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# Assessment of Locomotive Receivers' Sensitivity Using Test Loop with Crossing

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## ABSTRACT

*Main technical and operational characteristics of the locomotive receiver of the automatic locomotive signalling system, which is part of all types of core locomotive safety devices, comprise its sensitivity. This characteristic makes it possible to estimate by indirect methods the signal/noise ratio at the input of the locomotive receiver, and, therefore, to evaluate the noise immunity of its operation at the nominal parameters of amperage and current frequency of signals of automatic locomotive signalling system in the track circuit under operating conditions.*

*Thanks to correct adjustment of the sensitivity of the locomotive receiver, it is possible to significantly reduce the number of failures in operation of the main locomotive safety devices. Checking the sensitivity of the locomotive receiver and other parameters of safety devices is carried out at control points, usually equipped in depots, using stationary test loops that simulate the electromagnetic field generated by the signal current flowing in the track circuit. Sensitivity measurement results are influenced by various factors, primarily the position of the receiving coils along the test loop performed with crossings, as well as the distance between adjacent crossings. The influence of these factors may lead to the impossibility of checking the correct operation of locomotive safety devices at nominal signal parameters, as well as to an incorrect assessment of sensitivity.*

*The objective of this work is to evaluate the influence of these factors on the results of measuring the sensitivity of a locomotive receiver. A model developed as part of the work and based on the well-known methods of analysis and synthesis and the Biot−Savart−Laplace law describes the inductive connection «test loop−coil». Several characteristic dependencies have been also obtained. The results have been compared with the existing requirements for the position of the coils relative to the test loop performed with crossings.*

*To ensure the most accurate results of measurements of the sensitivity of the locomotive receiver, it is proposed to place the receiving coils of the locomotive safety devices at an equal distance from adjacent crossings of the test loop.*

*Keywords:* *railways, automatic locomotive signalling, safety devices, locomotive receiver, loop, crossing, control point.*

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## INTRODUCTION

Any system for managing or controlling train traffic has at least one channel for transmitting information from stationary or as they are otherwise called «track» infrastructure facilities to on-board equipment, that is «track–locomotive» channel. The network of Russian railways widely uses train traffic control systems which use inductive communication channels, where track circuits are used as signal transmission lines.

It should be noted that the deviation of the parameters of the «track–locomotive» channel from the nominal values can result in failures in operation of the systems under consideration and in the concomitant occurrence of abnormal states of the critical technological process of train traffic [1]. In this regard, highly important are the processes of maintenance and repair of equipment aimed at keeping the characteristics of the transmission channel «track–locomotive» in the range of permissible values [2]. The processes of maintenance and repair of automatic locomotive signalling equipment mounted on railway rolling stock are of particular interest. To assess its technical condition, in addition to the characteristics of each of the blocks, the technology for estimating which is described in the country in the Instruction No. L229[1], it is advisable to determine the level of noise immunity of the operation of the entire set of receiving equipment [3]. Direct calculation of this characteristic for locomotive receivers is not done since:

• Firstly, the dynamic range and frequency band of interference largely depend on the series of railway rolling stock units in operation, their operating modes, as well as other features of each section of railway lines [4].

• Secondly, such checks would take a long time (from several to tens of hours) since all possible combinations of interference and useful signals would have to be checked.

For this reason, the evaluation of noise immunity is carried out by indirect methods. On the one hand, the estimate can be implemented due to the peculiarities of the decoder algorithms [5]. On the other hand, the assessment can be carried out by measuring the EMF value at the input of the locomotive receiver, induced at the minimum possible current value in the inductive coupling line under operating conditions, leading to its emergence, and that is the sensitivity of the locomotive receiver [6]. The latter approach is the most widespread and is applied at specially equipped control points.

In most cases, control points are in the depot, where there is not always a technical or production possibility of organising testing of track circuits. Track circuits require a large amount of track equipment per one tested unit of rolling stock, in addition, they significantly reduce the processing capacity of production sites for maintenance and repair of traction rolling stock: one track circuit should be intended for one locomotive, while in most cases at a control point an average of three to five locomotives are serviced at the same time.

