PROBABILISTIC MODEL OF ECOLOGICAL CONSEQUENCES OF RAILROAD ACCIDENTS

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ABSTRACT

The paper discusses the processes of inertial reacting and self-regulation of the environment impacted by hazards of railway accidents involving dangerous goods and the queuing system Markovian model is proposed to determine the probable consequences of such accidents development.

Key words: railway transport, dangerous goods, accidents, ecosystem self-regulation, combustion, explosion, system inertia, queuing system, Markovian process, mathematical model.

1 INTRODUCTION

Rail transport carries a large number of dangerous goods with different properties, which in case of accidents may affect the environment. Therefore, it is clear that at all levels of dangerous goods transportation due attention should be given to environmental protection, thus ensuring the human life protection. Implementing appropriate measures should provide balance, stability and flexibility of natural systems, the violation of which can lead to serious negative consequences and environmental disasters.

The problems of stability, equilibrium, homeostasis of ecosystems and the biosphere are central to modern environmental science [1].

According to the laws of the biosphere, the basic principles and laws of human and biosphere evolution, their interdependence, the main causes of the ecological crisis are ill-conceived and erroneous human actions, which result not only dying species, but also destroys the ability of natural systems and components for the restoration and self-regulation.

The main feature of the biosphere and ecosystems is the ability of the environment to adapt to intense anthropogenic influence that reflects the concept of “environmental capacity” of natural systems.

In the recent literature on ecology there is a very large number of interpretations and definitions of the term, each of which reveals only part of attributes and properties that reflect the ability of ecosystems, and hence the biosphere as a whole to self-preservation, self-regulation and self-healing.

The environmental capacity of the ecosystem is understood as the maximum amount of energy or matter that may be involved in the circulation per unit of time without significant violations of its structure and stable operation [1].

The definition of ecosystem capacity is based on “substance-energy” approach, in which the functioning of ecosystems is considered as a process of transformation of energy and substance that are coming from the environment and returning to the same environment. In the process of transformation of energy and substance they turn into forms that provide a continuous circulation flow of substances in the ecosystem, its poise and balance in the biosphere, which is necessary to maintain stable operation of the structures and relationships that were formed in the ecosystem.

Thus, the ecological capacity characterizes the capability of the ecosystem to transform energy and matter that come into it, into the forms that carry on the ecosystem biological cycle, passing in historically determined path [1].

The ecosystem ability to cleanse itself is associated with the ability of ecosystems to involve in circulation slightly more matter than that which they pulled in before anthropogenic influences.

If using ecological capacity to characterize the potential ability of ecosystems to adapt and sustain stability during human impacts, the self cleaning ability is likely to consist of several stages, such as the inertia of the system towards the external negative influences, opposition to the transformation of its physical and chemical properties to the extent that can lead to catastrophic state, or attenuation of negative processes in the environment and preservation of the original ecosystem status, are all consequences of this ability, and describe the results of operation of the system in certain specific circumstances.

The sad history of railway accidents and disasters draws one’s attention to one of their features – sometimes with inscrutable reasons they occur, although seemingly nothing led to them, while in other cases – on the contrary. Why so? Let’s try to look for analogies with the processes occurring in living ecosystems.

2 FEATURES OF TYPICAL RAILWAY ACCIDENTS WITH DANGEROUS GOODS

Consideration of typical rail rolling stock accidents involving dangerous goods showed that the initial conditions of such accidents, in particular, are a leak, spill or release of gaseous and liquid hazardous substances caused by depressurization of rail tank cars or containers, destruction of pipelines, valve failures, emergency damage holes, etc. [2].

The formation of explosive concentrations zones in accidents involving dangerous substances is affected by two types of parameters: the parameters of the leakage source and meteorological and topographical parameters [1,3].

The intensity of the leakage of gas, vapor and liquid properties are due to such sources characteristics as leakage geometric size, velocity of a combustible substance, its concentration, temperature and pressure in the middle of the container or tank, the density and quantity of the liquid phase, evaporation and others.

Dimensions of clouds that are formed at leakage of combustible gas or vapor depend on the velocity of runoff and dispersion.

The intensity of leakage increases with the speed of leakage of combustible material and with increasing concentration of flammable gas or vapor in the combustible material, which is released.

At high velocity of outflow gas and steam can form a conical jet, which is pulling the air inside causing the ability to “self-dilution”. The level of explosiveness of gas mixture that is formed in this way does not depend on wind speed.

At low outflow speeds, or when jet speed decreases or any interference occurs, that causes the “self-dilution” of gas mixture explosiveness level and it is dependent on the speed of air [3].

Evaporation of combustible liquid depends mainly on vapor pressure and specific vaporization heat of combustible material.

