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# Errors in Measuring the Distance to an Obstacle by Technical Vision Means and in Forecasting Braking Distance in Driverless Train Control Systems

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## ABSTRACT

*Technical vision systems are sources of information about an obstacle on the track in the case of driverless train control. Based on the information received, the traffic control system decides to turn on the braking mode to prevent a collision with an obstacle.*

*In accordance with international and domestic expertise and standard ratings, it is necessary to ensure the probability of a dangerous failure, in this case, the probability of hitting an obstacle, not more than $10^{-8}$ with a confidence probability of 0,95 according to SIL-4 ([Russian state standard] GOST-R61508). Considering the presence of an error in measuring the distance to an obstacle by the technical vision system and an error in calculating the stopping distance, it is required to determine the coordinate of the braking start point when an object is detected on the track in such a way as to ensure that the train stops before the obstacle with a probability determined in accordance with SIL-4.*

*A feature of the problem being solved for estimating the errors in measuring the distance to an obstacle and calculating the stopping distance implies the need to determine the estimates of their maximum values and to develop an algorithm for using these estimates in such a way that the collision probability does not exceed the normalised value.*

*A technique is described for determining the maximum value of the error in measuring the distance to the obstacle, the probability of exceeding which is quite small (from $10^{-2}$ to $10^{-6}$). A proposed algorithm for multiple measurements of the distance to an obstacle allows choosing the minimum measurement result for deciding on the start of braking, which ensures meeting standard indicator of a probability of a train colliding with an obstacle according to SIL-4. A method for estimating the error in calculating the stopping distance has been developed, which, together with the algorithm of multiple measurements by the technical vision system of the distance to the obstacle, provides the standard indicator according to SIL-4. The need for the second channel of technical vision due to the presence of curves along the route is shown. The necessity of using algorithms for multiple measurements to an obstacle through the second channel located outside the train is also substantiated. It is noted that the methods described in this article for choosing the maximum values of random errors in measurements and calculations, the values of which can be exceeded with a very low probability, can be used to solve various applied problems of traffic control in transportation processes.*

*Keywords:* *transport, technical vision, error in measuring the distance to an obstacle, autonomous traffic control systems, calculation of the stopping distance, error estimation.*

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## INTRODUCTION

The most important function of an automatic intelligent transport system is the perception of the environment and the ability to detect the presence of obstacles, including in the process of movement as well [1–3]. Hence the main areas of application of technical vision are visual control and robotic vision [1; 4]. To solve the problems of detecting obstacles, many approaches are used in these areas. The most superficial approaches refer to «qualitative» algorithms, their feedback contains only «yes»/«no» answers regarding the presence of obstacles in the field of view [5]. Another common approach to obstacle detection refers to analytical and statistical methods that involve motion estimation and development of maps based on statistical information [6]. In recent years, most algorithms have begun to use stereo vision or 2D/3D sensor technology. Their main advantage is the ability to determine various parameters of the obstacle, for example, the height of the obstacle above the ground and the distance to it [5; 7; 8]. Stereo vision is based on spectral analysis methods [9], genetic algorithms and neural networks [10].

In driverless train traffic control systems, technical vision is used to prevent a moving train from colliding with an obstacle on the way [11]. The control device receives information about the distance to the obstacle and, at a fixed distance, generates a command to trigger an audible warning signal so that the obstacle is removed. In the case that the obstacle is at a distance equal to the distance of the service brake application (or emergency stopping), a braking start command is generated. The objective of safe control is to ensure that the train stops before the obstacle. The moment of formation of the braking command is selected from the condition of equality of the calculated stopping distance $S_{stop}$ of a train moving at a speed V to the distance measured by the vision system to the obstacle:

$$S_{stop}(V) = L_{measur}. \quad (1)$$

At the same time, the calculated value of the stopping distance $S_{stop}(V)$ may differ from the real one due to the always existing simplifications in the train model used in the calculation, to the presence of random perturbations that lead to a change in the resistance to train movement, to errors in setting track's horizontal alignment and profile in the zone of movement, etc. Measuring the distance to the obstacle in the technical vision system is also implemented with a random error.

