Original article
DOI: 10.21683/1729-2646-2018-18-3-39-45

On traffic safety incidents caused by intrusion of derailed freight cars into the operational space of an adjacent track[1]

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Aim. *Derailments of rolling stock units (cars, locomotive units) of freight trains cause damage to roadbed and rolling stock, as well as possible loss of transported cargo. Of special interest are cases when derailed rolling stock units intrude into the operational space ofan adjacent track. This, for instance, happened in the case of the Moscow – Chi in u train at the Bekasovo I – Nara line on May 20, 2014, when as a result of the derailment of freight cars with subsequent intrusion into the operational space of an adjacent track 6 people were killed as the result of collision with an opposing train. In some cases intruding units may collide with an opposing freight train, which may cause the death of that train's crew and derailment of its cars, which in case of transportation of hazardous loads (e.g. oil and gasoline) may have catastrophic consequences. Intrusion into the operational space ofan adjacent track also interrupts the traffic in both directions. In this context, evaluating the probability of derailed cars intruding into the operational space of an adjacent track is extremely important in order to maintain the tolerable level of risk in railway transportation, while the aim of this paper is to construct functional dependences between the probability of derailed cars intruding into the operational space of an adjacent track and various factors.* **Methods.** *Probability theory and mathematical statistics methods were used: maximum likelihood method, logistic regression, probit regression, Cauchy regression.* **Results.** *For each of the groups of incidents: derailments due to faulty cars/locomotive units, derailments due to faulty track, using the classic binary choice model an estimation was constructed of the probability of at least one derailed freight car intruding into the operational space of an adjacent track. This estimation turned out to be dependent upon the train loading and number of derailed units. As the number of derailed units is a priori (before the derailment) unknown, it was suggested to construct the probability of intrusion by at least one derailed freight car into the operational space of an adjacent track using a parametric model of dependence between the average number of derailed units and various traffic factors. The resulting dependences were compared. A numerical example was examined.* **Conclusions.** *There is a significant direct correlation between the random values that characterize intrusion by at least one unit into the operational space of an adjacent track and the number of derailed freight train units. A direct dependence between the train loading and intrusion by derailed units into an adjacent track was established. In case of derailment due to faulty track, for loaded trains the probability of at least one derailed unit intruding into the operational space of an adjacent track is extremely high.*

For citation: *Zamyshliaev AM, Ignatov AN, Kibzun AI, Novozhilov EO. On traffic safety incidents due to encroachments on adjacent track clearances by derailed freight cars. Dependability 2018;3: 39-45. DOI: 10.21683/1729-2646-2018-18-3-39-45*

[1] The deliverables were obtained with the support of RFBR and JSC RZD as part of research project no. 17-20-03050 ofi_m_RZD

Introduction

According to 2013-2016 Russian transportation incident records, there were 37 cases of rolling stock derailment out of switches when at least one of derailed freight train unit intruded into the operational space of an adjacent track. As the result of such derailments, 6 collisions with moving or stationary opposing trains (including 1 passenger train) took place, which caused 8 deaths in opposing trains, as well as damage to cars/locomotive units of opposing trains, some of which had to be excluded from the inventory fleet. The average service delay for the adjacent track was about six and a half hours. As it follows from the given data, the problem of freight train units derailment and subsequent intrusion into the operational space of an adjacent track is extremely relevant. However, the problem related to the prediction of intrusion by derailed units into the operational space of an adjacent track remained unresearched both in Russia and abroad.

Among the publications dealing with the subject matter of this paper a special attention should be given to the following: in [2-4] using Poisson streams the risk of side collision between a passenger train and a shunting consist caused by signal violation by one of them was calculated; [5] inquired how much the traffic density must be reduced in order to bring the probability of traffic incidents to the European level. In [6], an indicator for the estimation of a factor's effect on the frequency of transportation incident was developed, while in [7] a one-sided confidence interval was constructed for the conditional probability of a certain event subject to a certain factor. In [8], the technical availability coefficient of a line section subject to its partial operability was estimated. In [9] the effect of thedistance travelled by a gondola car on the failure of various components. In [10], the probability of train derailment was estimated that depended on the class of track, length of the train and number of cars, distance travelled, yet did not take into consideration, for instance, the track geometry. In [11], the distribution series of the number of derailed units was estimated that depended on a number of geometrical features of the track and train movement parameters.