If the vapor pressure is unknown, to determine the mixture explosiveness, its boiling point and flash temperatures are used. Explosive mixture can not exist if the flash point exceeds the maximum temperature of combustible substances. The lower is the flash point, the larger is explosive zone.

It should be noted that the temperature of the flash is not an exact physical quantity. Some fluids are not characterized by parameters such as flash point, although they may form an explosive gas mixture. In such cases, the established value of liquid temperature corresponding to the concentration of vapor at the lower concentration limit the outbreak (ie with a minimum content of combustible material in a homogeneous mixture with an oxidant at which flame propagation is possible at any distance from the source of ignition) is compared with maximum temperature of the liquid.

For a certain amount of leakage of combustible material, the lower the minimum concentration limit of flame propagation, the larger explosive area [3].

Research on air pollution and formation of zones of explosive concentrations have shown that such processes are greatly influenced by meteorological and topographical characteristics of the area, namely, air speed, real air density, volumetric concentration of gas (vapor), wind direction, humidity, precipitation, pressure, terrain, etc., which can either increase the size of explosive concentration zones or slow down the process of their formation and reduction of such zones size to the minimum [4].

3 FUNDAMENTALS OF PHYSICAL AND CHEMICAL PROCESSES OF COMBUSTION AND EXPLOSION OF DANGEROUS GOODS

Experience of eradication of railway failures and accidents shows that the greatest threat to people, rolling stock, railway infrastructure and the environment are those that are accompanied by fire of dangerous goods [2].

Let us consider the basic physical and chemical processes of combustion and explosion of hazardous materials in different aggregate states. First of all, it should be noted that combustion is a complex, rapidly leaking chemical transformations, which is accompanied by a significant amount of heat and bright glow. In most cases, burning is a result of exothermic oxidation of substances capable of burning (fuel) by oxidant (oxygen, chlorine, etc.). Some other processes are also considered as burning and are associated with the rapid transformation and thermal or chain acceleration of the processes: the decomposition of explosives, ozone, interaction of barium oxide with carbon dioxide; decomposition of acetylene, etc. [5].

Combustion is a complex of interrelated chemical and physical processes, the most important of which are heat and mass transfer [6]. The most common feature is the ability of fire burning flame that arose to move throughout the mixture by heat transfer or diffusion of active particles from the combustion zone into a new mix.

In the first case the heat transfer is realized, and in the second case the diffusion mechanism of flame propagation takes place. Typically, combustion occurs in combined thermal diffusion mechanism. It is important that combustion is characterized by critical conditions (mixture composition, pressure, temperature and geometric size of the system) for the emergence and spread of flame. In all cases, the combustion is characteristic of three typical stages: emergence, spread and flame extinction [7,8].

Depending on the physical state of fuel and oxidizer there are three types of combustion:

- Homogeneous combustion of gases and vapor flammable substances in the medium of gaseous oxidizer;
- Heterogeneous combustion of liquid and solid combustibles in medium of gaseous oxidizer (kind of heterogeneous combustion is the combustion of liquid fuels in liquid oxidizer);
- Combustion of explosives and powder.

Depending on the speed of flame propagation combustion is divided into deflagration that flows at subsonic velocities and detonation, which is distributed with supersonic velocities.

In its turn, subsonic combustion is divided into laminar and turbulent. Laminar burning speed depends on the mixture composition, initial values of pressure and temperature, as well as the kinetics of chemical reactions in the flame. Speed of propagation of turbulent flames, in addition to these factors, also depends on the flow velocity, the degree and scale of turbulence [6].

The explosion is a process of rapid discharge of large amounts of energy. The blast explosive (or explosive) mixture fills the volume where energy discharge occurred, the mixture is converted into highly heated gas at the high pressure. This gas affects the environment with great force, causing the formation of a blast wave. Destruction caused by an explosion is due to the action of such a wave. As the distance from the explosion mechanical action of the blast wave weakens.

Consider basic processes of combustion gases.

The first stage of combustion – ignition – is the initiation of the initial fire burning in the fuel mixture. Found that ignition of flammable gas mixture may be in their contact with hot surfaces (eg., gas exit from tank hole that is in the fire zone), or the appearance of sparks or flames in the middle of the mixture, as it may happen in a situation of liquefied hydrocarbon gases leakage, followed by leakage source fire.

