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Video Surveillance Systems for Railway Transport

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ABSTRACT

The article is devoted to analysis of ways to increase train traffic safety. One of ways to reduce accident rate on railways is timely detection of dangerous objects and notification of all traffic participants, primarily, the driver. Such a notification can be performed with the help of intelligent video surveillance system (IVS). The objective of the article is to study the possibility of using IVS to increase train traffic safety. Method (way to achieve the objective) consists of several stages: development of criteria of compliance of functional possibilities of IVS with tasks to increase train traffic safety, assessment, and calculation of permissible values of fitting criteria.

The work suggests a scheme of organization of IVS based on fiber-optic data transmission system (FOTS) and data transmission network, highlights advantages and disadvantages of IVS, formulates requirements for IVS.

Advantage of video surveillance is availability of video information about an object to a train driver, which allows to timely prevent an accident. Disadvantage of IVS is high probability of false detection, which can lead to false triggering of a system.

To reduce the number of false triggering there are two ways: improvement of algorithms of video analytics in recognition device (RD) and increase of quality of video signals at the input of RD. The work is devoted to reduction of probability of false triggering due to improvement of communication quality. It is noted that an efficient method is the use of a new element base of electronics based on nanostructured materials. These materials allow to improve optoelectronic characteristics of main elements of IVS which are photosensors and photoreceivers.

Keywords: transport, traffic safety, video surveillance, video analytics, photosensor, digital noise, detection error, optoelectronics, error probability.

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Background. Railway around the world is recognized as the safest mode of transport. However, accident statistics are high [1]. The most frequent consequences of accidents are vehicles and pedestrians are hit by rolling stock. This occurs in places where there are no railway guards, especially in high-speed sections, as well as at crossings due to violations of the rules for crossing the railway [2].

There are several cardinal ways to prevent accidents at level crossings: eliminating a single-level intersection of a railway track and a road; reduction in the number of crossings; timely warning of drivers about an approaching train, and, in case of a dangerous situation, timely detection of foreign objects and notification of special railway services and, above all, the train driver of an approaching train [3; 4].

The first option is very costly, and its use is justified only for railways with heavy traffic. The second option worsens social and transport infrastructure, communication between nearby settlements. The third way which is to timely notify all traffic participants is the most appropriate. Such a notification can be implemented using the technical means of intelligent video surveillance systems (IVS) [5, pp. 40–44].

The main idea of the «smart crossing» concept is creation of an intelligent monitoring system that can detect potentially dangerous objects, track movement of an object in a given observation zone and inform about the presence of a potential threat all the participants in the transportation process, especially the driver.

In the past few years, work has been carried out on the railways of the European Union, Japan, and North America to improve existing warning systems at level crossings by introducing advanced communication technologies, video surveillance and image processing. That concept is usually called «smart railroad crossing» [6].

For example, in the United Kingdom, Network Rail, with participation of telecom operators Amplicon and TEW Plus Ltd, is introducing a video surveillance system that automatically scans and detects obstacles at the crossings [7].

In the EU, in the framework of SELCAT (Safer European Level Crossing Assessment and Technology) project aimed at minimizing the impact of the human factor as the main cause of accidents, a strategy has been formed to control and reduce risks at crossings. The proposed solution is to detect obstacles (at the crossing) through the use of video analysis technology. This solution integrates other modern technologies, such as the use of satellite communications and radio transmission systems.

An example of the use of this technology is Germany: a camera with the function of internal video analytics is installed at level crossings. The incoming information is processed by the dispatcher, who can prohibit train passage if an obstacle is detected. One of the manufacturers who developed such a security system is Alstom [8].

JSC Russian Railways also implements advanced digital technologies. So in 2019, a long-term holding company development program was adopted, providing for transition to the Digital Railway. The concept of the Digital Railway is complete integration of intelligent communication technologies amidst a user, a vehicle, traffic control system and infrastructure [9].

Video surveillance is widely used at railways in the Russian Federation and abroad for various purposes, the main of which is protection of facilities. The function of improving train traffic safety differs in criteria and assessment of IVS efficiency.

The introduction of new warning systems is a promising area for improving traffic safety.