At control points, instead of track circuits, test loops are used which are the conductors laid in a certain way so that when an electric current of a given amperage and frequency flows through them, an electromagnetic field is formed around them, equivalent to the electromagnetic field of the track.

The use of test loops entails several obvious difficulties [7–9] related, among other things, to the need for the correct placement of onboard equipment for the period of testing.

There are works related to tentative assessments of the influence of the geometric position of the test loop on the magnitude of the magnetic field induction formed around it [10]. At the same time, despite a fairly detailed description of the features of the inductive connection of track circuits and stationary wires of loops with receiving coils of automatic locomotive signalling equipment in the sources [11–14], there are no works aimed at assessing the influence of the location of the receiving coils of the tested unit of railway traction rolling stock along the test loop or of test loop configuration (with or without crossing) on the measurement of the sensitivity of the locomotive receiver. In the specialised reference literature, in particular, in the Technical reference book of the railwayman[2], there are only mathematical expressions for estimating the magnitude of the

[1] Instructions for maintenance and repair of locomotive safety devices No. L229, approved by the Order of JSC Russian Railways dated March 12, 2019, No. 454/r (as amended by the Order of JSC Russian Railways No. 1677/r dated August 6, 2020). [Electronic resource]: consultantplus://offline/ref=3EFCC965A7D98E47C2DE4862AC4B7F4A77F3DBE093B33095DDE8542B41DB77AB46814B78A3F1C7BEDB0F3A7ACFDB53v2EAL. Last accessed 11.04.2022.

[2] Technical reference book of the railwayman. Vol. 8. Signaling, centralization, blocking, communication. Moscow, State transport railway publishing house, 1952, 976 p.

EMF induced in the receiving coil from a separate current-carrying conductor, that is from a rail. These expressions cannot be used to evaluate the effect of test loops on the measurement of the sensitivity of a locomotive receiver, since they do not consider either the presence of crossings in the latter, or the position of the receiving coils relative to the crossings.

It should be noted that foreign researchers also consider issues related to the operation of communication lines in automation and telemechanics systems on railways. At the same time, most modern research is devoted to the use of a radio channel. In [15], researchers analysed the effect of interference on the transceiver equipment of train traffic control systems based on a radio channel using numerical methods.

Issues related to the inductive channel of information transmission are considered much less often. Some of these works are related to the consideration of issues of electromagnetic compatibility of equipment with various sources of interference. So, the paper [16] presented the results of the analysis of the influence of traction current harmonics on the operation of the receiving equipment of track circuits. The work [17] considered issues related to the influence of contact wires on the communication lines of automation systems.

The work [18] using computer simulation made the assessment of the electromagnetic environment typical for electrified railway lines. It should be noted that to assess the distribution of current rates along the track section, the work used the provisions of the multiwire line theory, which is widely used by domestic specialists for the analysis of multiwire lines, including inductive coupling lines. However, the technique described in the work cannot be used in this study, because it does not allow evaluating the features of the «test loop–coil» inductive coupling.

See the above, the *objective* of this work is to evaluate the influence of the parameters of the test loop and of the position of the receiving coils along the test loop on the measurement of the sensitivity of the locomotive receiver. To achieve this objective, it is necessary to solve the following tasks:

• To develop a model that describes the process of signal transmission from an inductive communication line in the form of a test loop of arbitrary configuration and geometric dimensions to a receiving locomotive coil; at the same time, the model should answer the question: do the given parameters of the test loop and the geometric position of the receiving coils along the loop provide the possibility of measuring the sensitivity of the locomotive receiver and, if so, with what accuracy?

• To analyse the influence of the geometric position of the receiving coil along the test loop on the possibility and accuracy of measuring the sensitivity of the locomotive receiver.

