude of which depends on traffic loads, track's structural characteristics, environmental factors etc. Use of this approach is very problematic because of the large number of track parameters and wide range of values for each parameter.

For example R Dekker et al [3] uses a linear regression model based on a degradation coefficient and a random Gaussian error with an average value of zero. The experimental data given in [3] show a significant variation in the values of the degradation coefficient (from 0 to 5.5 mm per year) used for analysis.

Thus, the known methods of predicting track behavior are based on the use of a priori models or a priori laws of changing of track parameters. Such models cannot produce accurate predictions of the future changes in the track's geometric parameters, and cannot reflect the impact of individual 100-meter-segment's track parameters on the degree of its degradation. This approach does not take into account the actual behavior of specific track segments over time, and does not provide reliable information about the state of the track in the future.

2. General Overview of the Adaptive Multipoint Method

The method is based on three main principles:

1) using the ISDF function to describe track condition and changes therein,
2) using only the results of previous measurements for calculations as input information about the condition of the track without using any a priori models, for the first time such approach to analysis is formulated in our works [4, 5].
3) using the ISDF convergence process analysis to calculate future values of the track geometric parameters.

The outcome of the analysis is the set of predicted values of the ISDF function at the end of the prediction interval.

3. ISDF Function Properties

In today's track measuring systems, measurement results, as a rule, are presented in the form of tables, usually with 25 cm intervals between measurement points. Further processing and subsequent decision making is performed pursuant to the European standards EN 13848 or to the railroads' regulations based thereon.

From the probability theory point of view, a set of measurements' results of track geometry parameters is described by a random process. One of the quantitative characteristics of this process is the standard deviation (SD) which gives a spot assessment of the track technical condition. SD is a quantitative characteristic of the track quality index and track maintenance interventional threshold that are commonly used for track quality assessment, as defined by the European Railways.

We and other authors [6-8] have pointed out the problems of accuracy of analysis arising from the use of SD, and concluded that application of SD approach produces inaccurate and non-optimal results.

We performed a statistical analysis of the measurement results of track geometry parameters for 100-meter segments long (400 measurements for each segment).

We have determined that:

1) irregularity size in track geometry measuring results typically does not have a normal distribution, therefore, use of SD for track quality assessment and comparison is inappropriate,
2) track sections with different maximal irregularities sizes may have the same SD values and vice versa,
3) SD approach cannot distinguish between different-size defects, therefore for track sections with the same SD values, contact stress and the energy dissipated in the wheel-rail contact may be quite different.

A number of researchers investigated problems arising from the use of SD for assessment of track technical condition (for example, [7] recommends to use modified SD parameter).

For a complete and undistorted description of the track condition (unlike SD and TQI parameters), we have proposed using a function of the original random process (which is comprised by the population of measurement results for each track segment) called Irregularity Size Distribution Function. (ISDF). ISDF shows the cumulative length of each-size track irregularity within a track segment or part of a segment.

This function represents the results of direct measurements of the parameters that fully describe the condition of the track for each defect size.

ISDF describes the values of track geometry parameters and their changes over time unambiguously, without distortion, and with any pre-selected level of discreteness of defect sizes:

$$\Delta S = S_i - S_{i-1}.$$

The sum of the ISDF values is equal to the length of the analyzed track segment.

We should note that unlike the SD parameter, the values of ISDF are determined only by actual track condition, but not by the distribution function.

ISDF values are calculated based on measurements' results.

ISDF can be used both for current analysis and for predicting the values of track geometric parameters.

Table 1. shows the results of calculating the values of the ISDN function for longitudinal level irregularity for a 100-meter-long track segment.

Graphically, the calculation results are shown in Figure 1.