Objective and method

The *objective* of this work is to consider the possibility of using video surveillance systems to improve traffic safety. The *method* for solving this problem consists of several stages:

1) development of criteria of compliance with IVS objectives to improve traffic safety;

2) development of methods for assessing compliance criteria;

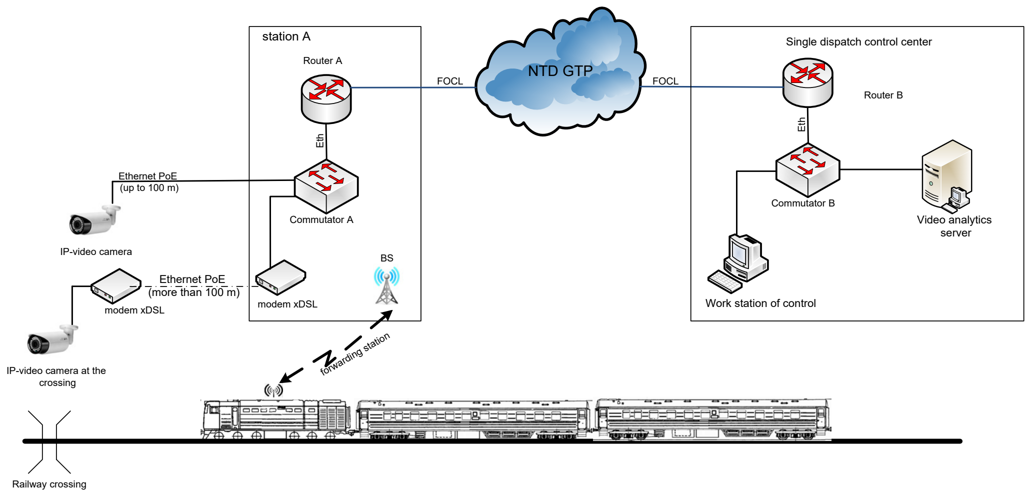
3) calculation of acceptable criteria values.

The article proposes two criteria of compliance of IVS with the objectives of improving railway safety:

1) video signal quality;

2) accuracy of the information received.

The first criterion characterizes the communication channel and is estimated by the reduced dispersion of total error δ^2_ε. The



Pic. 1. Organization of IVS on railway transport.

second criterion characterizes IVS recognition algorithms (video analytics) and estimates the probabilities of correct and false detections.

Such an assessment of compliance criteria is consistent with functional safety indicators for railway transport (GOST [State standard] 33358-2015 «Control systems and provision of train traffic safety»).

To calculate the acceptable values for assessing quality and reliability of IVS signals (criteria), the concept of loss function (the amount of economic damage that occurs as a result of missing or false detection of a dangerous object) is introduced.

Results.

The option of organizing an intelligent video surveillance system in railway transport

The simplest IVS provides for: installing video cameras at level crossings, transmitting a video signal to a video server of a single dispatch control center (SDCC), identifying dangerous objects using video analytics, transmitting braking commands to a locomotive from SDCC through train radio communications (TRC). The organization of IVS is shown in Pic. 1.

As a network infrastructure, a network for transfer of data of a general technological purpose (NTD GTP) of JSC Russian Railways was used. NTD GTP OTN meets the bandwidth requirements for communication channels. NTD GTP is a data transmission network based on TCP/IP protocol. As guide lines from the network element to the video camera at the object of observation, it is possible to use a copper core cable, or fiber optic communication line (FOCL). In case of connecting via a copper cable over a distance of more than 100 m, the use of xDSL modems (digital subscriber line) is required. It is possible to supply power to video surveillance equipment using Power over Ethernet (PoE) technology [10].

The advantage of video surveillance is the availability of video information about the object for the train driver, which allows to prevent an accident in a timely manner. However, IVS systems have a significant drawback: a high probability of false detection $P_{fal.det.} \geq 10^{-3}$, which can lead to unreasonable emergency braking commands and, as a result, to grave consequences in the form of passenger injuries, disruption of train schedules, etc. One of the reasons for false detections is insufficiently high quality of digital video signal formation [11, pp. 24–29].