Ignition of a combustible gas mixture resulting from the collision with the red-hot surface of the container is provided if the surface temperature exceeds the value of the temperature of ignition ($T_{\inf}$). The nature of the process is such that when the surface temperature (T_{sur}) is not sufficient for the process of progressive fuel mixture heating and self accelerating reaction, then the exothermic heat of transformation is given back to the cold mixture. If $T_{\inf} \succ T_{sur}$, then progressive self-heating occurs in the fuel mixture and at some distance from the heated surface the combustible mixture temperature becomes greater than T_{sur} that leads to the formation of a primary combustion chamber.

In addition, the ignition temperature depends on the nature of the container surface material faced by gas mixture for at red-hot surface ignition of gases, the catalytic properties of the surface are activated. Thus, if the catalytic effect found in branched chain reaction, the critical ignition temperature decreases, and vice versa, when the interaction of the gas with the surface leads to breaking the chain reaction, the greater ignition temperature T_{sur} is needed.

Ignition temperature changes also depending on the initial values of the mixture pressure – pressure reduction leads to an increase of $T_{\inf}$ [6, 7].

A great threat to the rolling stock, railway transport infrastructure and the environment is a situation where an electrical discharge occurs in a leakage zone of dangerous goods in gaseous aggregate state.

The emergence of electric discharge in combustible gas leads to ionization of the gas and transforms it into a plasma. This process is accompanied by a strong heating of ionized zone. In the discharge channel, the temperature exceeds 10000 K [7].

However, not any electrical discharge results in the emergence of fire flame in combustible environment. Flames arises only when the energy released during the discharge exceeds the value of the minimum ignition energy. In other cases, the fireplace flame does not occur.

Heating by electric discharge of an initial volume of combustible gas mixture causes additional heat by chemical conversion. Redistribution of heat pulse energy in a combustible mixture makes the energy of chemical reactions added together with the energy of the initial pulse. Increasing the size of the heating sector is accompanied by increasing the total amount of heat produced, and share of chemical reaction energy in it.

If the effect of an electric spark to combustible mixture led to involvement in chemical transformation enough of combustible material and temperature of the process of volume increasing of the heated mixture is committed to the combustion temperature, the system is set stationary.

The heat that is given from the reaction zone into fresh mix is offset by the heat produced during the reaction and there is a steady flame front.

If the distance from the flame front to the place of spark increases, the influence of initial momentum to the process that develops becomes less significant.

Thus, stable flame front is formed in the case when the energy level is sufficient to heat up to the temperature of combustion a spherical volume of combustible mixture, the critical radius r_{CR} should be several times larger than the characteristic width of the laminar flame zone δ_{FL} [9]:

$$r_{CR} \geq 3{,}7\delta_{FL} . \tag{1}$$

In this condition the mix layers surrounding the area that is burning, have enough time to catch fire before the volume around hot spark gets cooled.

If equation (1) is not satisfied, then the stationary regime is not established for the heat output from the reaction zone exceeds the heat produced inside the zone, the combustible mixture is cooled, and the reaction that occurred in the area of discharge stops.

Another common phenomenon that accompanies accidents involving dangerous goods during their transportation by rail is spontaneous ignition.

The essence of ignition is a sharp increase in the rate of exothermic reactions, resulting in the burning of substances in the absence of a source of ignition.

It should be noted that in many theoretical studies, investigations of combustion processes often do not distinguish between the terms “ignition” and “spontaneous ignition”. In papers devoted to fire and explosion hazard the term “ignition” is used for the process of forced ignition, i.e. initiating combustion by highly heated source of ignition, and the concept of “spontaneous combustion” for the processes of flame burning in the absence of such sources [7].

The condition of thermal ignition is to ensure that the initial self heating of a fuel mixture resulting from the oxidation reaction must exceed a certain critical value [10]:

$$\Delta T \geq RT_0 / E , \tag{2}$$

where R is the universal gas constant; T_0 is the temperature of the cooled mixture, K; E is the activation energy.

The time during which the reacting system is getting a heating which is defined by (2), is called the spontaneous combustion induction time. Induction period depends on the composition of the mixture, its initial temperature and pressure. Induction period is of practical importance when combustible gas-air mixture is exposed to low-power source of ignition (spark). Spark, getting into this mixture heats a mixture of volume and at the same time the spark is cooled. Thus, if the induction time is longer than cooling time, the ignition will not occur.

It is found that thermal ignition occurs more easily, the higher are the reaction rate and temperature of combustion, and the less are the heat transfer speed and pre-explosion heating [6, 7].

Particular attention is given to the temperature dependence of the spontaneous combustion on the fuel mixture composition. If the mixture has a small amount of combustible material and there is an excess of air, the ignition of the mixture is not possible. Also, the presence in the mixture of excess fuel and shortness of air, too, making impossible the ignition of the mixture.