Since only two outcomes of rolling stock derailment are possible, i.e. the operational space of an adjacent track will be either intrudedor not, then the random value that characterizes the intrusion into the operational space of an adjacent track has a Bernoulli distribution with the parameter of the desired probability of the derailed units intruding into the operational space of an adjacent track. This value can be estimated with the sample estimate of probability [12], however such estimate will be quite rough, as it considers neither the geometric features of the track nor train movement parameters. For a more precise estimation, some functional dependences between the probability and various factors should be sought, which is enabled by the maximum likelihood method that is used further. In cases when a random value that produced the sample has a Bernoulli distribution, the maximum likelihood method yields a binary choice problem [13]. In the context of railway transportation the binary choice was examined, in [14] in particular as part of the problem that involved finding the probability of derailment caused by broken rail. In [15], using a logistic regression, a functional dependence was constructed between the probability of collision between trains and automotive vehicles at a random level crossing over a certain period of time.

This paper examines the problem related to the estimation of the functional dependence between the probability of at least one derailed rolling stock unit intruding into the operational space of an adjacent track and various factors. For this purpose, various binary choice models are considered: logistic regression, probit regression, Cauchy regression. The resultant dependences are analyzed. An example of the use of the obtained formulas is given.

Preliminary data analysis

Let us identify three groups of derailments. The first group will include derailments of cars out of switches caused by car or locomotive unit malfunction. The second group will include derailments of rolling stock units outside of switches caused by faulty malfunction. The third group will include all other derailments, i.e. derailments at switches, derailments caused by violations of locomotive operating conditions, etc. Let us analyze how often car derailments cause their intrusion into the operational space of an adjacent track for different groups of incidents based on the 2013-2016 records.

Let us note that the sum of the number of incidents when derailed freight cars intruded or did not intrude intothe operational space of an adjacent track is not equal to the number of derailments. This is due to the fact that some records do not contain information on intrusion or non-intrusion intothe

Table 1. Frequency of car derailments with and without intrusions by at least one derailed unit into the operational space of an adjacent track

Group of events	Number of derailments	Number of encroachments on adjacent track clearance	Number of non-encroachments on adjacent track clearance
1	150	22	90
2	38	15	9
Total	188	37	99

operational space of an adjacent track, while some incidents occurred in single-track lines.

As it follows from Table 1, the relative frequency of derailments with intrusion by the derailed units into the operational space of an adjacent track is significantly higher in the case of derailments due to faulty track. At the same time, the number of derailments with intrusion by the derailed units into the operational space of an adjacent track is higher in the case of derailment due to faulty cars/locomotive units. Therefore, both groups of incidents should be studied in order to estimate the parametric dependence of the probability of intrusion into the operational space of an adjacent track and various operational conditions.

Primary designations

In the j-th group of incidents out of n_j transportation incident records involving freight train cars derailment during train operation, let us examine a certain i-th record. For the purpose of this record, let

c_{ij} be the total number of derailed units of rolling stock (locomotive units and cars);

χ_{ij} be a coefficient that characterizes the number of tracks at the location of derailment that equals zero if the derailment occurred at a single-track line, and equals one if otherwise;

y_{ij} be a coefficient that characterizes the intrusion by at least one unit (locomotive units and cars) into the operational space of an adjacent track that equals one if at least one derailed unit intruded into the operational space of an adjacent track, and equals zero if otherwise;

k_{ij} is the counting number (from the head of the train) of the first derailed unit;

v_{ij} be the speed of the train at the moment of derailment, km/h;

l_{ij} be the number of wagons in the train;

l_{ij}^L be the number of locomotive units in the train;

w_{ij} be the weight of the train, t;

$æ_{ij}$ be the rate of curve at the place of derailment (value inversely proportional to the curve radius; for tangents the rate of curve is taken to be equal to zero), m^{-1};

γ_{ij} be the track profile at the place of derailment measured in promille having the minus sign if the gradient is downward and the plus sign if the gradient is upward.

As in [11], let us introduce another auxiliary variable function $\tilde{\mu}(w,l)$ that characterizes the loading factor of the train that depends on the train weight and the number of transported cars that is calculated using formula

$$\tilde{\mu}(w,l) = \frac{w}{69l} - \frac{1}{3}.$$

Also, as in [1], let us introduce an auxiliary variable $c^{\max} = l^L + l - k + 1$ that is the realization of a certain random value $C^{\max} = l^L + l - K + 1$, where K is the random value that characterizes the number of the first derailed unit. Further, we will call random value $C^{\max}$ the remaining length of the train.

Since it is impossible to intrude into the operational space of an adjacent track on a single-track line, further we will consider only those derailments that occurred on lines with more than one track, i.e. those that have $\chi_{ij} = 1$. Let us renumber according to the respective dates the records of incidents remaining after the exclusion of the records of incidents in the single-track lines. Let $\bar{n}_j$ records remain for the j-th group of incidents.

