Dependability, vol. 19 no.2, 2019 Original article
DOI: 10.21683/1729-2646-2019-19-2-48-53

Economic assessment of the accidental risk of natural emergencies for train traffic

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Abstract. Aim. *The paper is dedicated to the evaluation of the risk of transportation accidents caused by natural emergencies affecting train traffic on a specific line. The ever-growing anthropogenic burden on the environment inevitably causes climate change that, in turn, gives rise to higher numbers of extreme weather events. The latter usually cause industrial accidents and disasters. The assessment of the factors of climate-related risk that quantitatively characterize their effect on the railway infrastructure is the starting point of calamity risk management and adaptation of human activities to the ever-changing climate.* **Methods.** *The authors propose a method of risk assessment that takes into consideration the effect of various natural emergencies that affect rolling stock in motion. The method is based on elements of the probability theory and mathematical statistics. The developed method enables the assessment of the risk of a transportation accident caused by natural emergencies specific to not only a line, but a route on a railway network.* **Results.** *For the Nevinnomysskaya – Tuapse line that includes 6 sections of the North Caucasus Railway, one of which was damaged due to abundant precipitations on October 24 and 25, 2018, the risk of transportation accident caused by the effects of three types of natural emergencies on the sociotechnical system of this line has been calculated:*
– flood,
– hurricane with wind strength of over 22 mps,
– heavy rain.
The parameters of such emergencies are characterized by the following factors:
– frequency as compared to other types of emergencies,
– average annual number of natural emergencies,
– characteristic spatial scale of the natural emergency,
– characteristic duration of the natural emergency.
The conditional probabilities of the effects on the railway sociotechnical system of an event that has characteristic spatial scale and duration and has caused a transportation accident involving a train were estimated based on the assumption that a train flow in space follows the normal Erlang distribution of the k-th kind. The risk of transportation accident involving up and down trains travelling along the i-th line of the j-th railway caused by a hazardous effect of a natural emergency of the m-th type is identified subject to the jointness of events. Using the discounting method, an equation was obtained for estimating the mathematical expectation of economic damage by traffic safety disturbances, which allowed estimating the economic component of the risk. **Conclusions.** *As the result, a method is proposed for estimation of the risk of transportation accidents caused by natural emergencies, an example is provided of such risk estimation, including the economic component, for the Nevinnomysskaya – Tuapse line.*

Keywords: *accidental risk, accidents, emergencies, railway transportation, natural emergencies, railway freight transportation, traffic safety disturbances.*

For citation: *Popov VG, Sukhov FI, Bolandova YuK Economic assessment of the accidental risk of natural emergencies to train traffic. Dependability 2019;2: 48-53. DOI: 10.21683/1729-2646-2019-19-2-48-53*

Today's world statistics show growing damage caused by hazardous weather and climate events around the globe. The diagram (Figure 1) shows that 90% worst economic losses are caused not by geophysical phenomena, such as volcano eruptions, tsunamis and earthquakes, but meteorological, climate and hydrological events, i.e. floods, strong winds, heavy rains, hail, droughts [1].

Importantly, hazardous climate events can initiate industrial emergencies. Significant social and economic losses were caused by mudflows that accompanied a deep depression with showers between August 6 and 9, 2002 around Novorossiysk on the Black Sea coast of Russia. According to operational messages of the EMERCOM of Russia, on August 6 powerful mud-and-stone flows with the total volume over 15 ths. m^3 destroyed 300 meters of railway track between Sochi and Tuapse, as well as the nearby motorway. 47 passenger trains were blocked. According to preliminary estimations, direct economic damage amounted to USD 71 mln. [2].

As the result of abundant precipitations on October 24 and 25, 2018 (275-330 mm) in three municipalities of the Krasnodar Krai, harm was inflicted on two road bridges and one railway bridge, sections of the Tuapse – Maykop and Dzhubga – Sochi motorways, roadbed in the Tuapse – Krivenkovskaya and Tuapse – Adler railway lines. 36 passenger trains were cancelled and 39 were delayed.

