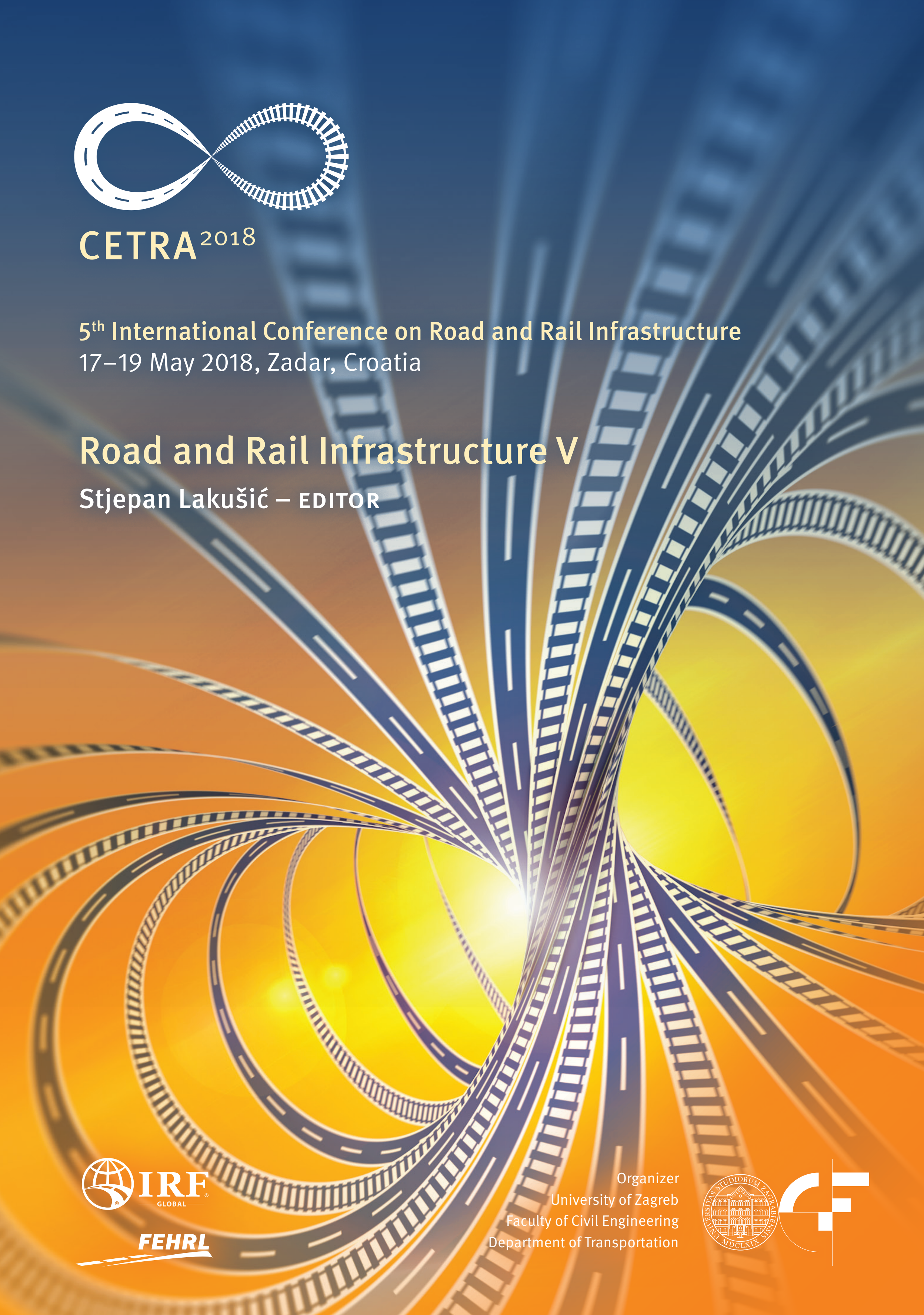

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – **EDITOR**

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IMPROVING TRACK CONDITION BY APPLICATION OF QUASI CUMULATIVE DISTRIBUTION FUNCTION (QCDF)