Let us note that, as in the case of construction of regression between the number of derailed cars and various factors in [11], in this paper there also is the problem of missed data. Records that miss at least one of the parameters required for the construction of a dependence of the probability of intrusion into the operational space of an adjacent track from various factors will not be considered.

Problem definition and method of solution

Let us consider the j-th group of transportation incidents. Let Y_j be a random value that characterizes the intrusion by at least one freight train unit intruding into the operational space of an adjacent track after derailment that equals one if the derailed units intruded into the operational space of an adjacent track, and equals zero if otherwise. Random variable Y_j can take values 0 and 1 with the probabilities $1-p_j(\cdot)$ and $p_j(\cdot)$ respectively, where $p_j(\cdot)$ is a function that contains the speed of the train at the moment of derailment v, length of the train l and other parameters. Therefore,

$$Y_j \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma \sim$$
$$Bi(1, p_j(c, c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma)).$$

Since the true function $p_j(\cdot)$ is unknown, we will seek its estimate $\hat{p}_j(\cdot)$. The simplest estimate $\hat{p}_j(\cdot)$ of the unknown function $p_j(\cdot)$ is the realization of the sample probability estimate, i.e.

$$\hat{p}_j(\cdot) = \frac{\sum_{i=1}^{\bar{n}_j} y_{ij}}{\bar{n}_j}.$$

However, this function does not allow taking into consideration either the track geometry or the train movement parameters.

In order to take account of the various train movement parameters we will seek function $\hat{p}_j(\cdot)$ as the function of train speed at the moment of the derailment v, train length l, rate of curve $æ$ at the location of derailment, the constants $a_{1j}, a_{2j}, \ldots, a_{m_j j}$ to be determined, as well as other parameters using the method of maximum likelihood. For convenience of notation, let us introduce the designation $a_j \overset{\text{def}}{=} (a_{1j}, a_{2j}, \ldots, a_{m_j j})^{\mathrm{T}}$. For function $\hat{p}_j(\cdot)$ the following formulas are true

$$P\{Y_j = 0 \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma\} =$$
$$= 1 - \hat{p}_j(a_j, c, c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma), \quad (1)$$

and

$$P\{Y_j = 1 \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma\} =$$
$$= \hat{p}_j(a_j, c, c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma), \quad (2)$$

while

$$M[Y_j \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma] =$$
$$= \hat{p}_j(a_j, c, c^{\max}, w, l^L, l, \tilde{\mu}(w,l), æ, \gamma).$$

By virtue of (1) and (2) the log-likelihood function is as follows:

$$\overline{L}_j(a_j, y_{ij}, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij}, i = \overline{1, \overline{n}_j}) =$$
$$= \sum_{i=1}^{\overline{n}_j} (1 - y_{ij}) \ln(1 - \hat{p}_j(a_j, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij})) +$$
$$+ y_{ij} \ln(\hat{p}_j(a_j, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij})).$$

Let us set the problem of finding the maximum likelihood estimates of parameters a_j:

$$a_j^* \overset{def}{=} (a_{1j}^*, a_{2j}^*, \ldots, a_{m_j j}^*)^T =$$
$$= \arg\max_{a_j \in R^{m_j}} \overline{L}_j(a_j, y_{ij}, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij}, i = \overline{1, \overline{n}_j}). \quad (3)$$

On the maximum likelihood estimate a_j^* of parameters a_j we have

$$\overline{L}_j^* = \overline{L}_j(a_j^*, y_{ij}, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij}, i = \overline{1, \overline{n}_j}).$$

Solution of the problem

The solution of problem (3) significantly depends on the choice of the structure of function $\hat{p}_j(\cdot)$. The structure of function $\hat{p}_j(\cdot)$ can be chosen, for example, according to the classic binary choice model: classic regression, probit regression, Cauchy regression that will be further used in this paper.

For the logic regression function $\hat{p}_j(\cdot)$ is as follows

$$\hat{p}_j(\cdot) = \frac{1}{1 + \exp\{g_{1j}(\cdot)\}},$$

where $g_{1j}(\cdot)$ is a function linear in parameters a_j, dependent on parameters $c, c^{\max}, w, l, l^L, \tilde{\mu}, æ, \gamma$.