Let $\Delta S_{stop}(V)$ and ΔL are absolute errors in calculating the stopping distance and measuring the distance to the obstacle, respectively; $S_{0stop}(V)$ and $L_0$ are the actual values of the stopping distance and the distance to the obstacle, respectively. Then, proceeding from the safety condition, the choice of the braking start moment is determined as:

$$S_{0stop}(V) = L_0, \quad (2)$$

and the expression (1) is transformed as follows:

$$S_{0stop}(V) + S_{stop}(V) \le L_0 + \Delta L. \quad (3)$$

From the point of view of traffic safety, the worst situation is when $\Delta S_{stop}(V) < 0$, $\Delta L > 0$, i.e., if condition (1) is met, while the calculated stopping distance is less than the really accomplished one, and the measured distance to the object is greater than the real one, the train will collide with an obstacle. Hence, the upper estimate of the probability of a collision between a train and an obstacle, given the distribution laws of the probability density of random variables $\Delta S_{stop}(V)$ and ΔL(L), with known V and L, is:

$$P_{col}(V,L) = \int_{-\infty}^{0} f(\Delta S_{stop} | V)\, d\,\Delta S_{stop}(V) \int_{0} f(\Delta L | L)\, d\,\Delta L, \quad (4)$$

where $f(\Delta S_{stop}|V)$ and $f(\Delta L | L)$ are distribution functions of conditional probability densities $\Delta S_{stop}(V)$ and ΔL(L). This estimate can be adjusted by determining, with known probability density functions of statistically independent random variables $\Delta S_{stop}|V$ and ΔL(L), the probability density distribution function φ(z) of the random variable $Z = \Delta S_{stop} + \Delta L$ at fixed V and L.

Then:

$$P_{col} = \int_{0}^{\infty} \varphi(z|V,L)\, dz.$$

This value can be estimated again from above:

$$P_{max.col} = \max P_{col}(V, L). \quad (5)$$

Determining the probability density distribution functions based on the results of processing the results of numerous calculations and measurements, when estimates of the probability of a dangerous situation of the order of $10^{-4}$–$10^{-8}$ are significant, require high reliability in the description of the «tails» of distributions, which is known to be difficult. Therefore, in this work, while the objective was to solve the problem of evaluation of the errors of measuring the distance to an obstacle and of stopping distance, to determine estimates of their maximum values and to develop an algorithm to use this estimate so that the probability of collision does not exceed the standard value, we have used a different method for solving the problem.

To reduce the probability of a train collision with an obstacle, a well-known technique can be used, replacing the expression in the conditions of generation of a command to start braking by the following:

$$S_{btop}(V) + \Delta S_{max} = L_{measur} - \Delta L_{max}, \quad (6)$$

where $\Delta S_{max} = \max \Delta S_{stop}(V)$ is the maximum value of the modulus of negative calculation error and $\Delta L_{max} = \max \Delta L_0(L)$ is the maximum value of positive measurement error.

In substance, this condition determines the length of the «protective section of the track» in front of the obstacle, which, as will be shown below, will be able to ensure the required safety indicator. At the same time, determination of the values $S_{stop\ max}$ and $\Delta L_{max}$ is also associated with probabilistic estimates of these values, which, in turn, determine the estimate of the probability of a train colliding with an obstacle. A feature of solving this problem is that the admissible safety estimates are determined by very small values.

The choice of the maximum values of random variables with always existing constraints on the number of trials is a task of probability theory and mathematical statistics. A feature of using this mathematical apparatus for the problem being solved is the small admissible probability of exceeding by the value of a random variable of its chosen maximum value [12].

Under conditions when the length of the protective section is chosen equal to $S_{max} + \Delta L_{max}$, a collision is possible when the sum of the errors exceeds the sum of the maximum values of these errors, selected with a calculated probability at a fixed confidence interval. Therefore, the probability of a dangerous situation $P_{max\ col}$ can be subject to upper estimate as the product of the probabilities of events $\Delta S_{btop}(V) > S_{max}$ and $\Delta L(L) > L_{max}$:

$$P_{max\,col} < P\left[\left(\Delta S_{brake}(V)\right) > \Delta S_{stop\,max}\right] \cdot \cdot P\left[\Delta L(L) > \Delta L_{max}\right]. \quad (7)$$

It should be noted that the problem of choosing the length of the «protective» section according to the given admissible probability of a dangerous event also requires its solution when analysing systems for ensuring man-driven train traffic safety on hauls [13].

## RESULTS

### Method for Estimating the Maximum Measurement Error

Let us consider an approach to estimating the maximum error $\Delta L_{max}(L)$ when determining the distance between a moving train and an object on the track. Knowing the maximum error allows choosing the starting point of braking of a moving train, which ensures, with a given normalised probability, that the train does not collide with an obstacle. Information about the random value of the distance measurement error is contained in the distribution law of the probability density of this value, obtained from the results of statistical processing of experimental data [14]. Since the probability of an outcome is allowed with a probability of $10^{-8}$ (within Safety Integrity Level-4, SIL-4), then determining the probability of the maximum error value under these conditions corresponds to the «tails» of the distribution. An approximate method for determining the confidence interval for a probability based on replacing the frequency distribution law with a Gaussian one is not applicable, since the probabilities are very small. Under these conditions, the following method can be used [12]. Let, following $n$ experiments, the value of the error $\Delta L_{max}$ has never been fixed. We denote this event as $B$. It is required to find the maximum value of the probability that $\Delta L > L_{max}$, which is compatible with the event $B$ observed in the experiment.