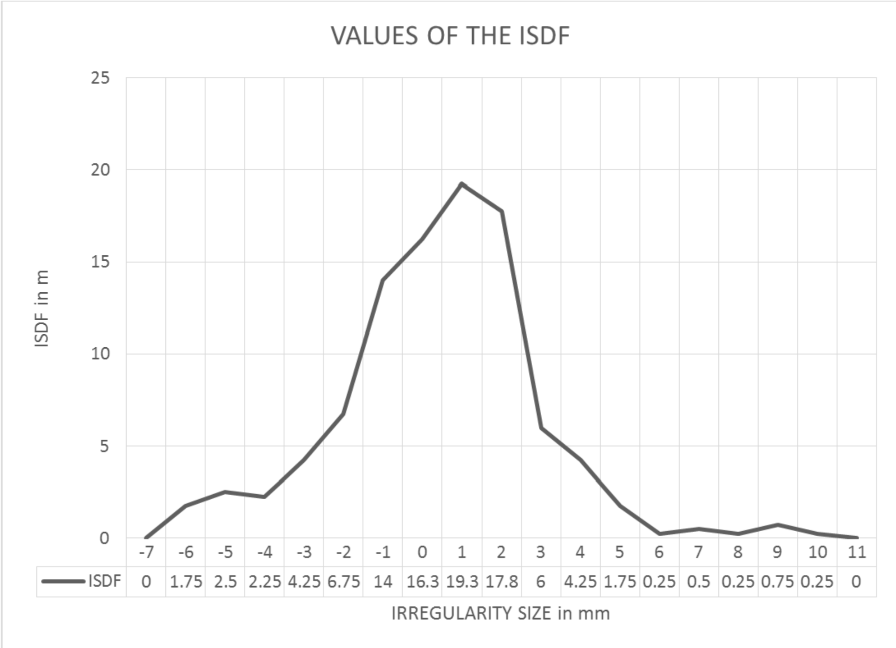

Figure 1. *Graphic Representation of the ISDF.*

Table 1. *ISDF Function.*

IRREGULARITY SIZE	ISDF
mm	m
-8	0
-7	1.75
-6	1
-5	0.75
-4	2
-3	6.5
-2	7
-1	9.25
0	10
1	16.5
2	20
3	12.75
4	6.25
5	1.25
6	0.75
7	1
8	2
9	0
TOTAL	98.75

4. Input Data

Complete information about the trend of changes in the condition of the track and its geometric parameters over time that factors in all the influencing factors, is contained in the results of periodic measurements that fully reflect the temporal properties of the geometric characteristics of the track. Therefore, we use an adaptive prediction method based solely on the analysis of relevant information about the track condition for each track segment, contained in the measurement results for previous periods.

From the mathematical standpoint, changes in the track technical condition constitute a random process that is characterized by random changes in all geometric parameters. Known approaches use only one parameter, the standard deviation, or variations thereof, to describe these changes.

This single parameter cannot define the multiple geometric characteristics of the track with the degree of accuracy that is required to ensure optimum track maintenance.

For prediction, our approach uses as input data the results of four previous measurements in the form of the ISDF values for each type and size of the defect for the selected track segment after pre-processing. The fifth measurement is a control one and is used to evaluate the accuracy of the method.

Table 2. *Source Data for Prediction Calculation.*

IRREGULARITY SIZE	MES.1	MES.2	MES.3	MES.4	MES.5
mm	m	m	m	m	m
-8	0.58	0.67	0.67	0.67	0.92
-7	0.92	0.92	0.92	1.00	1.08
-6	1.17	1.17	1.17	0.92	0.92
-5	1.25	1.17	1.25	1.75	1.75
-4	3.08	3.50	3.17	3.83	3.83
-3	5.17	5.50	5.00	5.75	5.58
-2	7.58	7.67	7.00	6.50	6.58
-1	8.75	8.33	8.25	7.42	7.17
0	11.92	11.50	11.50	10.25	10.17
1	15.50	15.33	15.17	14.25	13.25
2	16.42	16.42	16.75	16.42	15.92
3	13.00	13.17	13.50	14.17	14.08
4	6.75	6.75	7.58	8.58	9.08
5	2.75	2.83	2.83	3.42	4.00
6	1.00	0.92	1.08	1.17	1.08
7	1.25	1.33	1.25	1.25	1.33
8	1.00	0.92	1.00	0.92	0.92
9	0.67	0.67	0.58	0.50	0.58
TOTAL	98.75	98.75	98.75	99	98.75

Table 2 shows the results of calculating for 5 consecutive measurements of longitudinal level irregularity for a 100-meter-long track segment with a discreteness of ΔS=1 mm. During the operation of the track under train load there is a continuous dynamic interchange between ISDF values for neighboring defect sizes, which is expressed in a change in the values of the ISDF in such a way that, as can be seen from the table, the sum of the ISDF (si) values remains constant and equal to the length of the track segment with an error determined by the accuracy of the measurement results.

The results of our analysis for a representative number of track segments are consistent with the conclusion of Sato [9] that changes in the size of defects S<|3| mm occur much faster than changes in defects of large sizes.