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Abstract

We present a new method of Track Quality Assessment. The method is based on the application of the QCDF as the approach to assessment of the results obtained from periodic track geometry measurements. Results of track geometry measurements comprise a random set of data that can be fully described only by the Irregularity Size Distribution Function (ISDF). Currently, the common approach to track condition analysis and track maintenance planning includes the use of only one of this random process's parameters, namely, the Standard Deviation (SD). We have studied the properties of this random process and have evaluated the attainable degree of accuracy when using SD for: a) Track condition analysis and b) Selection of interventional parameter and its threshold value for maintenance planning. We have concluded that application of SD approach produces inaccurate and non-optimal results. Conversely, use of QSDF produces accurate description of the track condition based on analysis of defects' physical parameters, and allows to register with high resolution changes (even when SD value doesn't change) in track condition caused by both regular operation, and use of maintenance equipment. QCDF is the linear transformation of ISDF and returns the cumulative length of each type of track irregularities with size above threshold value. QCDF is invariant to ISDF distribution law and is monotone, continuous, and its use does not distort ISDF. Use of QCDF allows to identify intervention threshold for track maintenance based on objective assessment of track quality condition. QSDF can be used both as a stand-alone method and as application to SD analysis.

Keywords: track quality assessment, track geometry, irregularity size distribution function, quasi cumulative distribution function, track maintenance

1 Introduction

Formation of railway track maintenance strategy is based on the analysis of track geometry measurement conducted, as a rule, with track measuring car or track measuring trolleys. From the probability theory point of view, such measurement results are random variables that assume one of the possible discreet values with probability that depends on the track technical condition (random process). These results are fully and unambiguously described by the Irregularity Size Distribution Function (ISDF).

One of the quantitative characteristics of this function is the Standard Deviation (SD), which allows to assess the track technical condition in a single point. Currently, SD is the quantitative characteristic of both track quality index and track maintenance planning threshold and is a commonly used indicator for track geometry quality description, as defined by the European Railways and EN standards. Professional publications do not provide evidence of correlation between SD values and the track technical condition [1-3].

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G.H. Cope [1] justifier use of SD for track assessment quality as follows: “track profile has been found to have sufficiently similar statistical properties to random processes to enable a measure of the magnitude of track irregularities to obtained from standard deviation of the vertical and horizontal profile data”. Austrian railways [4], for example, do not rely on SD and recommend the use of modified standard deviation with $\sigma = 1{,}35m$ (m-mean track geometry deviation) instead of SD.

As already mentioned, ISDF is the objective and non-distorted description of the track geometry measurements results. Shape of ISDF defines the value of the fourth central moment of distribution function (kurtosis) Y. By definition, for normal distribution law $Y = 0$. Fig. 1 shows Y calculation results for set track segments with LL irregularities as function of SD. For most measurements shown in Fig.1, $Y > 0$, which proves that ISDF is not normally distributed as a function of irregularities’ size, and there is no correlation between SD and Y values. Anderson -Darling statistic test of normality and kurtosis values Y analysis [5] shows:

- as a rule, measurement results of the track irregularity size (ISDF) do not follow the normal distribution. Therefore, SD for a normal distribution formula cannot be used for SD calculation in such cases. In fact, SD for each non- normal distribution should be calculated using the formula that correspond to its individual distribution law. Once the individual calculation has been conducted, meaningful comparison can be possible;
- as a rule, track segments with the same SD correspond to different ISDFs;
- track segments with different Maximum Irregularity Size (MIS) may have same values of SD and vice versa;
- SD criterion does not determine the shape of the ISDF, and for track section with the same values of SD contact stress and energy dissipated in the wheel -rail contact area will be different.

We have estimated the attainable degree of accuracy when using SD for track condition analysis and selection of interventional parameter and its threshold value for maintenance planning. For set 200 m long track segments ($N = 466$) with the MIS LL level irregularity values from 6 up to 13 mm, the cumulative function depending on SD was calculated. The results of the calculation are shown in Fig 2.

