INCREASE IN INFORMATIVE VALUE OF RAILWAY TRACK MAINTENANCE ASSESSMENT

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ABSTRACT

Using the methods of statistical analysis based on the theory of random process emissions, the theory of random point processes, the method of least squares, the method of least modules, filtering algorithms, the choice of a type of a theoretical function and its parameters that allow reducing the error of the measured characteristics of defects and deviations of the track from the design position, a mathematical model is formulated that provides an increase in the informative value of the assessment of the actual state of the railway track. High information value is needed primarily for formation of adequate control actions on the track in order to ensure traffic safety.

Keywords: railway track, measured parameters, information-measuring system, defect detection, statistical analysis, theory of random processes, mathematical model.

Background. *The basis for ensuring the safety of the railway operation is a way to create a database of defects in the track operation and measures to eliminate them or prevent their occurrence. Let's consider a particular task of increasing the informative value of the track maintenance assessment according to the readings of a track measuring car and the possibility of obtaining a larger number of parameters in one pass of the track measuring equipment using the software and hardware monitoring and image processing system for detecting defects and determining their characteristics.*

Objective. *The objective of the authors is to consider informative value of railway track maintenance assessment.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, assessment method, statistical analysis, mathematical apparatus.*

Results. *The track measuring car [1] records the state of the geometry of the track gauge, including in the plan (narrowing, gauge widening, straightening) and profile (subsidence, misalignment), as shown in Pic. 1a for one of the parameters. The existing system of assessing the state of the rail track and planning work according to the readings of the track measuring equipment on the basis of the instruction [2], approved in 1997, does not regulate estimates for lines with speeds of up to 140 km / h.*

In addition, the instruction permits ambiguity in the interpretation of the track assessment, for example: a subsidence of 26 mm with a length of 6 m requires a speed limit of 60 km / h, and a subsidence of 7 m length and 50 mm in size allows a speed of 140 km / h; a skew of 21 mm with a length of 20 m implies a speed limit of 60 km / h, and a skew of 40 mm with a length of 21 m formally allows a speed of 120 km / h. The score of kilometers for which employees of structural units serving the railway track receive financial incentives does not always correspond to the procedure for eliminating deviations aimed at improving traffic safety. In fact, there is no differentiation within the same qualitative assessment of the kilometer. For example, for established speeds of 61–120 km / h of third-degree retreat – three skews of 19–20 mm or one skew of 17 mm lead to the same satisfactory estimate of a kilometer. Such an assessment does not stimulate the elimination of first and foremost dangerous deviations.