• To compare the existing governing documentation and modelling results.

In carrying out this work, conventional *methods* of synthesis and analysis were used. When synthesising the model, the provisions of the classical theory of the electromagnetic field were used in terms of determining the magnitude of magnetic induction and Faraday's law. In addition, the well-known provisions of trigonometry are used.

The developed model accounts for the dimensions of the railway rails used, as well as for the current regulatory documents in the field of design and equipment of control points.

## RESULTS

### Model Building

The developed model should be aimed at studying the influence of the test loop parameters and the geometric position of the receiving coils of the tested unit of traction railway rolling stock relative to test loop. The model characterises the inductive coupling between the following objects: receiving coil and test loop.

Model parameters are:

• Number of crossings of the test loop $N$ (when the parameter is equal to zero, we assume that the test loop is made in the form of a single frame).

• Length of the inductive coupling line of the test loop $L_S$.

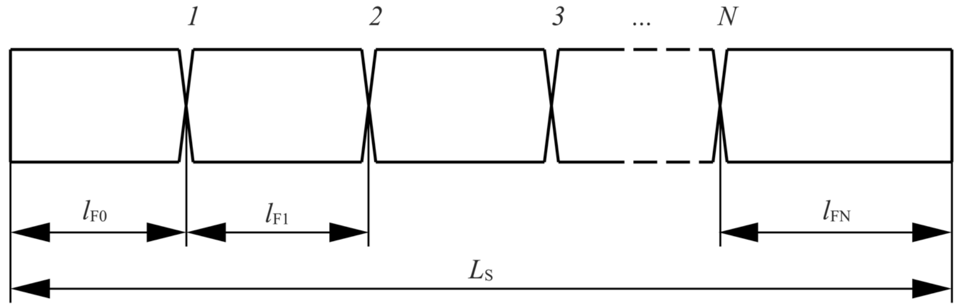
• Distance between the left edge of the test loop and the first crossing $L_{F0}$.

• Distance between the right edge of the test loop and the last crossing $L_{FN}$.

• Distance between adjacent crossings of the test loop $L_{Fs}$, where $s$ is natural number between 1 and $N-1$.

• Crossing numbered as $K$, behind which the receiving coil is located (counting is carried out from the left border of the test loop).

• Distance $l_K$ from crossing $K$ to the receiving coil.




*Pic. 1. Graphical representation of the essential parameters of the test loop model with crossings [performed by the authors based on the current regulatory documentation (Instruction 35002-00-00, 36090-00-00 MU)].*

• Height of the test loop relative to the level of the rail head $h_m$.

• Height $h_{r,k}$ of the suspension of the receiving coil $k$ relative to the level of the rail head $r$ (distance to the centre of the receiving coil core $k$).

• Geometric dimensions (height, width, length of the core, cross-sectional area of one turn $S_k$), core material (magnetic permeability of the core material $\mu_k$) of the receiving coil $k$.

• Number of winding turns of the receiving coil $N_k$.

All parameters characterising the geometric dimensions must be expressed in metres.

For understanding we offer a schematic illustration, which shows the essential geometric parameters of the test loop (Pic. 1).

The model is built based on the following assumptions:

1) The height of the suspension of the test loop relative to each of the running rails of the same track is the same; the height of the suspension of the receiving coils relative to the test loop is the same.

2) The EMF value induced in the considered receiving coil from the section of the test loop fixed on another running rail is equal to the value of the EMF induced from the considered section of the test loop in the other receiving coil (consequence from the first position) and therefore due to the counter sequential connection of the receiving coils each other may not be considered.