Fault-free and safe operation of railway transportation largely depends on the climate conditions. The assessment of the factors of climate-related risk that quantitatively characterize their effect on the railway infrastructure is the starting point of calamity risk management and adaptation of human activities to the ever-changing climate.

Risk assessment consists in its quantitative measurement [3]. Quantitative estimation of risk requires the analysis of the probabilities of occurrence of hazards and consequences of such hazards' realization.

The main purpose of risk management in railway transportation consists in achieving and maintaining the acceptable level of risk while ensuring the functional safety of infrastructure facilities and rolling stock [4]. As of late, special emphasis is placed on the matters of dependability of rolling stock and development of systems and methods of risk estimation and management aimed at ensuring the safety of transportation processes [5-8]. However, the latest research into this matter examines the system of railway infrastructure operation separately from the environment. The authors propose a method of transportation accident risk assessment that takes into consideration the effect of various natural emergencies.

A transportation accident is understood as train wrecks, train accidents, as well as derailments and collisions of rolling stock that do not cause train wrecks and accidents in accordance with the classification of the Decree of the Ministry of Transportation of the Russian Federation no. 344 of December 18, 2014 [10].

Let us introduce the following notations for the purpose of characterizing natural emergencies:

C_j,i,m, an event that is a natural emergency of the m-th type that occurred in the Russian geographical region where the i-th line of the j-th railway is situated,

D_j,i,m, an event that characterizes the effect of a natural emergency of the m-th type (event C_j,i,m) on the sociotechnical railway system on the i-th line of the j-th railway and causes a transportation accident,