Let us introduce the notation: $p$ – the probability that $\Delta L > \Delta L_{max}$, $p_m$ – the maximum value of $p$. The confidence interval range for $p$ is $0 \le p \le p_m$. Those values of $p$ for which the probability of the event $B$ is less than $\lambda = 1 - \beta$, where $\beta$ is the confidence interval, are incompatible with the event observed in the experiment.

For any probability $p$, the probability that for $n$ measurements there was no result $\Delta L > \Delta L_{max}$ is determined by the expression $P(B) = (1 - p)^n$. For $P(B) = \lambda$ we get the equation for $p_{max}$:

$(1 - p_{max})^n = 1 - \beta$.

Hence:

$$p_{max} = 1 - \sqrt[n]{1-\beta}. \quad (8)$$

Given the admissible probabilities that the error $\Delta L \ge \Delta L_{max}$ and the confidence interval $\beta$ it is possible to obtain from (8) what number ($n$) of experiments in which the event $\Delta L > \Delta L_{max}$ has never been observed, should be carried out to consider the value of $p_{max}$ not contradicting the results experiment:

$$n = \frac{\lg(1-\beta)}{\lg(1-p_{max})}.$$

The results of calculating the number of experiments with rounding to a larger integer for $\beta = 0{,}9; 0{,}99; 0{,}999$ and $p_{max} = 10^{-2}; 10^{-4}; 10^{-6}$ are summarised in Table 1.

**Table 1**

**The number of experiments (*n*) to determine $p_{max}$ with the set confidence interval [developed by the authors]**

| $p_{max} = 10^{-2}$ | | $p_{max} = 10^{-4}$ | | $p_{max} = 10^{-6}$ | |
|---|---|---|---|---|---|
| *n* | β | *n* | β | *n* | β |
| 229 | 0,9 | 23025 | 0,9 | 2302534 | 0,9 |
| 459 | 0,99 | 46050 | 0,99 | 4605168 | 0,99 |
| 688 | 0,999 | 69075 | 0,999 | 6907752 | 0,999 |

As follows from the data in the Table 1, it is advisable to conduct a number of experiments to select $\Delta L_{max}$ at $p_{max} = 10^{-2}$ at β = 0,9; 0,99; 0,999 and to justify safety conditions by choosing an algorithm using the value of $\Delta L_{max}$ at $p_{max} = 10^{-2}$.

Let the distance to the obstacle be measured twice at some point of the track: the first time the result of measurement is $L_1$, the second time the result of measurement is $L_2$. In each of these results, the probability that the measurement error exceeds $\Delta L_{max}$ is $p_{max} = 10^{-2}$ at a fixed confidence interval. Then the probability that in both cases the error exceeds $\Delta L_{max}$ is $p_{max} = 10^{-4}$. If we select the smallest value out of $L_1$ and $L_2$ and use this value to make a decision on braking, we can already justify the choice of $\Delta L_{max}$ with a probability of exceeding $10^{-4}$. Similarly, when using three measurements, $p^3_{max} = 10^{-6}$. To meet the requirements of SIL-4, the number of measurements is 4. Thus, using several measurements distributed over time in decision making reduces the likelihood of a dangerous situation. Obviously, knowing duration of one measurement and speed of a moving object, the value of $\Delta L_{max}$ increases by the length of the distance travelled by this object during *k* measurements.

Let's consider an example. Let it be known that as a result of 459 tests, the maximum error did not exceed 20 % of the measured distance. The maximum measurable distance is 2 km. Then $\Delta L_{max} = 400$ m and the probability that the error will exceed this value in accordance with the data in Table 1 with a confidence interval of 0,99 is $p_{max} = 10^{-2}$. If we choose the smallest of the values out of the results of three measurements, then the probability that $\Delta L_{max} > 400$ m is $10^{-6}$. Obviously, in this example, the maximum measurable distance exceeds the stopping distance of the train moving at the maximum allowable speed.

An additional way to reduce the probability of collision is to use the second measurement channel. In this case, the minimum measured distance to the object is selected out of multiple measurements through each of the channels. Let, for example, through each of the two channels, the results of two measurements are used at $p_{max} = 10^{-2}$. Then the choice of $\Delta L_{max}$ is ensured with the probability that the real error will exceed $\Delta L_{max}$ is $10^{-8}$.