We will assume that the ideal conditions ensuring the maximum value of the EMF induced in the receiving coil are under the situation when the receiving coil is fixed over an infinitely long straight thin current-carrying conductor. Under such conditions, the sensitivity of the locomotive receiver can be determined with absolute accuracy. We will consider as real ones the conditions under which the EMF in the receiving coil is induced from a straight thin conductor of finite length with a current. The ratio of the EMF induced under real conditions ER to the EMF induced under ideal conditions EI will be considered as *the test loop efficiency factor* $K_E$ (1):

$$K_E = E_R/E_I. \qquad (1)$$

At this stage, the conceptual design of the model can be considered complete. Let's move on to the direct construction of the model, which is reduced to the estimate of the EMF values on the right side of (1). First, we write down the fundamental expressions connecting:

• The magnitude of the induction $B_{s,k}$ of the magnetic field in the core of the receiving coil $k$, formed by the current $I_s$ in the loop wire $s$, fixed on the rail $r$, with the height of the receiving coil suspension relative to the axis of the loop wire $A_{r,k} = h_m + h_{r,k}$ (2).

• The value of the magnetic field induction $B_{s,k}$ for the receiving coil $k$ from the loop wire $s$ with the geometric position of the receiving coil relative to the loop wire $s$ of finite length (3), as well as the value of EMF $E_{s,k}$ in the receiving coil $k$ from the loop wire $s$ with magnetic field induction (4):

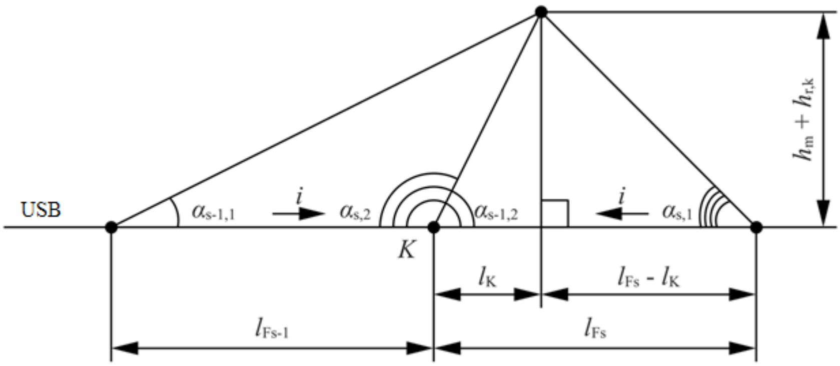
$$B_{s,k} = \frac{\mu_k \mu_0 I_s}{2\pi A_{r,k}}, \qquad (2)$$

$$B_{s,k} = \frac{\mu_k \mu_0 I_s}{4\pi A_{r,k}} \left(\cos\left(\alpha_{s,1}\right) - \cos(\alpha_{s,2})\right), \qquad (3)$$

$$E_{s,k} = -\frac{N_k d\Phi_{s,k}}{dt} = -\frac{N_k S_k \cos(\alpha_{r,k}) dB_{s,k}}{dt}. \qquad (4)$$

Substituting (2) into (4) and (3) into (4), we can obtain the final formulas for calculating the EMF in the receiving coil $k$ for an infinite length conductor (5) and a finite length conductor (6):

$$E_{s,k} = -\frac{N_k d\Phi_{s,k}}{dt} = -\frac{N_k S_k \cos(\alpha_{r,k}) dB_{s,k}}{dt}, \qquad (4)$$




*Pic. 2. Determination of cosine values for the model [performed by the authors].*

$$E_{s,k}^{MAX} = -\frac{\mu_k \mu_0 N_k S_k \cos(\alpha_{r,k})}{2\pi A_{r,k}} \bullet \frac{dI}{dt}, \quad (5)$$

$$E_{s,k} = -\frac{\mu_k \mu_0 N_k S_k \cos(\alpha_{r,k})}{4\pi A_{r,k}} (\cos(\alpha_{s,1}) - \cos(\alpha_{s,2})) \frac{dI}{dt}. \quad (6)$$