For probit regression

$$\hat{p}_j(\cdot) = \Phi(g_{2j}(\cdot)),$$

where $g_{2j}(\cdot)$ is a function linear in parameter a_j, dependent on parameters $c, c^{\max}, w, l, l^L, \tilde{\mu}, æ, \gamma$, while $\Phi(x)$ is a standard normal distribution function (Laplace function) that is determined by formula

$$\Phi(x) = \frac{1}{2\pi} \int_{-\infty}^{x} \exp\left\{\frac{-t^2}{2}\right\} dt.$$

For the Cauchy regression the following equation is true

$$\hat{p}_j(\cdot) = \frac{1}{\pi} \operatorname{arctg}(g_{3j}(\cdot)) + \frac{1}{2},$$

where $g_{3j}(\cdot)$ is a function linear in parameters a_j, dependent on parameters $c, c^{\max}, w, l, l^L, \tilde{\mu}, æ, \gamma$.

Now, for different groups of incidents, let us calculate the constraint force between random value Y_j, $j = 1, 2$ and various movement parameters: speed v, track plan æ andothers, as well as the residual length of train $C^{\max}$ and number C of derailed rolling stock units. We shall understand constraint force as the realization of the sample correlation coefficient in case when the analysis involves two random values, and the number calculated using the sample correlation coefficient realization formula if the analysis involves a random value and a non-random factor.

As it follows from Table 1 and Table 2, there is a significant positive correlation between the random vari-

Table 2.Constraint force between random value Y_1 that characterizes the encroachments by at least one derailed unit on adjacent track clearances in case of derailment due to faulty car and various factors.

Parameters	C	$C^{\max}$	v	w	$\tilde{\mu}$	æ	γ
Constraint force	0.518	0.034	-0.117	0.123	0.239	0.022	0.117
Sample size	112	109	107	110	110	102	88

Table 3. Constraint force between random value Y_2 that characterizesintrusions by at least one derailed unit into the operational space of an adjacent track in case of derailment due to faulty track and various factors

Parameters	C	$C^{\max}$	v	w	$\tilde{\mu}$	æ	γ
Constraint force	0.647	0.148	0.346	0.398	0.484	-0.277	0.127
Sample size	24	24	22	23	23	23	19

Table 4. Comparison of various models for prediction of intruding by at least one unit into the operational space of an adjacent track in case of derailment due to faulty car/locomotive unit (based on 110 observations)

Regression	Dependence	$\overline{L}_1^*$	Likelihood ratio	Significance
Logit	$g_{11}(\cdot)=a_1$	-55.04	–	–
	$g_{11}(\cdot)=a_1+a_2c+a_3\tilde{\mu}$	-40.15	29.78	$4\cdot10^{-7}$
Probit	$g_{21}(\cdot)=a_1$	-55.04	–	–
	$g_{21}(\cdot)=a_1+a_2c+a_3\tilde{\mu}$	-40.71	28.66	$6\cdot10^{-7}$
Cauchy	$g_{31}(\cdot)=a_1$	-55.04	–	–
	$g_{31}(\cdot)=a_1+a_2c+a_3\tilde{\mu}$	-34.32	41.44	10^{-9}

Table 5. Comparison of various models of prediction of intruding by at least one unit into the operational space of an adjacent track in case of derailment due to faulty track (based on 23 observations)

Regression	Dependency	$\overline{L}_2^*$	Likelihood ratio	Significance
Logit	$g_{12}(\cdot)=a_1$	-15.395	–	–
	$g_{12}(\cdot)=a_1+a_2c+a_3\tilde{\mu}$	-6.55	17.69	$1{,}4\cdot10^{-4}$
Probit	$g_{22}(\cdot)=a_1$	-15.395	–	–
	$g_{22}(\cdot)=a_1+a_2c+a_3\tilde{\mu}$	-6.43	17.93	$1{,}3\cdot10^{-4}$
Cauchy	$g_{32}(\cdot)=a_1$	-15.395	–	–
	$g_{32}(\cdot)=a_1+a_2c+a_3\tilde{\mu}$	-7.779	15.23	$5\cdot10^{-4}$

ables Y_1, Y_2 and C. There is also dependence between the intrusion by at least one unit into the operational space of an adjacent track and the train loading. Thus, functions $g_{kj}(\cdot)$ must contain parameters $c$and $\tilde{\mu}$, $k=\overline{1,3}$, $j=\overline{1,2}$. In the case of derailment due to faulty track, a positive constraint force between the intrusion by at least one unit into the operational space of an adjacent track and the speed can also be noted, however, due to the small number of observations, the effect of speed on the probability of intrusions into the operational space of an adjacent track will not be researched.

Let us compare different types of regression based on the likelihood ratio for the best (out of those constructed) functions $p_j(\cdot)$ in terms of the value of log-likelihood function.