Our approach uses not just one single parameter (SD or KPi) for describing track technical condition and predicting its behavior, but set of ISDF $\ell_{\sum}^{s}$ values for each irregularity size S. Thus, it is possible to predict values $\ell_{\sum}^{s}$ for any-size selected irregularity, regardless of its size.

Independent parameters are the length of the track segment and the discreteness of the defect sizes (ΔS=1mm). The model does not use the value of the time interval ΔT between measurements. Therefore, the accuracy of the method depends only on the structure and quality of the source data.

5. Prediction Function

The analytical process includes the calculation of ISDF values for previous ensembles of measurement results and the calculation of the values of the target function for each of the defect sizes.

Our approach in determining the prediction target function is based on the use of convergence theory in relation to the behavior of the track under train load, formulated by Sato [9]. In the literature, this phenomenon is also defined as path memory. Lichtberger [10] notes that the memory of track is the phenomenon that the track after tamping tends to return to the former defective position. If, in the case of analyzing the behavior of a single defect, its amplitude, as a rule, increases, then in the case of ISDF, the function may change nonmonotonically due to the continuous dynamic interchange between ISDF values for neighboring defect sizes.

An interesting experimental confirmation of the validity of the convergence theory is found in Soleimanmeigouni [11]. The figure on page 996 in the reference [11] shows the results of measurements of the magnitude of a single defect before tamping, a month after tamping and a year after tamping, when the dimensions of the defect returned to the original value.

The ISDF(i) function always trends toward some ultimate value of ISDF (lim) and may not reach it within the considered time interval. We solve the prediction problem as a problem of determining the ISDF (lim) value for each defect size. Our algorithm ensures the determination of this value with high accuracy. Unlike traditional mathematical methods, the use of convergence model to predict track behavior in the future, allows to take into account the peculiarities of the ISDF function over time with respect to each defect size.

6. Presentation of the Results and Evaluation of the Accuracy of the Method

The calculation results are presented in the form of a table containing ISDF(s) values for defect sizes S>|3| mm at the end of the period following the last measurement date.

The random nature of the change in the geometric characteristics of the track for each of the defect sizes does not allow using the traditional method of calculating prediction errors. The prediction error for each defect size is a random variable that depends primarily on the state of the track and the continuous dynamic interchange between ISDF values for neighboring defect sizes.

Taking into account the random nature of the process under study, the prediction accuracy was estimated statistically by the value of the average error.

In our opinion, as a generalized quantitative characteristic of the prediction quality, the average value of the difference between the values of predicted and the control value of ISDF should be used, using the result of the fifth (n+1) measurement as a control value.

$$ERR(S)= average(abs(\ell\sum s(5)-PREDICT(\ell\sum s)),$$

where $\ell\sum s(5)$ is the actual value of the ISDF function at the prediction point in time, obtained as a measurement result.

An example of calculating the prediction error for the data in Table 2. is shown in Table 3.

Table 3. *Calculation Results for PREDICT (ℓ∑s).*

Irrgularity Size	Predict value	Control value	Predict error
mm	**m**	**m**	**m**
-8	0.67	0.92	0.25
-7	1.00	1.08	0.08
-6	1.17	0.92	0.25
-5	1.75	1.75	0.00
-4	3.83	3.83	0.00
4	8.58	9.08	0.50
5	3.42	4.00	0.58
6	1.17	1.08	0.08
7	1.33	1.33	0.00
8	1.00	0.92	0.08
9	0.67	0.58	0.08
		AVERAGE	0.17

To assess the accuracy of the method, the prediction error value calculations were performed for randomly selected track segments and for prediction intervals of 2 and 6 months. Figures 2 and 3 show examples of analyzing the results of calculating predicting values.