It was previously stated that the test loop most often has crossings. Then, when considering a loop laid along one rail, it should be divided into $N + 1$ sections − individual conductors, the direction of the current in any two adjacent sections will be opposite. To consider the direction of the current, we introduce the coefficient $k_s$ into formula (6), which we will consider equal to 1 if the current flows from left to right (Pic. 1) and -1 if the current flows in the opposite direction. It should be noted that the value of the EMF induced in the receiving coil, in accordance with the principle of superposition, is equal to the sum of the EMF from each of the conductors, therefore, the EMF $E^R$ obtained in real conditions can be obtained by formula (7):

$$E_{s,k}^R = \frac{\mu_k \mu_0 N_k S_k \cos(\alpha_{r,k})}{4\pi A_{r,k}} \frac{dI}{dt} \bullet \bullet \sum_{s=0}^{N} -k_s \bullet (\cos(\alpha_{s,1}) - \cos(\alpha_{s,2})). \quad (7)$$

Substituting (5) and (7) into (1), simultaneously reducing the parameters of the receiving coil $k$ (taking advantage of the fact that one and the same coil is considered, and the influence of its parameters on the possibility of measuring the sensitivity of the receiver is not considered in this work), we obtain the formula (8):

$$K_Э = \frac{1}{2} \sum_{s=0}^{N} -k_s (\cos(\alpha_{s,1}) - \cos(\alpha_{s,2})) \ . \quad (8)$$

Further work is reduced to determining the values of cosines. Let us consider two cases: connection of the coil with the section of the test loop, over which it is located, and connection of the coil with the section of the loop, over which it is not located (Pic. 2). The universal serial bus (USB) line in the figure corresponds to the laying level of the test loop.

Based on the above, we can write formulas for the cosines of the angle in general form as (9) and (10) as they are shown in the next page.

Combining formulas (8)−(10) into a system, we can consider the construction of the model to be completed.

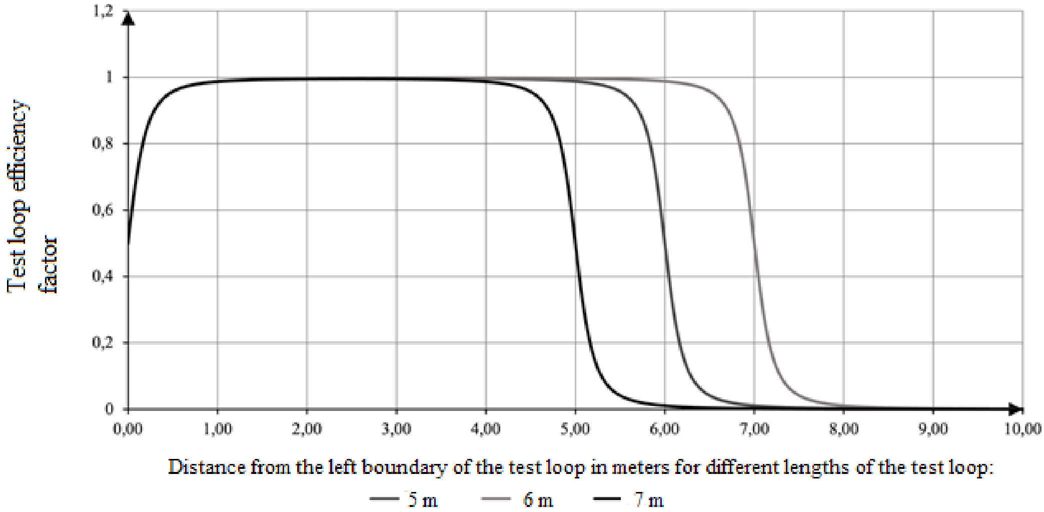
**Simulation Results**

Initially, we will simulate the efficiency factor for a test loop of arbitrary length without crossings. This is necessary to estimate the distribution of the efficiency factor along a part of the test loop between two adjacent crossings without considering the influence of adjacent sections of the test loop. To do this, we supplement system (8)−(10) with the following equation (11):

$$N = k = 0. \quad (11)$$

In addition, we will specify different lengths of the inductive coupling line of the test loop. Let $L_s$ take the values 4, 5, and 6 m. Let's plot the test loop efficiency factor without crossing (Pic. 3). The height of the receiving coil suspension relative to the level of the rail head is assumed to be 100 mm.