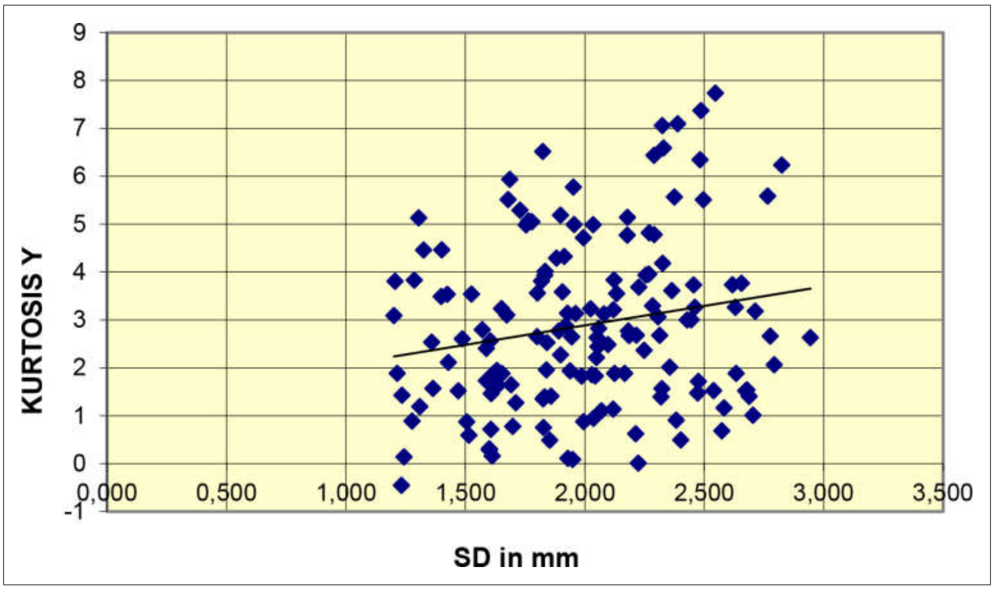

Figure 1 Y distribution as SD function

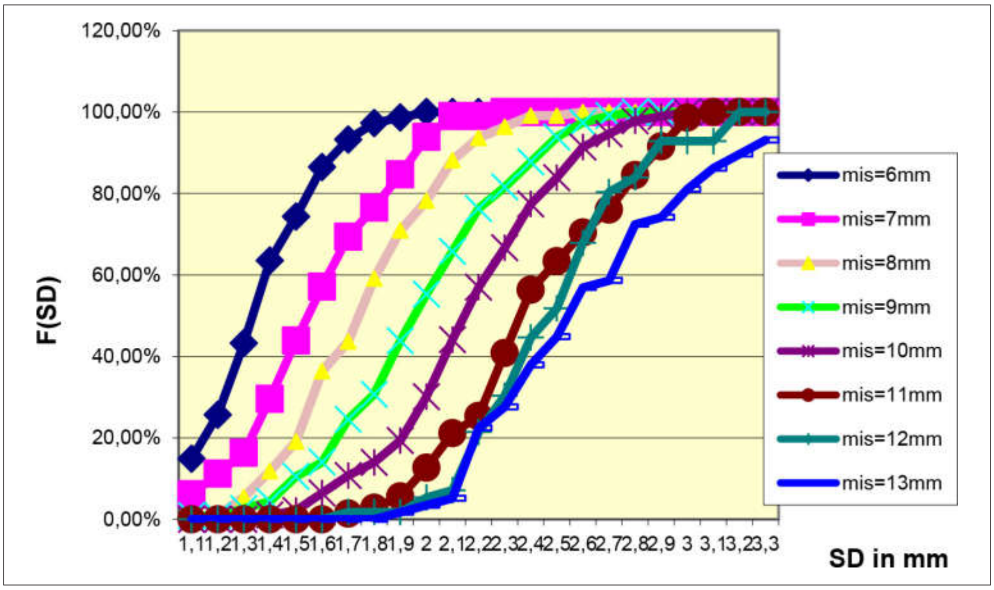

Figure 2 ISDF properties – cumulative functions F(SD) for track segments with different MIS

The curves in Fig. 2 characterize the properties of the ISDF which demonstrate that the same value of SD can have corresponding track segments with different MIS. We have concluded that application of SD approach produces inaccurate and non-optimal results.