It should be noted that the presence of the second technical vision channel, the equipment of which is located outside the train, is also necessary because on-board devices do not see obstacles if there are curves on a section. In this case, the admissible probability of a dangerous situation should be provided by the algorithm described above with *k* measurements through the second channel.

## Estimates of the Maximum Error in Calculating the Train Stopping Distance

A significant number of experimental and theoretical studies have been devoted to the analysis of the accuracy of target braking. Theoretical studies, as a rule, used mathematical modelling, in particular, simulation methods. In these studies [14–17], the train was simulated through its well-known mathematical models used in traction calculations, when analysing the braking process in long-haul heavy trains with distributed traction. Various control laws were modelled, implemented in the feedback of target braking systems belonging to the class of terminal systems [14–16; 18]. Target braking systems ensured that the train stopped with a given accuracy at a certain point on the track. Particularly high requirements are placed on such systems regarding metro, when it is required to stop the train in front of a fixed point with an error not exceeding 20 cm. It is required also to ensure minimum braking time since if this time is 1 sec longer within the set travel time along the haul, it increases the energy consumption for traction by about 1 %. On mainline railways, a similar error can attain 5 m. In traffic safety systems, in which the task of «avoiding a collision with obstacles» is solved, it is required, first, when an obstacle is detected, to ensure that the train stops before this obstacle, possibly even at a reasonably acceptable distance.

Target braking systems must provide a given stopping accuracy regarding a variety of track profile types located in front of the stopping point.

In some situations, it becomes necessary to apply emergency braking system. In this case, the maximum permissible braking force is used, the control system becomes open-loop system. The main requirement is to ensure the minimum length of the stopping distance.

To consider the influence of disturbances on the magnitude of the error in implementation of a given stopping distance, simulation methods were used, in particular, the method of statistical tests (Monte Carlo method). At the same time, a random value of the error of the measured speed used in the feedback of the target braking comparison system, random deviations of the value of additional resistance to movement from the calculated one are simulated. It should be noted that the additional resistance to movement, as a rule, is much less than the braking force, and its variations have an undesirable effect on the accuracy of the target stopping. In statistical modelling, different sets of track profile and horizontal alignment are selected. In the problem considered in this article, it is possible to set the «worst» track profile from the point of view of safety conditions. This reduces the amount of statistical testing.

When choosing stochastic models of random variables, there is always the question of substantiating not only their probability density distribution functions, but also of substantiating the range of changes in these variables. In particular, the range of change in the speed measurement error can be selected from the technical characteristics of the measurement channel, determined by the manufacturer under the conditions of using devices in good condition. At the same time, it is necessary to stipulate the measures regarding possible involvement of anomalous errors and the set of measures to parry them. For example, they may include the presence of several measurement channels and methods for diagnosing these channels, the presence of anti-skid systems, methods for adjustment of the measured path travelled by the train, etc. It should be noted that the existing experience in the operation of automatic target braking systems, many years of experience in comparing real parameters of train movement with the results of traction calculations, indicate the adequacy of models describing the movement of a train to real processes. The existence of instructions and rules for traction calculations, verification of the software for these calculations, allows us to consider these models as digital twins of trains.

We will consider the normal value of the stopping distance calculation result to be the value obtained under the assumption that all parameters of the mathematical model are determined accurately. The stopping distance calculation error is the difference between the nominal value and the braking distance calculated when the model parameters deviate from the given ones. Let us present the results of the analysis of the influence of measurement errors in the speed measurement channel on the magnitude of the error in calculating the stopping distance [15]. In simulation experiments, it is assumed that the maximum error in measuring the train speed does not exceed a tenth of the current speed value, the probability density distribution function of a random variable is the law of uniform probability density with zero mathematical expectation. Then:

$$\Delta V = 0{,}1V(rnd(2) - 1), \quad (9)$$

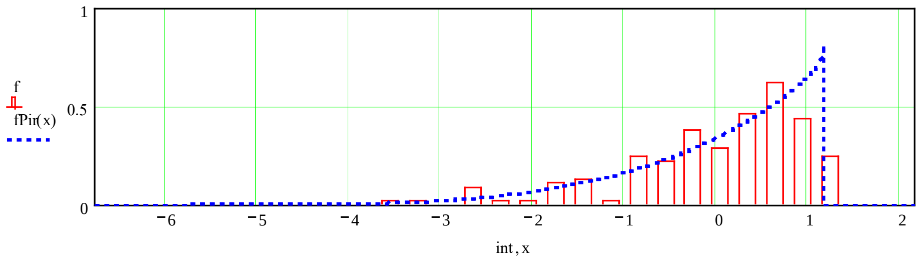
where $V$ is train speed; $\Delta V$ is speed measurement error;

*rnd(2)* is a function to generate evenly distributed numbers in the range from 0 to 2.