The spread of flame is worth special attention. Combustion initiation of gas mixture at one point leads to heating the neighboring layers of mixture, which starts the chemical conversion. Combustion of these layers entails initiating combustion of further layers and so on, until the complete burnout of combustible mixture. Thus, after the ignition, the flammable mixture burns by layers. Combustion zone moves across the mixture, providing flame propagation.

The area in which the chemical transformation occurs and there is intense warming of gas that burns, is called the flame front.

Before the flame front that is moving, there is a mixture of fresh mixture (not yet burned), and behind the front there are the products of combustion.

If fresh mixture moves toward the flame front at a speed equal to the speed of flame propagation, the flame will be fixed [11, 12].

Since the chemical transformation is highly dependent on temperature, bulk gas combustion is carried out in the area where the temperature is close to fresh mixture combustion temperature (T_B), so the length of time (τ) of the mixture stay in the combustion zone [12] is:

$$\tau = \tau_0 e^{E/RT_B} \tag{3}$$

And flame propagation velocity [12] is given by:

$$U = B_0 e^{E/RT_B}, \tag{4}$$

where B_0 is the value which depends on the properties of the mixture.

Redistribution of flame heat released by the reaction takes place, for heating of fresh mixture and partially coming into the surrounding environment. If the heat loss will be higher than a certain critical value, the progressive decrease in temperature and its attenuation will take place.

Taking into account the mutual influence of heat losses from the combustion zone, the combustion temperature and flame propagation velocity, the basic theory tenets can be formulated that limit the spread of flame. From this theory it follows that the condition for the possibility of flame propagation through combustible mixture is predicted by the relation [12]:

$$T_{CR} = T_{TH} - (RT_{TH}^2 / E), \tag{5}$$

where T_{CR} is the threshold value of T_B; T_{TH} is the theoretical combustion temperature.

The limit flame propagation speed U is given by [12]:

$$U_{CR} = U_{MAX} / \sqrt{e}. \tag{6}$$

Equation (5) indicates that the flame can not spread through the fuel mixture when the temperature is lower than the theoretical value that exaggerates (RT_{TH}^2 / E).

During the combustion of gases in open space the reaction products freely expand and pressure remains almost constant. Combustion in a closed volume is accompanied by increased pressure. The maximum pressure of the explosion in a closed volume is defined by thermodynamic properties of the combustible mixture and heat losses from the combustion zone.

Based on the above, it can be assumed that the nature of the phenomena that accompany the combustion of gases, tends to lag the ability to respond to external factors, and in some circumstances can completely prevent these factors to keep the development of the combustion process, until its termination.

The largest quantity of dangerous goods carried by rail is goods that are flammable liquids.

Consider basic processes that accompany the burning of liquids.

Burning of liquids is a complex physico-chemical process that takes place when mutual influence of kinetic, thermal and hydrodynamic phenomena occurs. Burning of liquids occurs in the gas phase. As a result of evaporation of the liquid surface a steam jet is formed and mixed with the air oxygen and chemical interaction ensures the formation of the combustion zone.

Burning zone is a thin layer of glowing gases, which come from the surface of the liquid flammable vapors and oxygen diffused from the air. Stoichiometric mixture is formed (i.e. such that has no excess of either fuel or oxidizer) which is burned in a split of second.

Shape and size of flame of burning liquids depend on the diameter of the tank (hole in the unit), which is burning. Flame height increases with the diameter of the reservoir holes [13].

The flame above the surface of the combustible liquid is stable, if there is a defined speed of coming fuel and oxygen.

Rate of fuel input depends on its vapor pressure above the liquid, and hence on its temperature. The lowest temperature of the liquid (T_B) in which the flame arose, and will not go out, is called flashpoint temperature.

Established that the ignition temperature is determined by formula [13]:

$$P_B = A/(D_0 \beta T_B), \tag{7}$$

Where P_B is saturated vapor pressure at the temperature of liquid ignition; A is a fixed device value; D_0 is diffusion coefficient of vapor in air; β is oxygen stoichiometric coefficient.

The process of liquid burning is also characterized by burnout speed. Burnout speed is not a physical or a chemical constant; it depends on the properties of flammable liquids, tank (holes) diameter and the conditions of heat and mass transfer in the fire zone.

Like the processes of gases combustion, during combustion of flammable liquids a tendency is observed when the combustion processes slowdown response time to external factors that cause their burning despite burning process. Under certain conditions, untill a significant slowdown or even, to a complete termination.

A significant proportion of goods transported by rail are solid combustible materials.

Combustion of solids differs from combustion of gases by the presence of stage of decomposition and gasification.

Combustion among gaseous oxidizer often comes as a result of ignition of volatile pyrolysis products. Converting solid combustible material into products of combustion is not concentrated only in the area of the flame.