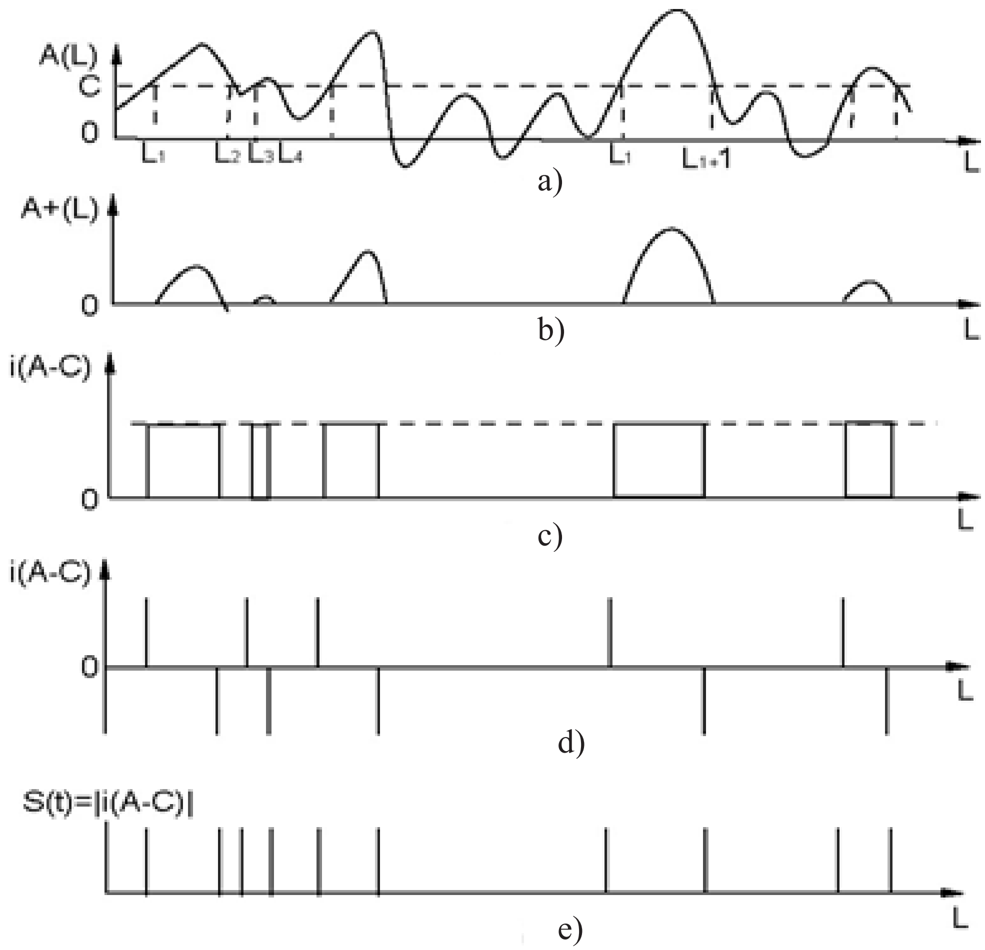
Estimation of the track maintenance according to the data of the track measuring car is to establish scores for exceeding the established threshold values from the track maintenance standards [2]. The set of estimates of each deviation on the site in the form of a sum of scores or the number of malfunctions of certain degrees of deviation is a complex estimate of the section of the track as a whole [3]. To reduce the effect of the described shortcomings, it is proposed to proceed from the assumption that the process of recording the track state by a track measuring car refers to random processes in which the time index is the coordinate counted along the track length (Pic. 1). At the same time, it can be considered that it is completely determined by the set of its implementations, and exceeding the established thresholds (the degree of deviation from the norms of the rail track maintenance) is the emissions of a random process.

Studies in the theory of random processes [4, 5], which proved the equivalence of the problems of level crossing theory, the theory of random process emissions and the theory of random point processes, make it possible to approach a mathematical model to increase the informative value of the actual state of the railway track, necessary for formation of control actions on the track for the purpose of ensuring traffic safety, maintaining it in a working condition without additional passage of vehicles with detection equipment.

If along the abscissa axis (Pic. 1) the track length L is laid out, and along the ordinate axis – the amplitude of the unevenness of the track gauge A, we obtain a sample function of the continuous random process A(L) for the section $L \in \{L_{0,} L_0 + L\}$*, that intersects threshold levels* C_i*, characterizing deviations from the norms of the maintenance of the track gauge.*

For simplicity of representation of the proposed model, we take only one threshold level C, corresponding, for example, to the third degree of deviations from the track maintenance norms, which in turn forms one point process n(L), corresponding only to this threshold value C. The function A(L) characterizes the state of the track in the region $\{L_{0,} L_0 + L\}$ *with respect to the threshold level C, its behavior can be described by the number of positive* $n^+(C, L)$ *and negative* $n^-(C, L)$ *emissions. That is,* $a_+(L) = (a-C)I(a-C)$*, where a = a(L) is the realization of recording the readings of the track measuring car as a random process A(L), I (a) is the unit jump.*

The process I (a–C) as a function of the length of the estimated area is a random sequence of rectangular pulses of unit amplitude (Pic. 1c). They are synchronous with the transitions of the function A(L) through the level