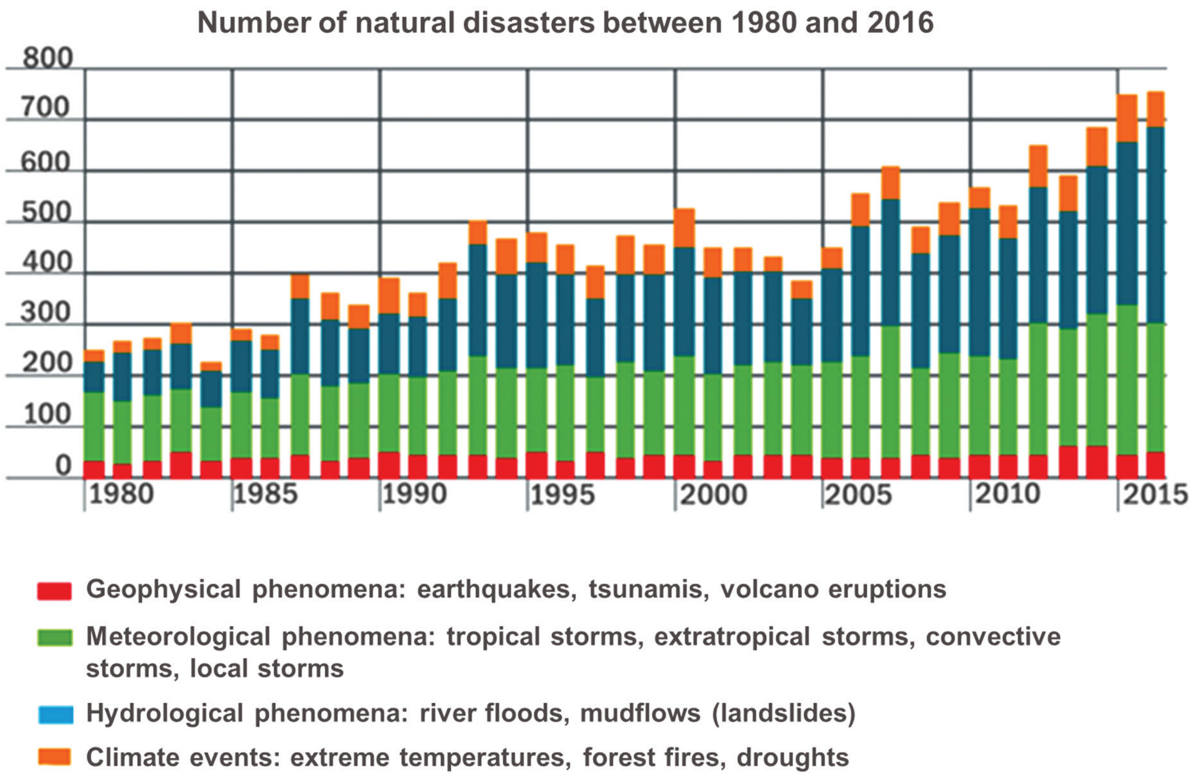

Figure 1. Number of natural disasters between 1980 and 2016

$B_j,i,m = D_j,i,m$ Ч C_j,i,m, a transportation accident [10] caused by the effect of a natural emergency of the m-th type on the sociotechnical railway system on the i-th line of the j-th railway,

N_j,i,m, the average yearly number of natural emergencies of the m-th type that occur in the Russian geographical region where the i-th line of the j-th railway (m = 1, 2, ..., M) is situated, 1/year,

L_j,i,m, the characteristic spatial scale of a natural emergencies of the m-th type that occurs in the Russian geographical region where the i-th line of the j-th railway (m = 1, 2, ..., M) is situated, km,

T_j,i,m, the characteristic duration of a natural emergency of the m-th type that occurs in the Russian geographical region where the i-th line of the j-th railway (m = 1, 2, ..., M) is situated, h,

We will estimate the probability of a transportation accident affecting an up train on the i-th line of the j-th railway caused by a natural emergency of the m-th type using the following formulas:

$$R''(B_{j,i,m}) = R''(D_{j,i,m} \times C_{j,i,m}) = \\ = P''(C_{j,i,m}) \cdot P''(D_{j,i,m} | C_{j,i,m}), \quad (1)$$

where $P''(D_{j,i,m} | C_{j,i,m}) = P''(L_{j,i,m} | C_{j,i,m}) \cdot P''(T_{j,i,m} | C_{j,i,m})$.

$P''(C_{j,i,m})$ is the probability of occurrence in the specific geographical region of a natural emergency of the m-th type with the characteristic spatial scale L_j,i,m within the average time of presence of an up train on the i-th line with the length of $L_{j,i}$ [9],

$$P''(C_{j,i,m}) = 1 - \exp\left(-\frac{N_{j,i,m} \cdot t''_{j,i}}{365 \cdot 24}\right), \quad (2)$$

where $t''_{j,i} = L_{j,i} / V''_{j,i}$, $V''_{j,i}$ is the up service speed on the i-th line of the j-th railway,

$P''(L_{j,i,m} | C_{j,i,m})$ is the conditional probability of the effect on the sociotechnical railway system of event C_j,i,m with characteristic spatial scale L_j,i,m causing a transportation accident involving an up train on the i-th line of the j-th railway [9]

$$P''(L_{j,i,m} | C_{j,i,m}) = 1 - \exp(-k_x \lambda''_x L_{j,i,m}) \sum_{k=0}^{k_x - 1} \frac{(k_x \lambda''_x L_{j,i,m})^k}{k!}; \\ \lambda''_x = 1 / \Delta\bar{X}''_{j,i}, \quad (3)$$

where k_x is the kind of the standard Erlang distribution,

$\Delta\bar{X}''_{j,i} = V''_{j,i} \times \Delta\bar{T}''_{j,i}$ is the average spacing of up trains on the i-th line of the j-th railway, km,

$\Delta\bar{T}''_{j,i}$ is the average headway between up trains on the i-th line of the j-th railway, h,

$P''(T_{j,i,m} | C_{j,i,m})$ is the conditional probability of the effect on the sociotechnical railway system of event C_j,i,m with characteristic duration T_j,i,m that caused a transportation accident involving an up train on the i-th line of the j-th railway [9]

$$P''(T_{j,i,m} | C_{j,i,m}) = 1 - \exp(-k_t \lambda''_t T_{j,i,m}) \sum_{k=0}^{k_t - 1} \frac{(k_t \lambda''_t T_{j,i,m})^k}{k!}; \\ \lambda''_t = 1 / \Delta\bar{T}''_{j,i}, \quad (4)$$

wherek_t is the kind of the standard Erlang distribution,

In formula (1) written to estimate the probability of a transportation accident involving a down train on the i-th line of the j-th railway $R'(B_{j,i,m})$, the corresponding values $P'(C_{j,i,m})$, $P'(L_{j,i,m} | C_{j,i,m})$, $P'(T_{j,i,m} | C_{j,i,m})$ are identified according to formulas similar to those for up trains subject to appropriate data.