Combustion of solids has a multistage nature. Under the influence of external heat the solid phase is heating, which is accompanied by decomposition and release of gaseous products. Then these products are ignited and burned. Heat from the torch that is formed affects the solid surface, causing revenues to the combustion zone of new portions of combustible gases.

Model of solid substance burning presupposes such zones [14]:

- Heating of the condensed phase. Thermoplastic materials are melting in this zone. The thickness of this zone is defined by the coefficients of thermal conductivity and burning rate and is about 3 mm;
- Pyrolysis or reaction zone in the condensed phase, where gaseous combustible substances are formed;
- Pre-flame zone in the gas phase, where a combustible mixture is formed;
- Flame zone or reaction zone in the gas phase, where the pyrolysis products are conversed into the gaseous products of combustion;
- Combustion products zone.

The intensity of the reactions that occur in the surface layer of the solid and heat exchange conditions of gaseous decomposition products with the environment define the processes of combustion – spontaneous ignition or ignition.

In case of spontaneous ignition, the warmth that comes to the surface of the solid from the heat source is uniformly distributed throughout the thickness at the surface layer, which corresponds to the characteristic size of the material. With ignition from an external source which is the warmed external layer, where the heterogeneous reaction is occuring the layer thickness is substantially less than characteristic size of the material.

Thus, as in the process of combustion gases and liquids, the combustion of solids phenomenon of inertia of combustion processes is also observed. Under certain conditions, the system “solid material that burns – environment”, tends to inhibition of combustion processes, until their termination.

Some classes of dangerous goods transported by rail can form powders in accidents.

The powder mixture burning process is determined by the heat transfer mechanism in the flame front. There are several theories that explain the pattern of flame spread by means of conductive, radiative and conductive-radiative heat transfer from the combustion zone into the fresh mixture.

For organic systems, heat transfer is mostly carried out by conductivity and convection. Because of low fuel gasification temperature, and narrow zones of combustion the predominant mechanism of heat transfer is thermal conductivity of the gas. Effect of gravity on powder-gas mixture combustion is found in particles settling down under gravity, which leads to a relative velocity of phases in the fresh mixture, as heated products of combustion are affected by Archimedean force.

Model of the flame front in this case we can apply in some way like this. Under the influence of heat flow from high temperature zone where powder cloud burns, particles have time to evaporate before ignition. Flame front spreads in homogeneous gaseous mixture of fuel vapor and air. Reaction of fuel with oxidizer flows in the kinetic region, obeying certain thermal theory laws.

The movement of the flame front leads to partial scattering of fresh mixture near the leading points of flame. This gas phase (oxidizer) is dissipated to a greater extent than condensed phase (fuel), resulting in phases having relative velocity and thus changing the fuel and oxidizer ratio in the flame front.

Increasing the fuel concentration is accompanied by the growth of the flame velocity in these areas, causing further growth of convex parts of the flame front and lagging concave regions.

This effect leads to the fact that the flames can spread throughout suspension mixture with average fuel concentration below the concentration limits of flat flame front propagation in the gas mixture. Approximate estimates show that the minimum content of fuel in homogeneous mixtures with an oxidizing agent, which may spread the flames to mixture at any distance from the source of ignition is about two times less than the same minimum content of fuel gas mixtures of the same substances. This property of organic substances suspension mixture is detected since the particles diameter of 10 microns [15].

Particularly noteworthy are combustion processes of natural fuels suspension mixture, which account for a substantial proportion of goods transported by rail (coal, peat, some fertilizers).

Solid fossil fuels differ from most chemicals the presence of three components: the flying particles, coke and ash. The processes of ignition and flame propagation of each of these components have certain features.

Flying share of solid fuel is a gaseous component released from the fuel during heating without oxidant. Coke in its composition is similar to carbon. Speed of coke burning is much lower than burning rate of volatile particles.

In this regard, participation of coke in powder explosions of natural fuels is negligible. In the ash, which is part of the mineral fuels, a number of components are contained that can participate in combustion (alkali metals, Pirita and pyrite). But ash, in general, plays the role of an inert material.

Explosions of solid fuels suspension mixtures are typical thermal explosions. Flame propagation in mixtures is a result of heat transfer from combustion products into the fresh mixture. Heat can be transmitted by different mechanisms depending on the particle size, concentration, composition and parameters of gas medium and other factors [15,16].

Unlike combustion processes in gas mixtures suspension mixtures of natural fuels are constrained by the duration of particles heating and the possibility of fuel oxidation reaction to occur in kinetic as well as in the diffuse field. In general, the temperature of the particles differs from the temperature of the ambient gas both in the area of chemical interaction and in the area of heating [16].