2 Properties of QCDF

Work [5] presents the definition and basic properties of the Quasi Cumulative Distribution Function (QCDF) for the irregularities' sizes.This function is a linear transformation of ISDF and shows the cumulative length ℓ_Σ^s of the track irregularity with size equal or larger than the threshold S. (Fig.3).

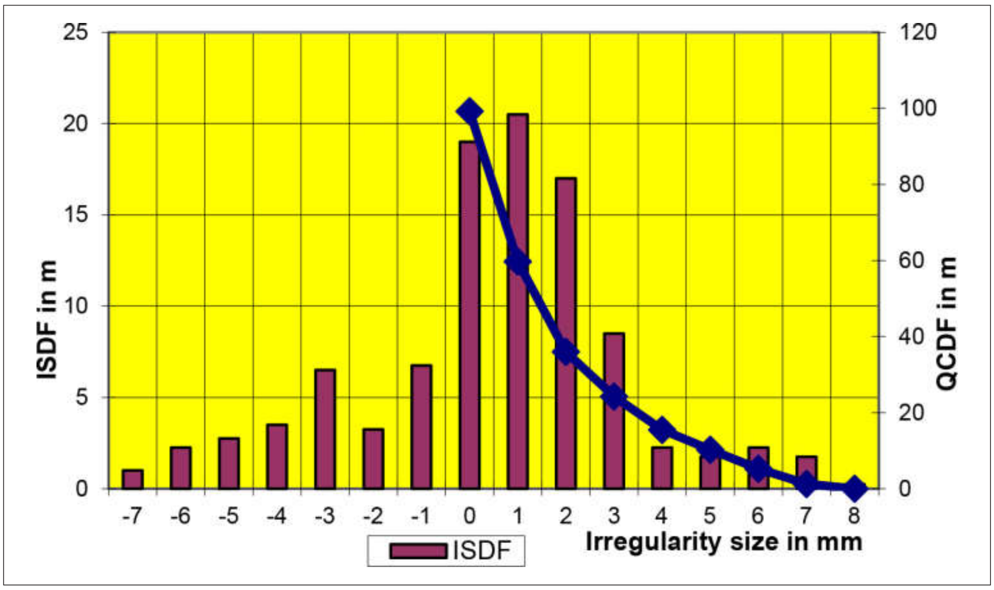

Figure 3 QCDF concept

As can be seen from Fig.3, track technical condition is characterized by the position of a point on a plane QCDF- Irregularity size. QCDF(ℓ_Σ^s)is characterized by the following properties:
- $0 \le \ell_\Sigma^s \le L$ – QCDF value can vary from 0 to the track segment length L;
- $\ell_\Sigma 0 = L$ – for $s = 0$ cumulative length equal to the length of the track segment L;
- $\ell_\Sigma \infty = 0$ – the cumulative length for irregularity value ∞ is 0;
- if $s1 < s2$, then $\ell_\Sigma^s 1 < \ell_\Sigma^s 2$, QCDF is monotonically decreasing.

The values of the QCDF depend only on the values of the ISDF, but not on the distribution type. QCDF is characterized by high resolution and allows to distinguish track segments even with the same values of SD. This property is illustrated in Fig. 4, the shows the graphs for the four track segments with the same SD values (SD = 2.2 – 2.3 mm).