From the graphs it follows that the decrease in the efficiency of the test loop occurs only in the area near its boundary. At a distance of 1,1 m or more from the boundary of the test loop, the value of the magnetic induction generated by the test loop is at least 0,99 of the same value under

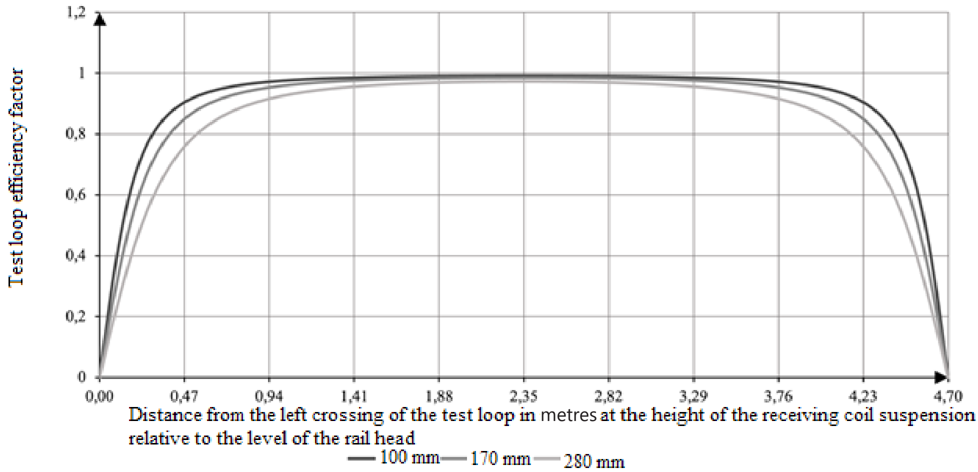



*Pic. 3. Dependence of the test loop efficiency factor on the location of the receiving coil above it [performed by the authors].*

$$\cos(\alpha_{s,1})=\begin{cases}\dfrac{l_k+\sum_{i=s}^{K-1}l_{Fi}}{\sqrt{\left(l_k+\sum_{i=s}^{K-1}l_{Fi}\right)^2+\left(h_m+h_{r,k}\right)^2}}, & if \quad s<K;\\[2ex] \dfrac{l_k}{\sqrt{\left(l_k\right)^2+\left(h_m+h_{r,k}\right)^2}}, & if \quad s=K;\\[2ex] -\dfrac{-l_k+\sum_{i=K}^{s-1}l_{Fi}}{\sqrt{\left(-l_k+\sum_{i=K}^{s-1}l_{Fi}\right)^2+\left(h_m+h_{r,k}\right)^2}}, & if \quad s>K;\end{cases} \tag{9}$$

$$\cos(\alpha_{s,2})=\begin{cases}\dfrac{l_k+\sum_{i=s+1}^{K-1}l_{Fi}}{\sqrt{\left(l_k+\sum_{i=s+1}^{K-1}l_{Fi}\right)^2+\left(h_m+h_{r,k}\right)^2}}, & if \quad s<(K-1);\\[2ex] \dfrac{l_k}{\sqrt{\left(l_k\right)^2+\left(h_m+h_{r,k}\right)^2}}, & if \quad s=(K-1);\\[2ex] -\dfrac{-l_k+\sum_{i=K}^{s}l_{Fi}}{\sqrt{\left(-l_k+\sum_{i=K}^{s}l_{Fi}\right)^2+\left(h_m+h_{r,k}\right)^2}}, & if \quad s>(K-1).\end{cases} \tag{10}$$

$$K_{\mathrm{E}}=\frac{l_\kappa}{\sqrt{\left(l_\kappa\right)^2+\left(h_m+h_{r,k}\right)^2}}+\frac{-l_\kappa+l_{F1}}{\sqrt{\left(-l_\kappa+l_{F1}\right)^2+\left(h_m+h_{r,k}\right)^2}}-\frac{1}{2}\left(\frac{l_\kappa+l_{F1}}{\sqrt{\left(l_\kappa+l_{F1}\right)^2+\left(h_m+h_{r,k}\right)^2}}+\frac{2l_{F1}-l_\kappa}{\sqrt{(2l_{F1}-l_\kappa)^2+(h_m+h_{r,k})^2}}\right). \tag{12}$$