Mostly recognized is the model of flame propagation in suspension mixtures of fossil fuels particles, which was proposed in [16].

According to this model, the maximum speed of flame propagation U_{FL} at sufficiently large thickness of the front is:

$$U_{FL} = \frac{\sigma T_E^4}{c\rho\mu(T_S - T_0)}, \tag{8}$$

where T_E is effective radiation temperature of the flame front; σ is constant Stefan - Boltzmann; c, ρ, μ are respectively, volumetric heat capacity, density and concentration of the solid phase; T_S is the temperature of spontaneous combustion; T_0 is initial temperature of the mixture.

The initial period of flame propagation in suspension mixtures is characterized by hopping rate, due to the size of initially inflamed area, duration of heating to a temperature of spontaneous combustion, which depends on the thickness of the flame front radiating, and dust particles burning.

Based on the above, it is natural to assume that the phenomenon of dust burning is accompanied by inertia, that is able, under certain conditions, to slow down combustion process, or stop it completely.

4 MATHEMATICAL MODEL OF THE ECOLOGICAL SYSTEM

In order to forecast the state of the environment a large number of mathematical and simulation models is used. To build such models, differential equations are used that describe the various physical and chemical processes of pollution spread in soil, rivers and reservoirs under various boundary conditions, taking into account the spread of contamination, given weather conditions, power of pollution sources and physical properties of the underlying surface (its relief, development, forest areas, etc.). Methods of linear regression analysis, pattern recognition, image sequential regression and others [17, 18] are also widely used.

In our view, next to the above models, to predict the consequences of accidents involving rail transport of dangerous goods, models of queuing theory are also quite useful. Having examined in this paper the processes of accidents development with dangerous goods of different physical state, we can conclude that the environment has some lag of response to an external hazardous accident factors. That prevents the environment to change its condition and behavior due to the properties of self-support and self-regulation that, under certain conditions, may lead to inhibition of catastrophic processes until their termination.

Let us consider the ecological system of “emergency rolling stock – the environment” as a Markovian queuing system (QS). In Markovian queuing system all flows of events (arrival of customers) that lead the QS from one state to another are stationary Poisson flows. This means that the time intervals between adjacent events in the flow have exponential distribution with parameter λ equal to the intensity of the corresponding flow (or reciprocal value of time interval between events).

In this QS an arrival flow of “customers” enters the system – subsequent portions of hazardous accident factors (HAF) that impact the QS in with intensity λ. As such “portions” can be seen, for example, some smallest quantities of hazardous liquid or gas escaping under great pressure from the holes in the tank, creating (or not creating) an explosive gas-air mixture, etc. Then, the arrival flow rate λ can be defined as the reciprocal expected time to reach an explosive concentration of the mixture.

Inertial action time of “emergency rolling stock – environment” system has exponential distribution with intensity ν, and the time of self-healing (recovery ability of the system to return to the original safe state) has a parameter of intensity μ. In this sense μ is the reciprocal average time of system self-healing, while ν is the reciprocal average time lag (delay of system responses to HAF). Service of a portion customer in that QS consists of two phases.

The essence of the service is that a portion arriving to the first phase reach a critical concentration value and after that servicing the next portion customer is refused and the portion is moved into the second phase of service (QS-2).

The first phase of the HAF portion service is a single-channel queuing system with queue and a service channel “heating-up”, which is considered in [19]. In this case, the “heating-up” type of service channel is the realization of the inertial properties of the system. The graph of this QS-1 is shown in Figure 1.

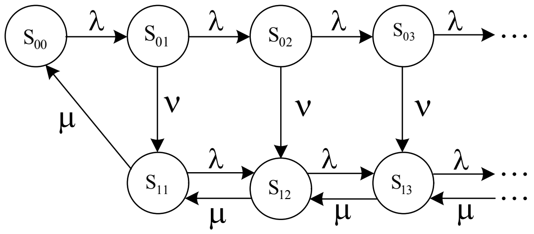

Figure 1. Graph of QS-1 states with queue and "heating-up" service channel

The states of QS-1 (Fig. 1) are as follows:

S_{00} - Channel free, not heated;

S_{01} - One portion of HAF arrived and is waiting till the channel is heated; system inertia is in action;

S_{11} - The channel is heated, one portion of HAF is being serviced, no queues;

S_{02} - The channel is being heated up; there are two portions of HAF in a queue;

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S_{0k} - The channel is being heated up; there are k portions of HAF in a queue;

S_{1k} - One portion of HAF is being served in a channel; there are $(k-1)$ portions of HAF in a queue, etc.