Then, the probability $R(B_{j,i,m})$ of a transportation accident affecting up and down trains on the i-th line of the j-th railway caused by a hazardous effect of a natural emergency of the m-th type can be identified using the following formula (accounting for the jointness of events):

$$R(B_{j,i,m}) = R''(B_{j,i,m}) + R'(B_{j,i,m}) - R''(B_{j,i,m}) \times R'(B_{j,i,m}). \quad (5)$$

Out of formulas (1), (5), we can obtain the following estimates of the probability of a transportation accident affecting a moving train.

I. We will estimate the probability of a transportation accident affecting a train on the i-th line of the j-th railway caused by all possible natural emergencies of M types (m = 1, 2, 3, …, M) using the following formula:

for an up train

$$R''(B^M{}_{j,i}) = \sum_{m=1}^{M} \phi_m \cdot R''(B_{j,i,m}), \quad (6)$$

for a down train

$$R'(B^M{}_{j,i}) = \sum_{m=1}^{M} \phi_m \cdot R'(B_{j,i,m}), \quad (7)$$

for up and down trains

$$R(B^M_{j,i}) = R''(B^M_{j,i}) + R'(B^M_{j,i}) - R''(B^M_{j,i}) \cdot R'(B^M_{j,i}), \quad (8)$$

whereц$_m$ is the frequency of emergencies of the m-th type out of all the other types of emergencies, $\sum_{m=1}^{M} \phi_m = 1$,

$B^M_{j,i}$ is a transportation accident, an event that followed the effect of all possible M types of natural emergencies on the sociotechnical railway system on the i-th line of the j-th railway.

II. We will estimate the probability of a transportation accident affecting a train on I (i =1, 2, 3, …, I) lines of the j-th railway caused by a natural emergency of the m-th type using the following formulas:

for an up train

$$R''(B^I_{j,m}) = 1 - \prod_{i=1}^{I} [1 - R''(B_{j,i,m})], \quad (9)$$

for a down train

$$R'(B^{I}_{j,m}) = 1 - \prod_{i=1}^{I}[1 - R'(B_{j,i,m})], \qquad (10)$$

for up and down trains

$$R(B^{I}_{j,m}) = 1 - \prod_{i=1}^{I}[1 - R(B_{j,i,m})], \qquad (11)$$

where $B^{I}_{j,i}$ is a transportation accident, an event that followed the effect of a natural emergency of the *m*-th type on the sociotechnical railway system on *I* (*i* =1, 2, 3, …, *I*) lines of the *j*-th railway.

III. We will estimate the probability of a transportation accident affecting a train moving along *I* (*i* = 1, 2, 3, …, *I*) lines of the *j*-th railway caused by all possible natural emergencies using the following formulas:

for an up train:

$$R''(B^{I,M}_{j}) = 1 - \prod_{i-1}^{I}[1 - R''(B^{M}_{j,i})], \qquad (12)$$

for a down train:

$$R'(B^{I,M}_{j}) = 1 - \prod_{i-1}^{I}[1 - R'(B^{M}_{j,i})], \qquad (13)$$

for up and down trains:

$$R(B^{I,M}_{j}) = 1 - \prod_{i-1}^{I}[1 - R(B^{M}_{j,i})], \qquad (14)$$

where $B^{I,M}_{j}$ is an event that followed the effect of all possible *M* types of natural emergencies of the sociotechnical railway system on *I* (*i* =1, 2, 3, …, *I*) lines of the *j*-th railway.