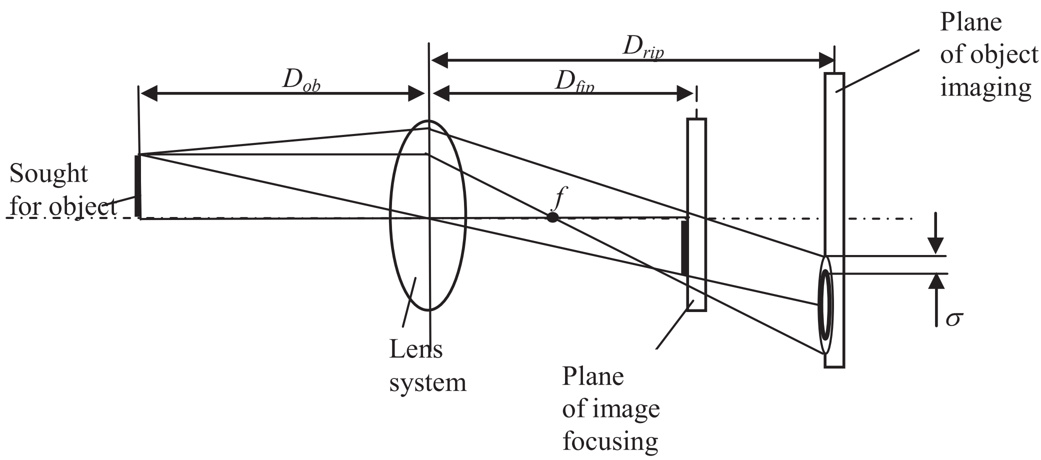
Pic. 1. Record of the state of the rail track according to the readings of the track measuring car:
a) readings of the track measuring car as a function of the random process on the track section; b) non-linear transformation A→l(A–C) as an ideal limiter (detector) in C; c) a random sequence of rectangular pulses of unit amplitude; d) single impulses of emissions; e) duration of emissions.

C, that is, they have the same duration as the impulses of irregular shape shown in Pic. 1b. The number of intersections N(C, L) of a given level C is determined from the condition that the process of recording the state of a track gauge in space can be considered differentiable. This value is determined for the average number of intersections N(C, L) of a given level C with the trajectory of the random process A(L) on the estimated section L. To determine the number of emissions on the site, the function l (A–C) is differentiated with respect to L, which gives g impulses positive for $A^I > 0$ *and negative for* $A^I > 0$.

In reality, estimating the magnitude of the emission is not enough, since subsidence and skew can be characterized by the same emission, but their impact on traffic safety is different and is determined not only by the fact of the emission, but also by its duration. The emission duration can be written as $\Delta L_v = L_{i+1} - L_i$, *and the average length of stay of the trajectory A(L) over the level C is represented as* $L^+(C) = 1 - F_A(C, T)$, *with* $F_A(a, L)$ *being the distribution function.*

The total duration of all the emissions L_v *in the interval (0, L) is equal to the arithmetic sum* $L_v = \sum \Delta L_i$ *and coincides with the residence time of the realization a(L) in the region A > C. The pulses l(A-C) have the same total duration, and since the pulses are not negative and have single amplitudes, the duration of the emissions can be determined from the expression* $L_v = \int_0^L 1(A-C)dt$.

An increase in the informative value of the estimation of the state of the railway track is also possible with the use of modern video monitoring and measurement systems, in which algorithms for stereo vision [6, 7] can be distinguished as methods for obtaining primary information about the state of the objects under study (defects and deviations from the design position) [6–11], a set of intelligent cameras that allow to get video in real time [8], use of a camera that gives a three-dimensional image (one of its parameters is the distance to individual elements [9]), but the use of such technology is associated with large computational loads on hardware, so usually only points of the object located along its boundary at equal distances from each other are singled out [10]. The method of three-dimensional reconstruction, which is based on additional illumination of the object under



Pic. 2. Scheme of blur formation in case of defocusing with $D_{rip} \geq D_{fip}$.

study and the study of the shape of the formed shadows, is developing quite actively in solving engineering problems [11].