The system of equations for the final probabilities P_{lk} is as follows:

$$\begin{cases} \lambda P_{00} = \mu P_{11} \\ (\lambda + \nu) P_{01} = \lambda P_{00} \\ (\lambda + \mu) P_{11} = \nu P_{01} + \mu P_{12} \\ (\lambda + \mu) P_{02} = \lambda P_{01} \\ (\lambda + \mu) P_{12} = \nu P_{02} + \lambda P_{11} + \mu P_{13} \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ (\lambda + \nu) P_{1,k} = \lambda P_{0,(k-1)} \\ (\lambda + \mu) P_{1,k} = \nu P_{0,k} + \lambda P_{1,(k-1)} + \mu P_{1,(k+1)};\dots. \end{cases} \tag{9}$$

In the second phase of the service when the next $(l+1)$-st portion of HAF is rejected, because the number of customers in the QS-1 exceeds the limit (one portion), it comes for the service in the QS-2.

QS-2 is a single-channel queuing system with failure (Fig. 2).

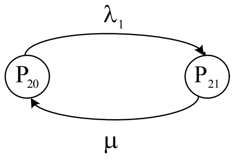

Figure 2. Graph of QS-2 states

The equations for the final probabilities will be the following:

$$\begin{cases} \mu P_{21} = \lambda_1 P_{20} \\ P_{20} + P_{21} = 1 \\ \lambda_1 = \lambda P_{12} \end{cases} . \tag{10}$$

Hence the probability of catastrophic consequences of the accident is:

$$P_{21} = \frac{\lambda_1}{\lambda_1 + \mu} = \frac{1}{1 + \frac{\mu}{\lambda_1}} = \frac{1}{1 + \frac{\mu}{\lambda P_{12}}} . \tag{11}$$

Figures 3a, 3b and 3c show dependences of probability of catastrophic consequences of accidents against the intensity of the recovery processes of the system μ at different values of inertia ν and arrival flow λ_1. These figures with upper and lower indices in the intensity or inertia values, for example ν'^{IV}_3, mean the relevant series of computational experiments.

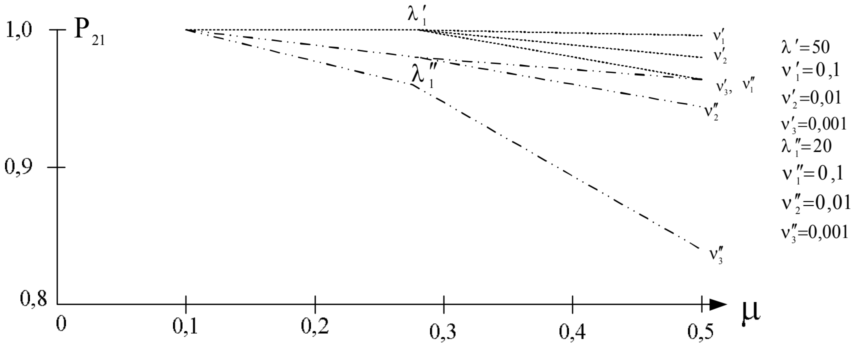

Figure 3a. Probability of catastrophic consequences of accident P_{21} against the system self-recovery intensity μ for large rate of HAF arrival flow λ_1 and small values of inertia of the system ν.

Figure 3a shows that for large values of HAF portions flow intensity at QS-2 entry, that were rejected in the QS-1, significantly higher than the intensity of response on the violation of its equilibrium ν (for large values of the average inertia time of the system) and with increasing intensity of recovery processes μ (reducing the value of the mean recovery time), the probability of the catastrophic consequences of the accident for example, considered is somewhat reduced, but still remains quite high.

Figure 3b presents dependence of probability P_{21} on intensity of recovery processes μ at moderate λ_1 and small ν values.

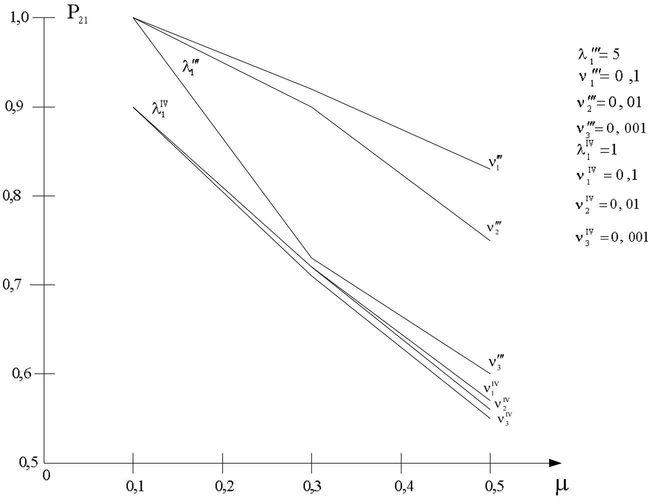

Figure 3b. Probability of catastrophic consequences of accident P_{21} against the system self-recovery intensity μ for moderate intensity of HAF arrival λ_1 and small values of system inertia ν.