IV. We will estimate the probability of a transportation accident affecting a train on *I* (*i* = 1, 2, 3, …, *I*) lines of *J* (*j* = 1, 2, 3, …, *J*) railways caused by all possible natural emergencies using the following formulas:

for an up train

$$R''(B^{J,I,M}) = 1 - \prod_{j-1}^{J}[1 - R''(B^{I,M}_{j})], \qquad (15)$$

for a down train

$$R'(B^{J,I,M}) = 1 - \prod_{j-1}^{J}[1 - R'(B^{I,M}_{j})], \qquad (16)$$

for up and down trains

$$R(B^{J,I,M}) = 1 - \prod_{j-1}^{J}[1 - R(B^{I,M}_{j})], \qquad (17)$$

where $B^{J,IM}$ is a transportation accident, an event that followed the effect of all possible *M* types of natural emergencies on the sociotechnical railway system on *I* (*i* =1, 2, 3, …, *I*) lines of *J* (*j* = 1, 2, 3, …, *J*) railways.

If in formulas (9) to (14) for *I* we take all the lines of the *j*-th railway, we can obtain the corresponding estimates of accidental risk for the *j*-th railway as a whole (*j* = 1, 2, 3, …, *J*). If in formulas (15) to (17) we take *I* (*i* = 1, 2, 3, …, *I*) lines of *J* (*j* = 1, 2, 3, …, *J*) railways, we can obtain the corresponding estimates of accidental risks for various routes.

For the economic assessment of the consequences of transportation accidents let us use the information set forth in [11–16]. According to [10], transportation accidents, i.e. traffic safety disturbances (TSD) are subdivided into train wrecks, B_1, train accidents, B_2, transportation accidents (derailment or collision without consequences in the form of train wreck or train accident), B_3.

Using the discounting method [11] and statistical data of [12, 13], we can write the estimation equation of the mathematical expectation of economic damage caused by TSD as B_n ($B_n = B_1, B_2, B_3$):

$$Y(B_n) = Y_0(B_n)(1 + r)^p, \qquad (18)$$

where $Y_0(B_1) = 2 \cdot 10^6$ rubles, $Y_0(B_2) = 0.5 \cdot 10^6$ rubles, $Y_0(B_3) = 7 \cdot 10^3$ rubles are the average values of economic damage caused by one event of types B_1, B_2, B_3 in 2000 rubles,

$p = Y - 2000$ is the conventional year,

Y is the calendar year of risk analysis,

r is the rate of discounting ($r = 0.1$–0.12).

The practical impossibility of predictive estimation of the economic damage caused by TSD of type B_n associated with the effect of natural emergencies on sociotechnical railway systems and causing transportation accidents involving moving trains forces us to resort to using conservative assumptions and a posteriori statistical data on the TSD that affect trains. Given the above, the equation can be written as follows:

$$Y(B) = \sum_{n=1}^{3} \alpha_n \cdot Y\left(B_n\right), \qquad (19)$$

where α_n is the relative rates of TSD of type B_n ($n = 1, 2, 3$) that according to [14, 16] can be estimated as $\alpha_1 = 0.01$, $\alpha_2 = 0.1$, $\alpha_3 = 0.89$.

Then, the economic estimate of the risk of transportation accident affecting a train on the *i*-th line of the *j*-th railway caused by a natural emergency of the *m*-th type can be obtained using the following formulas:

$$\begin{aligned}&\text{up } R''_E(B_{j,i,m}) = R''(B_{j,i,m}) \cdot Y(B),\\ &\text{down } R'_E(B_{j,i,m}) = R'(B_{j,i,m}) \cdot Y(B),\\ &\text{up and down } R_E(B_{j,i,m}) = R(B_{j,i,m}) \cdot Y(B).\end{aligned} \qquad (20)$$

The economic estimate of risks for cases $B^{I}_{j,m}$; $B^{I,M}_{j}$; $B^{I,J,M}$ (for *I* lines in one railway or *J* railways) can be obtained similarly by multiplying the corresponding probability of a transportation accident (formulas (6) – (17)) by the size of damage *Y*(*B*).