3 Use of QCDF for optimization of track maintenance

The use of QCDF method significantly increases the efficiency of track maintenance works' planning. Fig. 5 is shown as an example of MIS cumulative function for several SD values. Graphs allows to see the problems encountered when planning of the works based on SD value. Graphs showed that for SD > 2 mm (n = 357) MIS is 15 mm, and 40% of the track segments have a MIS less than 11 mm. For SD parameter value within 1.4-2.4 mm range (n = 443), as prescribed by EN 13848-5,our calculation produced the value of MIS = 11 mm. But the curve in Fig.5 shows that for SD in this range for 45% of the track segments MIS is less than 8 mm. So, if maintenance work is planned using the SD approach, it will be scheduled for many segments where it is unnecessary. This leads to both wasted resources and reduction of the service life of the track.

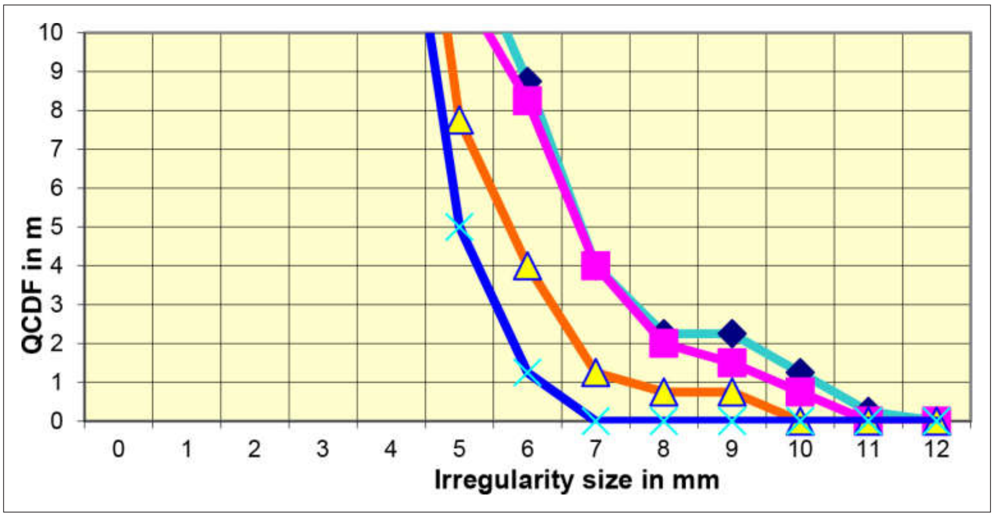

Figure 4 QCDF for 4 track segments with the same SD (2.2-2.3) mm

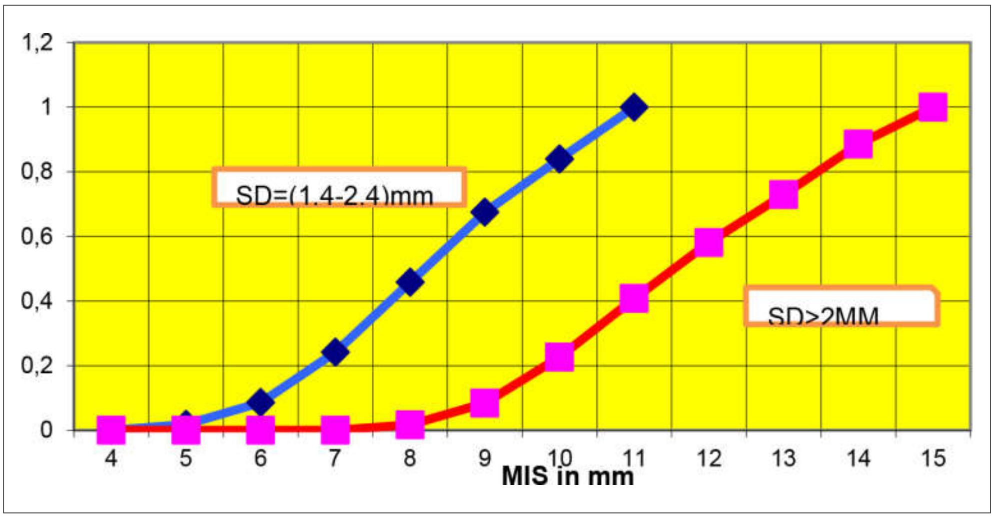

Figure 5 MIS cumulative function for different SD

For optimization of track maintenance planning, track segments with irregularities' size above the preset S threshold should be chosen. Based on the shape of QCDF analysis for these track segments, including the ℓ_Σ for varying sizes of irregularities and other factors (track deterioration, subsoil position, etc.), one can make optimal decision regarding the work planning.