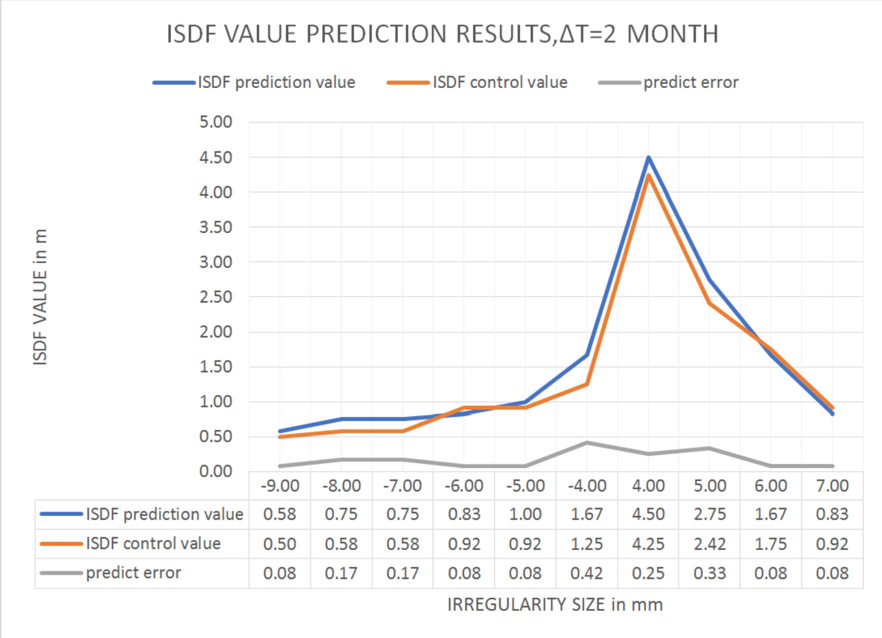

Figure 2. *ISDF Value Prediction Results, ΔT=6 Month.*

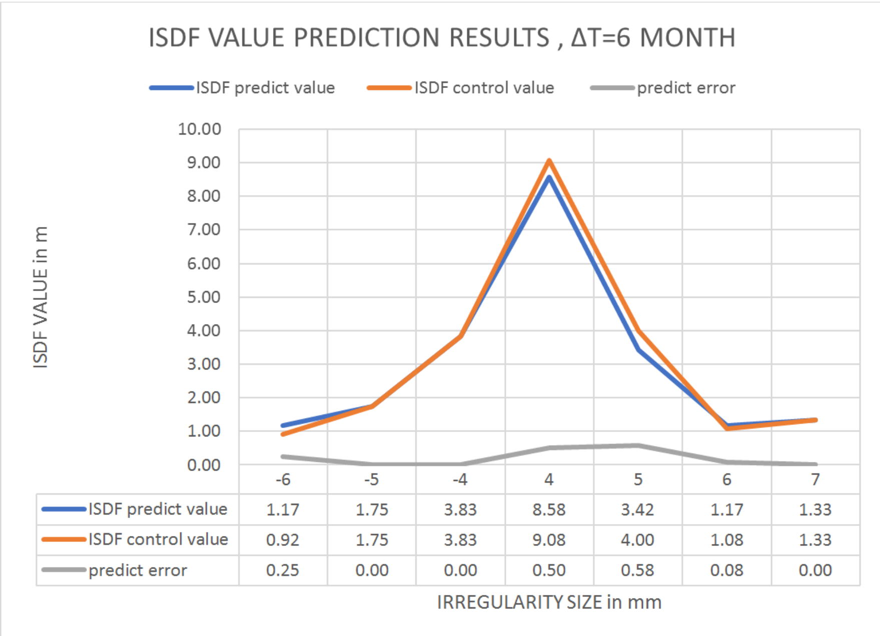

Figure 3. *ISDF Value Prediction Results, ΔT=2 Month.*

The generalized results of the prediction quality calculation are given in Table 4.

Table 4. *Prediction Accuracy Assessment.*

	Prediction interval	**Number of track segments**	**Number of measuring points**	**Average prediction error**
	Month			**%**
1.	6	15	97	0.25
2.	2	15	88	0.25

7. Conclusion

A theoretical justification and experimental verification of the adaptive multipoint method for predicting changes in the geometric characteristics of the track is carried out.

The method automatically takes into account the influence of all external factors on changes in the geometric characteristics of the track. Only the results of routine sequential measurements of the track geometry at random intervals are used for analysis.

Prediction results are presented in the form of values of the ISDF function, which uniquely, without distortion, and with a pre-selected accuracy describes the state of the geometric parameters of the track and their changes for each defect size.

The method is universal and allows to predict changes for all parameters of the track geometry.

The method can be incorporated in existing analysis programs as an application.

For longitudinal level irregularity, the average error in predicting ISDF values for S>|3| mm does not exceed 0.3% for 100-meter segments.

The method allows to assess the condition of the track and its changes in the future, and effectively plan track maintenance work.

Note

Source data tables used for calculation of predict (ℓ∑s) can be provided upon request.

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