Examination of the graphs in Figure 3b shows that at moderate values of arrival flow rate λ_1, the low intensity of the system inertia ν and increase the intensity of recovery μ, the probability P_{21} tends to decrease. The largest decrease of the probability of catastrophic consequences is having place with decreasing HAF arrival intensity to QS-2. For example, given $\lambda^{IV}_1 = 1$, $\nu^{IV}_3 = 0.001$ and at $\mu = 0.5$ the value of $P_{21} = 0.545$. Meanwhile, the probability of catastrophic consequences of accidents for example in question is still considerable.

With increasing ν values (reducing the average time of the system inertia) and decreasing the average time recovery (increase of μ), the probability P_{21} is significantly reduced and becomes insignificant as λ_1 decreases (Fig. 3c).

The calculations show that at $\lambda_1^{VII} = 20$, $\lambda_1^{VIII} = 50$ and $\nu = 1, 2, 3$ with an increase, the probability P_{21} is from 0.005 at $\mu = 0.1$ to 0.004 at $\mu = 0.5$, ie catastrophic consequence is practically impossible.

Similar conclusions can be drawn and at $\lambda_1^{IX} = 20$, $\lambda_1^{X} = 50$ and $\nu = 10, 20, 30$, when at certain μ changes the probability P_{21} in the highest value does not exceed 0.4, and the lowest is 0.01.

Note that in the examples of this mathematical model application (graphs in Fig. 3), somewhat “abstract”, dimensionless (relative) values of HAF arrival flow and service rate are used. This enabled us to focus on the demonstration of a new theoretical approach proposed by the authors for this class of problems. In certain practical applications of this theoretical approach and mathematical model one should apply appropriate values and their parameters. Features of the practical application of the model for different conditions that occur during transportation of dangerous goods by rail and other transport modes obviously require some specific research and scientific analysis.

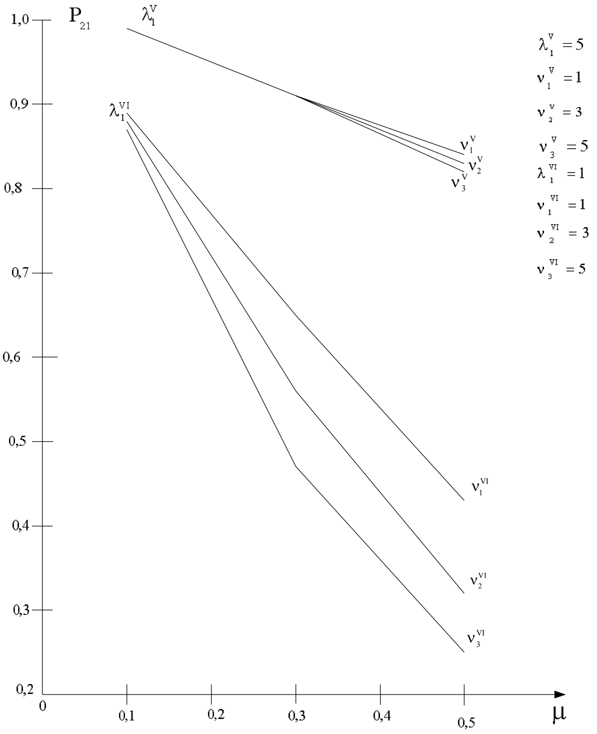

Figure 3c. Probability of catastrophic consequences of accident P_{21} against the system self-recovery intensity μ for moderate intensity of HAF arrival flow λ_1 and system inertia ν.

5 CONCLUSIONS

1. Natural processes and anthropogenic factors of hazards in rail rolling stock accidents as having properties similar to natural ecosystems against hazards of accidents, such as inertia and self-recovery are considered in this study on the basis of general theoretical provisions of ecosystems, combustion and explosion theories, probability and queuing theory.
2. Formal description of hazards development process in rail accidents is done on the basis of mathematical tools of queuing theory, which is used in other applications (communications, transportation, etc.), to simulate conditions and quantify the factors that characterize accidents involving dangerous goods carried by rail.
3. Specific numerical examples are proposed and examined, based on the mathematical model of a two-phase queuing system and the conditions of disastrous effects are analyzed depending on the intensity of hazardous accident factors, inertia and self-recovery properties of systems “emergency rolling stock – the environment”.

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