There are two ways to reduce the number of false triggering: improving video analytics algorithms in a recognition device (RD) and improving quality of video signals at the input of RD. The work is devoted to reducing the likelihood of false triggering by improving quality of communication. The insufficiently high quality of digital video signal generation has a significant impact on recognition efficiency of dangerous objects. Therefore, the main tasks associated with implementation of IVS are to assess quality of video signal transmission and develop ways to reduce the likelihood of false detection.

The most effective way to reduce the probability of false detection is to use a new element base of electronics on nanostructured materials, which will significantly improve the optoelectronic characteristics of photosensors (PS) and photoreceivers (PR). It should be noted that when using fiber-optic information transmission systems (FOTS) as the communication lines, video signal distortions due to chromatic and polarization dispersions (subject to constant monitoring) are two orders of magnitude lower than from PS and PR [12].

The main areas of research

The solution of the task consists of several stages:

1) selection and justification of criteria for assessing conformity of quantitative and qualitative characteristics of IVS to safety requirements in railway transport. As a loss function, the economic losses of railways due to accidents at crossings have been selected, which made it possible to obtain acceptable values of $P_{fal.det}$, $P_{cor.det.}$;

2) development of methods for assessing quantitative and qualitative indicators of IVS efficiency in railway transport;

3) determination of permissible values of IVS functioning indicators based on working conditions of railway transport and taking into account loss function;

4) development of proposals to improve IVS efficiency (due to element base of electronics of new generation on nanostructures);

5) calculation of merit value in terms of indicators of IVS efficiency assessment (reduced dispersion of total error and probability of correct detection) for two element bases: microelectronics and nanoelectronics.

The implementation of each stage is based on studies of the features of operation of PS and PR, their optoelectronic characteristics and the effect of semiconductor material on them.

Criteria for assessing IVS efficiency for railways

As criteria for IVS efficiency to increase train traffic safety, one should choose an indicator of quality of video surveillance signals (ratio of signal and noise powers) and a reliability indicator estimated by the probability of correct detection of dangerous objects.

To analyze IVS efficiency, it is necessary to develop the following methods:

1. *Method for calculating the quality indicator*, which includes:

1) assessment of quality of SIV signals using the reduced total dispersion of current error δ^2_{ε}, which takes into account signal distortion by a photosensor, a communication line, and a photoreceiver (reciprocal of the signal-to-noise ratio);

2) assessment of quality of IVS signals at the photosensor output using the reduced dispersion of anomalous error δ^2_{ps}, arising from internal noise of pixels;

3) assessment of quality of IVS signals at the PR output using the reduced dispersion of anomalous error δ^2_{an}, arising from the thermal noise of the photoreceiver.

2. *Method for calculating the reliability indicator of IVS signals* using the probability of correct detection of $P_{cor.det.}$, carried out on the basis of the Neumann–Pearson criterion.

3. *Method for substantiating proposals to improve quality and reliability of IVS signals* through the use of a new element base using nanostructured materials, which involves finding solutions to the following problems:

1) designing a new semiconductor material with specified optoelectronic characteristics;

2) calculation of performance indicators of a new material on bulk crystals (microelectronics) and quantum structures (nanoelectronics) in the form of quantitative estimates of increase:

a) light absorption coefficient;

b) quantum efficiency;

c) sensitivity;

d) signal/noise ratio;

3) estimates of improving quality of IVS signals due to the new semiconductor material in the form of calculations:

a) probability of error P_{er} at the output of PR;

b) merit value in the parameter δ^2_{an};

c) merit value in the parameter δ^2_{ps};

d) merit value in the parameter δ^2_{ε} for the worst conditions (s/sh).

4) estimates of increasing reliability of IVS signals due to new material by calculating the probability of correct detection $P_{cor.det.}$.

Justification of loss function

As a function of losses, the amount of economic damage that occurs as a result of missing or false detection of a dangerous