In this case, it is proposed to use the software and hardware video monitoring system to increase the informative value of track condition estimates obtained using track measurement equipment, which helps to determine the presence (recognize [12]) the parameters of defects (size, location, shape). The video monitoring system uses algorithms and methods that allow to switch from photodetector parameters to physical distances based on the defocus analysis for objects whose images are represented in the image [6, 8]. To establish the relationship between the parameters of real objects and the characteristics of their images, photodetectors and shooting modes, blurred images are convenient. The «blurring» of the image may appear due to the movement of the object or the detector, the features of the image boundaries, the aggregate state, and also due to the different settings of the photodetector (focal length, aperture, shutter speed and aperture) (Pic. 1). As a functional, connecting the main characteristics of the detector and the location of the image of the object in the exposure, the ratio [6, 13] is applied:

$$1/f = 1/D_{ob} + 1/D_{fip}\ , \qquad (1)$$

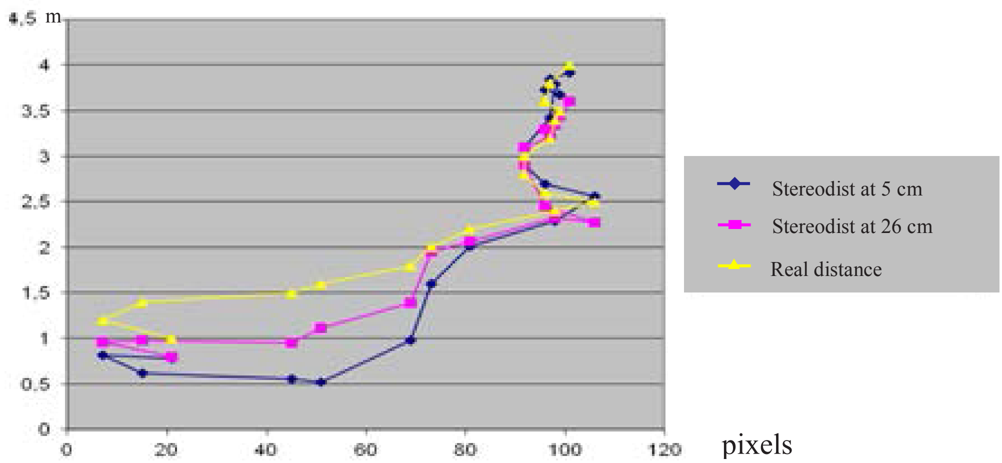
where f is focal length, D_{ob} is distance from the given object point to the photodetector objective, D_{fip} is distance between the center of the lens and the focused image of the object under study.

From expression (1), it is required to determine the values of D_{ob} and D_{fip} for a given focal length. The blurring of the image can be represented in the form [5]

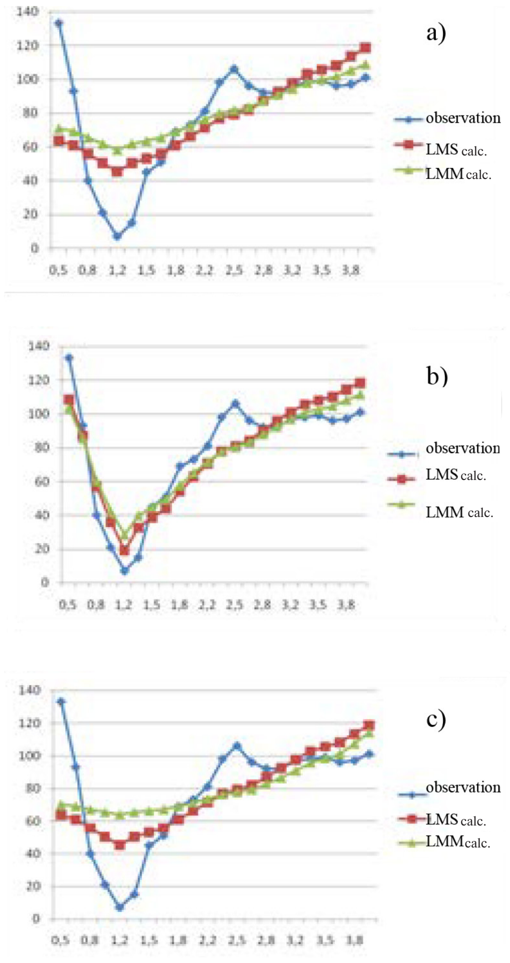
$$\sigma = B\left|D_{rip} - D_{fip}\right| / D_{fip}\ , \qquad (2)$$