4 Use of the QCDF for combined evaluation of track condition

According to EN STANDARD 13848-6, "assessment of overall track geometry quality of a track section can be done by combination weighted SD of individual geometric parameters CoSD", which can be calculated as follows in Eq. (1):

$$CoSD = {}_{AL}\, SD_{AL}^{\ 2} + w_G SD_G^{\ 2} + w_{CL} SD_{CL}^{\ 2} + w_{LL} SD_{LL}^{\ 2})^{0.5} \tag{1}$$

Where:
SD – standard deviation of the individual geometry parameters;
w – weighing factor of the individual geometry parameters determined by the infrastructure manager;
AL – alignment, average of left and right;
G – track gauge;
CL – cross level;
LL – longitudinal level, average of left and right.

For the QCDF method, the following equation is used to determine the combination track geometry quality parameter for irregularities AL and LL, Eq. (2):

$$Co\ \left(\ell_\Sigma^{\ s}\right) = 0.5\left(\ell_\Sigma^{\ s}(\ ALleft\ ) + \ell_\Sigma^{\ s}(ALright)\right) + 0.5\left(\ell_\Sigma^{\ s}(LLleft) + \ell_\Sigma^{\ s}(LLright)\right) \tag{2}$$

where ℓ_Σ^s () – QCDF of the individual geometry parameters for S value.

For 234 of 100 m long track segments with $1.0 < SD < 3.8$, CoSD and Co (ℓ_Σ^s) were calculated. When calculating (1), we assumed the condition $w_{AL} = w_{CL} = w_G = w_{LL} = 1$. When calculating (2), we assumed s(AL,AR) = 6 mm and s(SL, SF) = 8 mm. Comparison of the values of CoSD and Co(ℓ_Σ^s) shows (Fig. 6) that the same CoSD values correspond to several significantly different values of Co(ℓ_Σ^s). So Co(ℓ_Σ^s) is more sensitive to changes in the track condition, and describes he track condition unambiguously and more accurately.