Table 1

Economic damage from a railway crossing accident

Train hitting an object as a result of missing a dangerous situation		Emergency braking due to false detection of an object	
Description of incident consequences	Description of expenses	Description of incident consequences	Description of expenses
1. Severe or slight injury to a person. Death of a person	a) treatment in a hospital; b) rehabilitation; c) payment of disability benefits or compensation to the family of the deceased	1. Severe or slight injury to a person	a) treatment in a hospital; b) rehabilitation; c) payment of disability benefits
2. Complete loss or damage of an economic object (for example, a car)	Cost of an economic object, cost of repair, cost of disposal, insurance compensation	2. Damage to the internal equipment of cars, structural elements of braking systems, etc.	Cost of repairing damaged equipment of cars and a train as a whole
3. Violation of train schedule	Damage from violation of production relations of enterprises using the services of the transport system; damage from a decrease in efficiency of the transport system	3. Damage to cargo (baggage)	Cost of cargo (baggage), insurance compensation
		4. Violation of train schedule	Damage from violation of production relations of enterprises using the services of the transport system; damage from a decrease in efficiency of the transport system

object is accepted. The analysis of all possible emergency situations at crossings regarding calculation of the probabilities of missing and false detection showed that the most dangerous cases are when the signal from IVS arrived (or did not arrive) at the moment when braking is possible only in emergency mode. Emergency braking is a special process that is strictly regulated by service instructions [13].

When a false signal is received from IVS about the presence of a dangerous object, the driver applies emergency braking. If the system passes a dangerous object, the driver does not have information about the situation at the crossing and cannot immediately turn on emergency braking and, as a result, the object collides. When approaching an object, the braking process takes place in another safer mode for passengers.

Table 1 provides a description of dangerous cases with rolling stock in the form of collisions and emergency braking as a result of which the railway will incur large economic losses [14, pp. 12–13].

Maximum probabilities of missing the case $P_{miss.}$ and false detection $P_{fal.det.}$ and minimum value of probability of correct detection $P_{cor.det.}$ are defined as follows:

$$P_{miss} = \frac{Q_{min}}{\kappa \bullet Q_{miss}}; \quad (1.1)$$

$$P_{miss.cor.det.}; \quad (1.2)$$

$$P_{fal.det.} = \frac{Q_{\min}}{l \bullet Q_{fal.det.}}, \quad (1.3)$$

where Q_{min}, $Q_{miss.}$, $Q_{fal.det.}$ – expenses, respectively, minimal, in case of missing, in case of false detection;

κ, l – average number of, respectively, missed cases (collisions) and false braking for one road, respectively, per year.

Calculations showed the following values of probabilities:

$P_{miss.} = 0{,}0007$;
$P_{cor.det.} = 1 - P_{miss.} = 0{,}9993$;
$P_{fal.det.} = 10^{-4}$.

Thus, the video surveillance systems used to improve traffic safety should provide performance indicators $P_{cor.det.} \geq 0{,}9993$; $P_{fal.det.} \leq 10^{-4}$.

Calculation of an indicator of IVS signals quality

Train traffic safety is largely determined by the result of operation of IVS hazardous object recognition device. The result of image recognition in IVS video server depends on many factors: quality of digital signal generation on the transmitting side (resolution of the camera's photosensor, digital conversion errors, weather conditions, lighting, extraneous light sources, etc.), noise and distortion in the communication line, noise of the photoreceiver and interpolation errors on the receiving side, recognition algorithm. Most of these factors cause video signal distortion, which can be estimated by the quality indicator in the form of the total error dispersion δ^2_ε reduced to the power of the useful signal at the input of IVS recognition device [12; 15, p. 12]:

$$\delta^2_\varepsilon \approx \delta^2_{ps} + \delta^2_{an}. \quad (2)$$

The main cause of errors introduced by the photosensor is digital noise [16, p. 400]. Therefore, the effect of internal pixel noise must be analyzed taking into account the digital processing of the video signal.

The features of PS operation are that the internal noise of the pixels is added to the photocurrent of the video image. After the process of sampling a continuous signal, the pulse amplitude consists of the sum of the signal λ and noise *h*. The positive difference between the sum *(λ + h)* and the nearest integer (quantization level) can be less than half the quantization step ($\Delta_{qu}/2$). In case of rounding down (according to the rules of arithmetic rounding), the noise is discarded. In other variants of signal-to-noise ratios, abnormal errors can occur, i.e. errors in assigning a quantization level number. The value of the anomalous error δ^2_{ps} under the condition of a Gaussian distribution of the probability density of the photocurrent can be calculated as follows [15, p. 13]:

$$\delta^2_{ps} \approx 12 \bullet [\frac{1}{2}\exp(-\frac{9\rho^2_{out.ps}}{2L^2_{qu}})], \quad (3)$$

where $\rho^2_{out.ps} = \frac{\sigma^2_\lambda}{\sigma^2_h}$ is ratio of the photocurrent power and noise at the output of the photosensor and the input of the analog-to-digital conversion device (ADC);

$L = a^K$ is the number of quantization levels;

a is code length;

K is the number of bits in the code combination.