As it follows from Tables 4 and 5, when predicting the intrusion by at least one unit into the operational space of an adjacent track in case of derailment due to faulty rolling stock it is advisable to use the Cauchy regression, while in case of faulty track probit regression should be used. For both groups of events the significance level of the model is close to zero. That means that the obtained estimate $\hat{p}_j(\cdot)$ of function $p_j(\cdot)$ is sufficiently good. Among the disadvantages of the constructed model is the fact that the number of derailed units is a priori (before the derailment) unknown. For this reason, estimating the probability of intruding into the operational space of an adjacent track some estimates of the number of derailed units, e.g. average as in [11], can be used. For example, for the 2-nd group of incidents we obtain

$$\hat{P}\{Y_2=1\,|\,C=c,C^{\max}=c^{\max},w,l,l^L,\tilde{\mu}(w,l),æ,\gamma\}=$$
$$=\Phi(a_1+a_3\tilde{\mu}+a_2M[C\,|\,C^{\max}=c^{\max},w,v,l,\tilde{\mu}(w,l),æ,\gamma]),$$

where $a_1=-2{,}43$, $a_2=0{,}19$, $a_3=1{,}87$ (found while solving problem (3)), while

$$M[C\,|\,C^{\max}=c^{\max},w,v,l,\tilde{\mu}(w,l),æ,\gamma])=$$
$$=M[C\,|\,C^{\max}=c^{\max},v,\tilde{\mu}(w,l)])=$$
$$=1+\exp\{-6{,}04+1{,}01\tilde{\mu}+0{,}68\ln(v)+1{,}48\ln(c^{\max})\}$$

(found in [11]). Since the counting number of the rolling stock unit that derails first is a priori unknown, according to the formulas of multiplication of probabilities and composite probability [16] we conclude that

$$\hat{P}(A)=\chi\sum_{i=1}^{l^L+l}\Phi(-2{,}43+1{,}87\tilde{\mu}(w,l)+0{,}19M[C\,|\,C^{\max}=$$
$$=i,w,v,l,\tilde{\mu}(w,l),æ,\gamma])P(C^{\max}=i\,|\,w,v,l,\tilde{\mu}(w,l),æ,\gamma),\quad(4)$$

where A is the event that consists in that in case of derailment due to faulty track at least one unit of the freight train encroaches on the adjacent track clearances provided the movement parameters of each unit are fixed: w, v, l etc., $P(C^{\max}=i\,|\,w,v,l,l^L,\tilde{\mu}(w,l),æ,\gamma)$ is the probability that in case of derailment the realization of the residual length of the train is i rolling stock units, $i = 1, l^L + l$, while χ is the coefficient that equals one if the derailment occurred on a non-single-track line section, and equals zero if otherwise.

Example

Let the speed $v = 60$ km/h, train weight $w = 5400$ t, number of cars $l = 70$, number of locomotive units l^L=2, and traffic is not on a single-track line. A derailment due to faulty track occurs. Let us find the estimate of the probability that after this derailment at least one freight train encroaches on the adjacent track clearances.

We deduce

$$\tilde{\mu}(5400, 70) = \frac{5400}{69 \cdot 70} - \frac{1}{3} = 0,785.$$

For simplicity let us assume that

$$P(C^{\max} = i \mid w, v, l, l^L, \tilde{\mu}(w,l), æ, \gamma) =$$
$$= P(C^{\max} = i \mid l, l^L) = \frac{1}{l^L + l} = \frac{1}{2+70} = \frac{1}{72}, i = \overline{1,72}.$$

Then, according to formula (4) we deduce that the estimate of the probability of the sought for event is

$$\hat{P}(A) = \frac{1}{72}\sum_{i=1}^{72}\Phi\left(\begin{array}{c} -2,43 + 1,87 \cdot 0,785 + 0,19 \cdot \\ \cdot\left(\begin{array}{c} 1 + \exp\{-6,04 + 1,01 \cdot 0,785 + \\ +0,68 \cdot \ln(60) + 1,48 \cdot \ln(i)\} \end{array}\right) \end{array}\right) = 0,822.$$

The number turns out to be quite significant, which means that measures must be taken to keep the track in working order or significantly restrict the speed of the given train in order to avoid the intrusion by at least one derailed unit into the operational space of an adjacent track.

Conclusion

The paper examines the problem of probability estimation of at least one derailed freight train unit intruding into the operational space of an adjacent track for various types of incidents: derailment due to faulty track, derailment due to faulty rolling stock. Dependences between the random value that characterizes the intrusions into the operational space of an adjacent track and various factors, including random ones, were analyzed. The paper sets forth estimations of the probability of at least one derailed freight train unit intruding into the operational space of an adjacent track in random location on a line based on the maximum likelihood method for various types of incidents.

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Received on: 23.04.2018