where σ is blur of the object, B is aperture value, D_{rip} is distance from the center of the lens to the plane of the object.

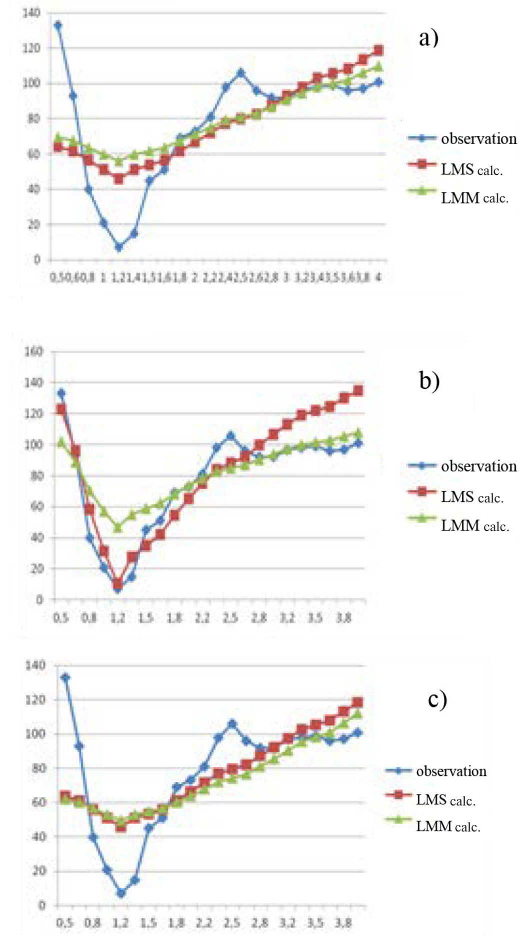
When determining the size of the smearing spot, it is assumed that the blurring at the point occurs identically in all directions [7, 8, 13]. It is proposed to install a stereopair on the track measuring car that forms the image of the track superstructure for further



Pic. 3. Distances obtained by stereo vision schemes and the real distance, depending on the average blur value.



Pic. 4. The dependence of the blur on the distance to the object from the function η_i (X): a) linear, b) logarithmic, c) exponential.



Pic. 5. Dependence of dispersion on distance with a filtration coefficient K = 0,1 for different models: a) linear, b) logarithmic, c) exponential.

processing in the monitoring and measuring system. The parameters of detected defects are determined on the basis of a complex technique that aggregates the stereoscopic algorithms and estimates the blurring of the object images obtained from two cameras (Pic. 3) [13, 14].

Each measured blur can be represented as a sum:

$\theta_i = \eta_i (X) + \Delta_i$, *(3)*

where $\eta_i (X)$ is some known function, with respect to which we shall consider the estimates of the distribution; Δ_i is measurement error; $X=(X_1, ..., X_M)^T$ is vector of the location of the object (defect); $\theta_1, \theta_2, ...\theta_n$ are results of measurements of the average blur of the object.

To estimate the defect parameter vector a $X=A_j(\theta)$ it is suggested to use M-estimates, which are a minimum of the sum of functions from the data:

$X(\theta) = \arg\min_X (\Sigma^n_{i=1} L(\theta_i - \eta_i (X)))$, *(4)*

where $L(\theta)$ is function corresponding to the estimation method (for the least squares method – $L = z^2$; for the least modulus method – $L = |z|$). Based on the analysis of these estimates, the function $\eta_i(X)$, is chosen as it is most closely approximated to observations, according to the properties of unbiasedness, consistency and efficiency.