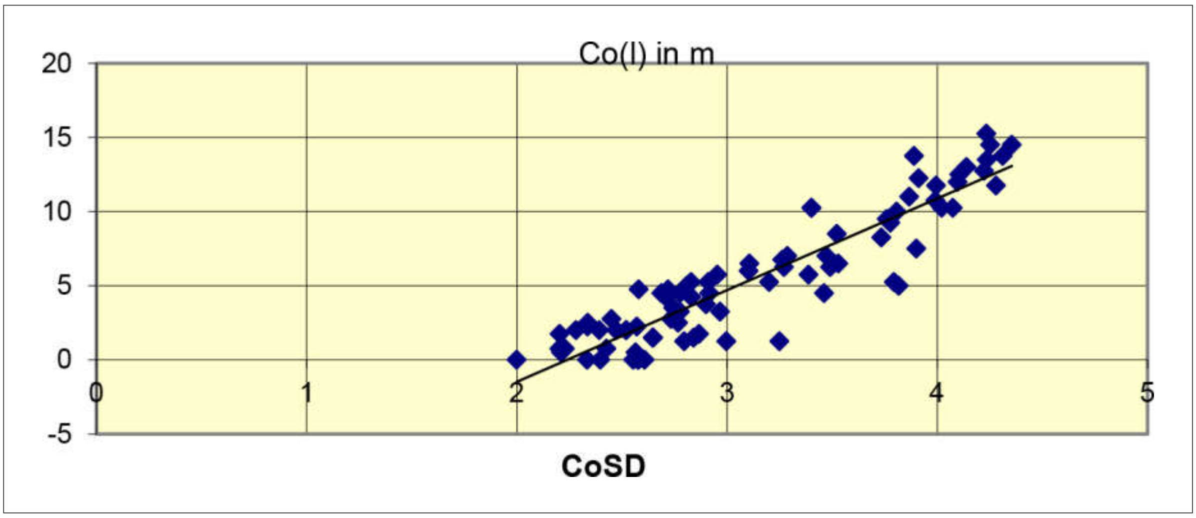

Figure 6 Correlation between Co(ℓ_Σ^s) and CoSD

5 Use of the QCDF for track condition monitoring

In known publications, the change of track condition is described by a corresponding change of SD. QCDF makes it possible to use two parameters to describe change in track condition after track maintenance by the mechanical equipment:

- S_{MIN} – minimum size [mm] of an irregularity that the equipment was able to correct;
- μ – coefficient of efficiency, $\mu = (\ell_{\text{after tamping}} / \ell_{\text{before tamping}})*100(\%)$.

The table below illustrates the application of the QCDF method for analyzing the changes of characteristics of LL type irregularities using μ coefficient. Table 1 shows that for different track segments and working conditions S_{MIN} varies from 5 to 9 mm. The results of the analysis show that there is no correlation between ΔSD and S_{MIN}. Different values of μ reflect the following situations:

- $\mu > 100$ – natural increase of the length of small size irregularities (from 1 up to 3 mm);
- $\mu = 0$ – elimination of irregularities of large sizes (from 5 to 12);
- $0 < \mu < 100$ – decreasing the length of irregularities of medium size (from 2 up to 9 mm);
- $\mu = > 100$ – increased or unchanged length of irregularities.

Table 1 Example of QCDF analysis

		Irregularity size [mm]											
SD	**ΔSD**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
[mm]	**[mm]**	**coefficient of efficiency [%]**											
2,113	1,098	205	85	23	3	0	0						
2,533	1,202	133	115	44	28	100	0	0	0				
2,758	1,229	130	123	98	61	16	0	0	0	0	0		
1,941	0,611	105	111	122	46	50	40	0	0	0			
2,324	0,681	148	91	71	66	33	20	29	0				
2,798	0,934	131	131	66	84	41	32	14	0	0	0		
2,348	0,788	151	63	72	79	58	80	17	0	0	0	0	
2,234	0,731	129	106	76	42	10	33	33	0	0	0		
2,411	0,599	92	124	135	72	129	100	400	0	70	0	0	0
2,373	0,600	123	97	78	66	86	64	44	0	0			
2,256	0,575	105	114	88	61	175	33	150	0	0	0	0	0
1,746	0,188	103	105	78	100	100	0	150	75	0			
2,275	0,312	121	93	104	76	40	40	33	100	0	200		
3,123	1,306	135	132	57	33	29	71	120	60	0	0	0	0
1,981	0,283	101	117	91	73	33	100	25	100	0			
2,432	0,344	116	106	76	44	100	117	29	33	33	0	200	
3,234	0,693	118	107	91	90	61	133	186	20	43	0	0	
2,444	0,770	162	76	34	48	47	75	38	40	50	0		
2,315	0,458	122	88	88	32	67	43	33	67	60			
1,998	0,323	118	115	75	31	47	200						
2,297	0,424	149	75	66	53	61	11	80	100	200			
2,220	0,418	114	114	73	44	50	129						

6 QCDF-based prediction of changes in track condition

There are a variety of mathematical models describing the track condition changes used to predict the future track geometry parameters. All these models describe behavior of the track with some inaccuracy. the magnitude of which depends on traffic loads, track 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 in [6] the author assigns track segments to 17 groups by size evolution rate. Formula for the calculation of the rate of track deterioration [7] contains 15 different parameters. All these models use SD value as the parameter. From mathematical point, of view the change of the track technical condition is a random process that can be described statistically, so using deterministic models of track behavior is not valid. In this work we use adaptive method based on analysis of relevant information about the track condition in the form of measurement results for the previous period.