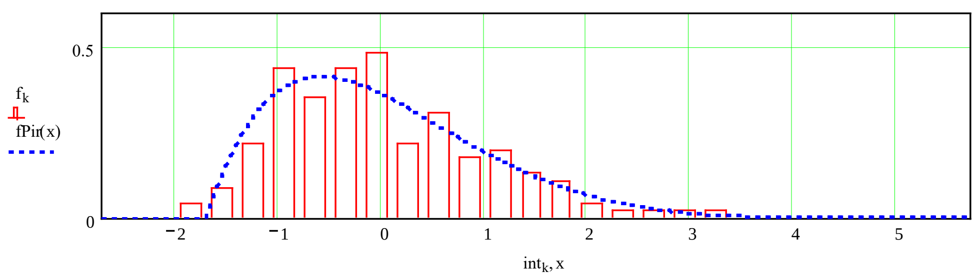
The results of simulation experiments were obtained for suburban train models equipped with braking control systems with different control laws [15; 16].

For each of these models, based on the results of at least 200 simulation experiments, histograms of the relative error frequencies were constructed (Pics. 1; 2), the distribution laws for probability density of errors in the calculation of the stopping distance were proposed; in accordance with the Pearson criterion $\chi^2$, it was shown that the chosen laws of density distribution of the probabilities do not contradict the results of the experiment.

The resulting statistics is described by the Pearson type I distribution. When building a braking control system based on acceleration [16], the experimentally observed range of measurement errors in calculating the stopping distance was $-3m \le \Delta S_{stop} \le 1{,}5$ m; when building a braking control system based on speed [15] it was $-2m \le \Delta S_{stop} \le 3{,}5$ m. The number of simulation experiments carried out and sufficient to determine the distribution law of the probability density of a




*Pic. 1.*




*Pic. 2.*

random variable of the error in calculating the stopping distance does not allow us to assert with the necessary probability required by international standards that the random variable is within this range. Therefore, it is additionally necessary to increase the number of simulation experiments in accordance with the data in Table 1, for example, to increase their number to 229, to state with a probability of $10^{-2}$ and a confidence interval of 0,9 that the maximum modulo value of the negative value of the error in calculating the stopping distance will not exceed 3 m (Pic. 1) when using speed braking control systems. For the same statement with a probability of $10^{-4}$ and a confidence interval of 0,9, it is necessary (see Table 1) that 46050 simulation experiments are carried out.

To reduce the number of experiments, another approach is possible, also using modern computer technology. With a known mathematical model of the object, it is required to solve the optimisation problem of minimising the module of the negative value of the error in calculating the stopping distance for given areas of determination of variables that affect the results of the calculation. This approach, due to the limited volume, is not considered within the scope of this article.

The set of results that allow, with a given probability, to determine the limiting values of the error in measuring the distance to an obstacle and predicting the stopping distance, make it possible to develop algorithms for operation of the safety system and to justify its compliance with international requirements.

## CONCLUSIONS

1. When building driverless traffic control systems, it is necessary to ensure that the train stops in front of an obstacle that appears on the way. This function must be implemented with a probability close to one. In accordance with international standards, the permissible probability of a dangerous situation is $10^{-8}$ for SIL-4. Technical vision systems are used as an obstacle sensor. To fulfil the required safety conditions, it is necessary to use the algorithm of multiple measurements of the distance to the obstacle with the choice of the minimum measurement result to decide on the start of braking.

2. Given the presence of curves along the route, which leads to the impossibility of indicating an obstacle by the onboard technical vision system, it is necessary to have the second vision channel with equipment located outside the locomotive. It is also necessary to use multiple measurements of the distance to the obstacle through this channel.

3. The choice of the number of measurements through each channel to justify the unconditional

fulfilment of the safety indicator is not carried out according to the methodology considered in this paper.

4. The length of the protective gap in front of the obstacle is equal to the sum of the maximum modulo value of the negative error in calculating the stopping distance and the maximum value of the positive value of the error in measuring the distance to the obstacle. The choice of these values is determined by the requirements of unconditional fulfilment of safety standards.

5. The methods under consideration for choosing the maximum values of random errors in measurements and calculations, with a very low probability to exceed their values, corresponding to the «tails» of the probability density functions, can be used in solving various applied problems of traffic control in transportation processes.

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