To calculate the anomalous error at the output of the photoreceiver δ^2_{an}, it is possible to use the method of calculating the probability of error when receiving an elementary pulse based on the analysis of *Q*-factor [17, p. 96], which depends on the ratio of signal power and noise at the output of PR $\rho^2_{out.pr}$.

The value of the anomalous error at the PR output for Gaussian distribution of signal probability densities is calculated by the formula [18, p. 392]:

$$\delta^2_{an} = 12 \bullet \frac{2}{\sqrt{2\pi\rho^2_{out.pr}}}\exp(-\frac{\rho^2_{out.pr}}{8}). \quad (4)$$

Hence the expression of reduced dispersion of total error of IVS is (1):

$$\delta^2_\varepsilon \approx 12 \bullet [\frac{1}{2}\exp(-\frac{9\rho^2_{out.ps}}{2L^2_{qu}}) + \frac{2}{\sqrt{2\pi\rho^2_{out.pr}}}\exp(-\frac{\rho^2_{out.pr}}{4})]. \quad (5)$$

Components (2), (3) of reduced dispersion of total error (4) have different weights, depending on the ratio of signal power and noise at the output of PS and PR.

Calculation of reliability criterion of IVS signals

The reliability criterion is estimated using the probability of correct detection $P_{cor.det.}$ according to the Neumann–Pearson algorithm.

The probability of correct detection at the output of IVS detection device, implemented as a matched filter, is calculated as follows [12, p. 12; 18, p. 173]:

$$P_{cor.\text{det}.} = V[\frac{H}{\sqrt{2/\delta^2_\varepsilon}} - \sqrt{2/\delta^2_\varepsilon}], \quad (5)$$

where

$V(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-z^2/2}dz$ is table integral.

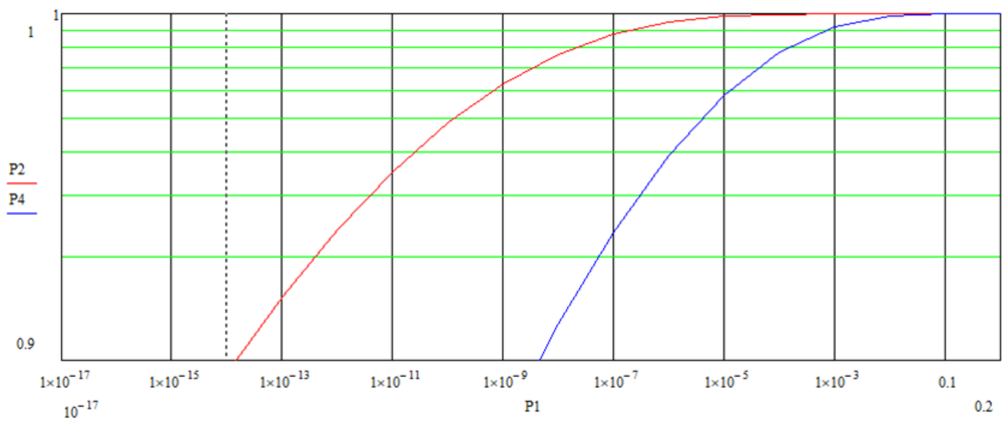
The calculation algorithm is as follows:

a) sets the probability of false detection;

b) according to the table integral *V(x)*, the response threshold of the receiving device *H* is found taking into account the ratio of signal powers and noise α^2_{det};

c) according to the formula (5), the probability $P_{cor.det.}$ is determined.

The ratio of signal power and noise α^2_{det} (s/n) is the reciprocal of reduced dispersion of total error $(\alpha^2_{\text{det}} = \frac{1}{\delta^2_\varepsilon})$.



Pic. 2. Dependence of probability of correct detection on probability of false detection $P_{cor.det.} = f\bullet(P_{fal.det.})$.