***Pic. 4. Dependence of the test loop efficiency factor on the position of the receiving coil along the section of the test loop between adjacent crossings [performed by the authors].***

ideal conditions for a given height of the receiving coil. Note that the test loop efficiency factor when the receiving coil is placed outside it at a distance of at least 1,5 m from the boundary is practically equal to zero. This greatly simplifies the model and the reasoning associated with it. In any case, it will be sufficient to consider only three sections of the test loop: above which the receiving coil is directly located and two adjacent to it, provided that the length of the test loop $L_s$ >> 1,5 m (in practice, the minimum allowable distance between two adjacent crossings is 4,7 m according to table G.1 of Instruction No. 35002-00-00[3]). Then, assuming that all sections of the test loop have the same length lF1, system (8)−(10) can be written as a single equation in a simpler form (12).

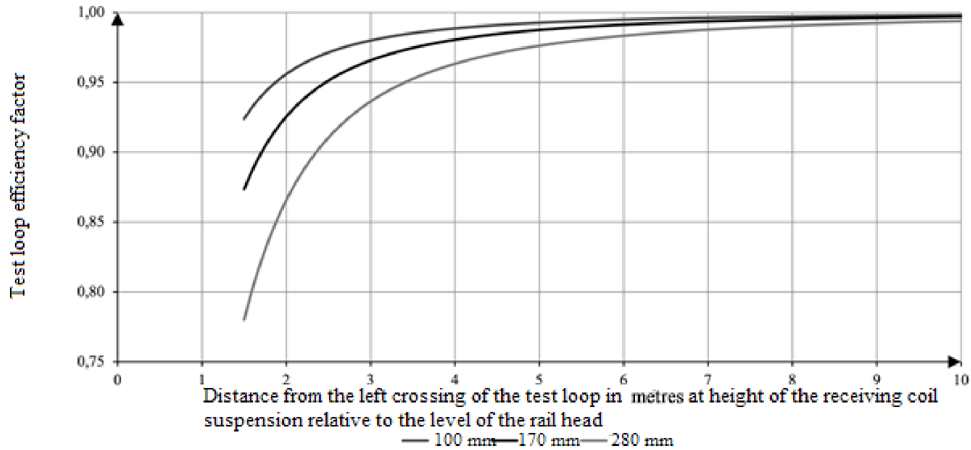
Further, regarding loops with crossings, we will operate only with formula (12). This will significantly reduce the number of calculations with a sufficient degree of accuracy for the study.

Let us consider the case when the lengths of all frames are the same and equal to the typical minimum possible value $L_s$ = 4,7 m in accordance with the requirements of Table G.1 of Instruction No. 35002-00-003 (Pic. 4). As we have already seen, with an increase in the length of the inductive coupling line, the test loop efficiency factor is approximately equal to 1 over most of its length. The worst operating condition will be the shortest possible distance between crossings.

The resulting picture allows us to judge the following. The lower is the height of the receiving coil suspension relative to the level of the rail head when using a loop with crossings, the smaller is the area near the crossings of the latter, in which the test loop efficiency factor changes significantly. With equal distances relative to adjacent crossings of the test loop, the test loop efficiency factor with the given length of the loop and the height of the receiving coil suspension is maximum (this statement can be quite simply proved by determining the maximum of the function defined by expression (12) with respect to $L_K$). Near the crossing points of the test loop, the test loop efficiency factor is sharply reduced due to the influence of the adjacent section of the test loop, which makes it impossible to measure the sensitivity of the locomotive receiver in this area at the rated current in the test loop. With this in mind, we will plot the dependence of the test loop efficiency factor when placing the receiving coil at an equal distance from its adjacent crossings (Pic. 5).