Let us estimate the probability of transportation accident $R(B^{M}_{j,i})$ involving trains on the Nevinnomysskaya – Tuapse line of 6 sections (*i* = 1, 2, 3, …, 6) of the North Caucasus Railway caused by the effect of three types of natural emergencies below on the sociotechnical system:

– flood ($m = 1$), frequency as compared to other types of emergencies $ц_1 = 0.06$, average annual number $N_1 = 1$, characteristic spatial scale $L_1 = 15$ km, characteristic duration $T_1 = 1$ h,

Table 1. Calculation data of transportation accident probability

i	Name of line	Length of line, km	Amount of traffic, trains per day	Flood (m = 1; φ_1 = 0.06; N_1 = 1; L_1 = 15; T_1 = 1)	Hurricane with wind strength not less than 22 mps (m = 2; φ_2 = 0.11; N_2 = 2; L_2 = 300; T_2 = 120)	Heavy rain (m = 3; φ_3 = 0.83; N_3 = 15; L_3 = 1; T_3 = 3)	Probability $R(B^M_{j,i})$
				Probability $R(B_{j.i.m})$	Probability $R(B_{j.i.m})$	Probability $R(B_{j.i.m})$	
1	Nevinnomysskaya – Armavir Rostovsky	77	46	$1.506\cdot10^{-4}$	$9.058\cdot10^{-4}$	$1.028\cdot10^{-9}$	$1.087\cdot10^{-4}$
2	Armavir Rostovsky – Kurgannaya	40.5	40	$5.165\cdot10^{-5}$	$4.765\cdot10^{-4}$	$2.122\cdot10^{-10}$	$5.552\cdot10^{-5}$
3	Kurgannaya – Belorechenskaya	63.8	41	$8.830\cdot10^{-5}$	$7.506\cdot10^{-4}$	$3.944\cdot10^{-10}$	$8.786\cdot10^{-5}$
4	Belorechenskaya – Komsomolskaya	19.8	42	$2.961\cdot10^{-5}$	$2.33\cdot10^{-4}$	$1.44\cdot10^{-10}$	$2.741\cdot10^{-5}$
5	Komsomolskaya – Krivenkovskaya	87.6	42	$1.31\cdot10^{-4}$	$1.03\cdot10^{-3}$	$6.361\cdot10^{-10}$	$1.212\cdot10^{-4}$
6	Krivenkovskaya – Tuapse	18.2	77	$8.89\cdot10^{-5}$	$2.142\cdot10^{-4}$	$7.187\cdot10^{-9}$	$2.89\cdot10^{-5}$

– hurricane with wind strength over 22 mps (m = 2), frequency as compared to other types of emergencies $ц_2$ = 0.11, average annual number of natural emergencies N_2 = 2, characteristic spatial scale L_2 = 300 km, characteristic duration T_2 = 120 h,

– heavy rain (m = 3), frequency as compared to other types of emergencies $ц_3$ = 0.83, average annual number of natural emergencies N_3 = 15, characteristic spatial scale L_3 = 1 km, characteristic duration T_3 = 3 h.

The calculation data is given in Table 1.

Using formula (14), let us estimate the probabilities of a transportation accident involving trains on 6 (i = 1, 2, 3, …, 6) lines of the North Caucasus Railway (j = 1) caused by three hazardous states (M = 3) of environmental objects: $R(B^{6.3}_1) = 4.295\cdot10^{-4}$. The mathematical expectation of the economic damage of TSD calculated as of 2019 will amount to $Y(B)$ = 429474.42 rub (formula (19)).

Then, the estimate of the economic risk of a transportation accident involving a train traveling on 6 (i = 1, 2, 3, …, 6) lines of the North Caucasus Railway (j = 1) will be (similarly to formula (20)):

$$R_E(B_j^{I,M}) = R(B_j^{I,M})\cdot Y(B) = R(B_1^{6,3})\cdot Y(B) =$$
$$= 24,295\cdot10^{-4}\cdot 429474,42 \cong 184,45 \text{ rub}.$$

If, for instance, we consider the case of transportation of 1 t of hazardous freight on this route that amount to approximately 6000 rub, the obtained economic estimate can be considered as the amount of coverage for the purpose of risk management (risk treatment) by means of transfer.

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Received on: 17.12.2018