Justification for the use of a new element base of electronics

Improving quality of video signals is possible by reducing thermal noise and increasing sensitivity of optoelectronic devices (OED) that underlie PS and PR. This result is achieved through the use of element base of a new generation. The main difference between these OED is the use of nanostructured materials previously purified from heavy isotopes. The effectiveness of isotopic purification can be estimated by the example of the most common compounds, namely, solid solutions based on gallium arsenide. It is known that isotopic purification of semiconductor silicon made it possible to increase speed of microprocessors by more than two times [19, p. 409]. A greater effect can be expected from isotopic purification of solid solutions from gallium arsenide, since gallium is lighter than silicon (the ratio of the effective masses of electrons

$$\frac{m_{eSi}}{m_{eGa}} = \frac{0{,}19m_0}{0{,}067m_0} = 2{,}84.$$

The main indicator of improvement of quality of PS and PR due to purification of semiconductor material from heavy isotopes is an increase in sensitivity of R_i OED. The sensitivity is directly related to quantum efficiency of the material η, which depends on *n* (concentration of heavy isotopes), and light absorption coefficient α [16, pp. 393, 399].

Studies have shown that an increase in quantum efficiency will increase sensitivity R_i of an optoelectronic device (respectively, PS or PR) on a semiconductor crystal by 1,23 times, on a quantum well by 1,325 times. Accordingly, the thermal noise power decreases, the signal-to-noise ratio at the output of OED increases.

So, the value $\rho^2_{out.ps.}$ for pixels on a bulk crystal from gallium arsenide will increase by 1,23 times, which will significantly reduce the magnitude of reduced dispersion of current PS error δ^2_{ps}.

Similarly, the ratio of signal power and noise $\rho^2_{out.pr}$ at the output of the photoreceiver at multiple quantum wells (MQW) after isotopic cleaning of the material will increase. The value of $\rho^2_{out.pr}$ will increase by 1,255 times. This fact will affect the value of reduced dispersion of anomalous error δ^2_{an} PR, as well as reduced dispersion of total error δ^2_{ε} and probability of correct detection of IVS object recognition device. Thus, improvement of optoelectronic characteristics of the material of PS and PR allows one to reduce reduced dispersion of total error by more than 5,76 times.

The calculated merit value in the ratio of signal power and noise at the input of the recognition device leads to an increase in probability of correct detection, a decrease in probability of false detection of dangerous objects, and an increase in safety of train traffic.

Pic. 2 shows two dependencies $P_{cor.det.} = f\bullet(P_{fal.det.})$ of probability of correct detection ($P_{2,4}$) on probability of false detection (P_3).

The probabilities are calculated for the case of using matched filters as recognition devices by the Neumann–Pearson criterion for versions of OED without cleaning the semiconductor material (P_2) and with cleaning (P_4). As can be seen from the graphs, isotopic purification of the material gives a significant increase in the probability of $P_{cor.det.}$ and a decrease in the probability of $P_{fal.det.}$.

Thus, a 5,76-fold increase in the signal-to-noise ratio obtained above, after cleaning the material of PS and PR pixels, increases $P_{cor.det.}$ more than an order of magnitude, and reduces $P_{fal.det.}$ three orders of magnitude. The calculations showed (Pic. 2) that the probability of false triggering $P_{fal.det.} = 10^{-4}$ and correct detection $P_{cor.det.} = 0{,}9993$ necessary to prevent accidents can only be achieved using the new element base of electronics.

Conclusions.

1. As foreign and domestic experience shows, IVS are successfully used for many functions on railways: facilities security, fire safety, identification of criminals in places of passenger congestion. But for the function of improving traffic safety, it is necessary to increase quality and reliability of signals (compliance criteria).

2. To improve quality and reliability of IVS signals, it is necessary to improve optoelectronic characteristics of OED by using a new generation of nanostructured material.

3. Improving safety of train traffic using IVS depends on the probabilities of correct $P_{cor.det.}$ and false detection $P_{fal.det.}$, which are determined by the magnitude of reduced dispersion of total error δ^2_{ε} of IVS. The efficiency of IVS, estimated in the form of quality (δ^2_{ε}) and reliability ($P_{fal.det.}$) indicators are improved with the help of new-generation OED by more than 5,76 times and 10^3 times, respectively.

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