Our approach uses not just one single parameter (SD) for describing track technical condition and predicting its behavior, but set of values of ℓ_Σ^s parameters for each irregularity size. Thus it is possible to predict values ℓ_Σ for any selected irregularity size, no matter how small. To calculate ℓ_Σ^s, we applied autoregressive model to the input data by minimizing (least squares method) the forward and backward errors.

The accuracy of prediction is determined by the properties of input information. As a rule, high accuracy of prediction is achieved in those cases when the initial random process is stationary. In this case, stationary random process characterizes a natural change in track technical condition through normal operation.

The track maintenance works significantly changes the track parameters. In this situation,the random process describing the behavior of the track becomes non-stationary, and the prediction accuracy decreases. The choice of timing parameters of prediction is based on frequency characteristics of the process. The behaviour of the geometric parameters of track is characterized by a relatively high-frequency change of small size irregularities.

Therefore, the prediction of dimension changes of such irregularities for time intervals that are significantly longer then the period of natural changes, makes no sense. The analysis showed that it is sufficient to use the results of the previous four measurements to obtain adequate results.

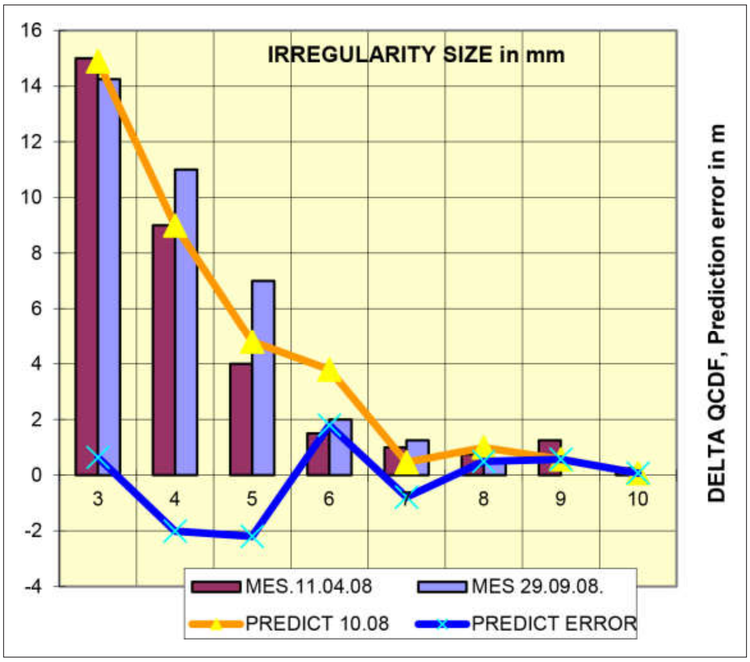

Figure 7 Results of 6-months track condition prediction

In Fig. 7, we show the results for 6-month prediction of the change in the characteristics of the irregularity of LL type within a 100 m-long track segment and comparison of these data with the results actually measured. The error in the QCDF-base prediction of ℓ_Σ^s for time intervals of 2, 4, 6 months, for irregularities sizes 3 mm or more, does not exceed 2.5 m.

7 Conclusions

The use of QCDF method creates fundamentally new possibilities for analyzing track technical condition on the base of the results of direct measurements and the presentation of undistorted information about the physical characteristics of irregularities, including:

- optimisation of planning – it is possible to exclude the maintenance plan track segments with irregularities of obviously small size, which provides saving of resources and increases the service life of the track;
- effective monitoring of the track changes, including quality of the tamping and feedback for adjusting tamping parameters;
- the unambiguous assessment of the track condition and its changes on the basis of the objective complex quality index in the form of total length of irregularities with size exceeding the threshold values for each irregularity type;
- prediction of changes of the geometric characteristics of the track with high accuracy, which facilitates effective track maintenance in the short and long term;
- QCDF method can be used both as a stand-alone method and as application to SD analysis.

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