One way to obtain stable estimates of observations θ_i is to vary the form of the function $\eta_i(X)$ with the unknown error distribution Δ_i and use the root-mean-square deviation θ_i. As $\eta_i(X)$ we propose to consider a number of functions: $\eta_i (X) = a+b \cdot |x-x_0|$ (linear); $\eta_i (X) = b \cdot |ln(x-x_0)| + a$ (logarithmic); $\eta_i(X) = b \cdot |exp|(c \cdot x-x_0)|| + a$ (exponential). After substituting these expressions into the defining equations, we can represent them in the form of graphs of the dependence of the blur on the distance to the object (Pic. 4).

To smooth existing and possible emissions, it is suggested to apply filtering to the initial observations and to analyze the estimation of least-squares (LSM) and least-modulus (LMM) methods for three functions considered after applying the filter. The filtering procedure can be represented in the form of iteration expressions:

$\theta^{opt}_{k+1} = K \cdot \theta_{k+1} + (1-K) \cdot (\theta^{opt}_k + u_k)$, *(5)*

$u_k = \eta(x_{k+1}) - \eta(x_k)$ *– for linear function;*

$\theta^{opt}_{k+1} = K \cdot \theta_{k+1} + (1-K) \cdot (\theta^{opt}_k \cdot u_k)$, *(6)*

$u_k = \eta(x_{k+1}) / \eta(x_k)$ *– for logarithmic and exponential functions.*

Here $0 \leq K \leq 1$ is filtering coefficient; θ_k^{opt} and θ_{k+1}^{opt} are current and next values of observations after filtering; θ_{k+1} is follow-up observation; u_k is parameter of the system change; $\eta(x_k)$ and $\eta(x_{k+1})$ are current and subsequent values of the function taken as theoretical; x_k is distance to the object.

In the iterative procedure, it is proposed to take as the initial value after filtering the observation itself, i.e. $\theta_1^{opt} = \theta_1$. Using the filtration scheme, it is possible to reduce the error variance by choosing the coefficient K, and using the methods LSM and LMM – to estimate the influence of the function $\eta_i(X)$ for its different types on the finite determined geometric parameters of the defects after applying the filtering algorithms to the measurements (Pic. 5).

With the help of the proposed filtering algorithm, taking into account the variation of the coefficients K, we obtain error distributions with a smaller variance in the analysis of the obtained functions, than without using a filter, that is, the estimate is more efficient, and therefore it can be concluded that the filter provides an opportunity to obtain a more accurate theoretical function. The minimum variance estimate is the estimate of LSM for the theoretical function is the function: $y_{calc} = a+b|\ln(x-x_0)|$, where a = 10,696, b = 93,122 for the filtering algorithm with a coefficient of 0,1.

Conclusions. *The increase in the informative value of the track state assessment according to the indications of geometric and optical means of monitoring of the track measuring car using the methods of statistical analysis makes it possible not only to increase the reliability of the assessment of a particular section, but also to solve other tasks of maintenance of the railway track. The determination of the duration of each emission, the interval between emissions and the variance of the errors that arise is directly related to the assessment of the amount of work to eliminate deviations from the standards for the maintenance of the track gauge and, first of all, the values of the shifts and lifts of the track and the volume of the rubble to be filled in case of schedule preventive smoothing. In this case, the most effective algorithms for statistical analysis of real measurements will work together with an algorithm for determining curvature parameters in terms of plan, elevation in level: the beginning (end) and length of transitional curves in plan and in level, radii and elevations in circular curves; unevenness in the longitudinal profile, which will solve the problem of calculating the required volume of crushed stone not only to eliminate the local unevenness of the track, but also to smoothly straighten out the track to the design position.*

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