Considering the graphs presented in Pic. 5, it can be concluded that with a known allowable range of heights of the suspension of the receiving coils relative to the level of the rail head, when assessing the sensitivity of the locomotive receiver, it is necessary, firstly, to determine the required accuracy (it can be set by the test loop efficiency factor; characterises the difference between the obtained EMF measurement results induced in the receiving coils and the maximum possible values), and,

[3] Instructions for the equipment, maintenance and repair of test loops and track devices ALS control point ALSN No. 35002-000-00, approved by the Order of JSC Russian Railways dated July 12, 2021 No. 1510/r. [Electronic resource]: consultantplus://offline/ref=ACFC0F802E265D5609396C61FA2297645A36CD 753B15BBF0F0683C6B87B643E0101F73D15E3E927DF0C91393978316kCG2L. Last accessed 11.04.2022.




*Pic. 5. Dependence of the test loop efficiency factor on the distance between adjacent crossings of the test loop [performed by the authors].*

secondly, to determine the minimum distance between the crossings, at which the specified accuracy will be achieved when the receiving coil is placed symmetrically with respect to neighbouring crossings.

The results obtained allow us to analyse the existing standards established by various documents: clause 1.8.4 of the Guidelines 36090-000-00 MU[4] and clause 3.4.6.6 of Instruction No. 35002-00-003. From these regulatory documents it follows that «the receiving coils of a unit of traction railway rolling stock must be located no closer than 200 mm to the place of a test loop crossing». According to the simulation results at the indicated distance, the test loop efficiency factor is in the range from 0,45 to 0,67, therefore, the sensitivity of the locomotive receiver cannot be determined at the nominal values of the current in the test loop (the induced EMF will differ from the nominal value by almost two times).

To confirm the data obtained as a result of modelling, a full-scale experimental study is required to clarify the value of the test loop efficiency coefficient in the test loop crossing zone.

## CONCLUSION

Based on the results of the study, the following main conclusions can be formulated:

1. Based on the hypothesis that, depending on the position of the receiving coils along the test loop, the conditions for assessing the sensitivity of the locomotive receiver change significantly, a mathematical model was developed that allows modelling the value of the test loop efficiency factor depending on the position of the receiving coil and the parameters of the test loop. The model was developed in conformity with the requirements of the current regulatory documents for laying test loops.

2. Based on the simulation results, it was found that the lower is the height of the receiving coil suspension relative to the level of the rail head when using a loop with crossings, the smaller is the area near the crossings of the latter, in which the efficiency coefficient of the test loop changes significantly. The form of dependence of the test loop efficiency factor at its various lengths is the same and has the same characteristic points.

3. Based on a comparison of the simulation results with the current standards for placement of the receiving coils of the tested unit of traction railway rolling stock, their discrepancy was established. For the distance between the receiving coil and the crossing point of the test loop specified in the regulatory documents, the test loop efficiency factor is only 0,45–0,67, which does not allow providing conditions for assessing the sensitivity of the locomotive receiver. To obtain accurate results of assessing the sensitivity of the locomotive receiver, the receiving coils should be located at an equal distance from the crossing points, and the distance between the crossings of the test loop should be selected considering the previously accepted measurement accuracy.

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[4] ALS checkpoint. Guidelines for design and equipment. 36090-00-00 MU: Approved by the Deputy Head of the Signaling, Communications and Computer Engineering Department on 30.12.1996. Album 1. Total albums 2. Moscow, 1996, 24 p.

To clarify the simulation results, it is necessary to conduct appropriate experimental studies, that has already started to be developed by specialists from the Department of Railway Automation, Telemechanics and Communications of Russian University of Transport.

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