Assessment of Risks of Derailment by Means of Computer Simulation

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Summary

The article presents method for assessment of the significance of factors of risk of the roiling stock derailment based on the computer experiment. The purpose of development of the method is to identify the most significant reasons for derailment among the possible mechanical reasons, i.e., those in the absence of which the derailment would not be possible. This includes the use of computer simulation of the dynamics of motion of separate railway rolling stocks and trains in general. Specifically designed dynamic models include the required parameters representing the state of railway rolling stock in operation. The proposed method can be used to analyze the tendency of the vehicle towards derailment according to the quantitative changes in safety parameters. The application of the developed method offer opportunities to find areas of further improvement of the running safety requirements in relation to the state of maintenance of freight cars and track and conditions of their rational operation to ensure an acceptable level of running safety.

Keywords: rolling stock, running safety, derailment, dynamics of motion, computer simulations of derailment factors

1. Introduction

The task of determination and elimination of common reasons for the rolling stocks derailment arises at the provision of the required level of traffic safety. Identification of factors that probably caused derailment is the task of the cause-and-effect analysis that is hard to cope with. This task is complicated by the large number of mechanical factors that collectively influence the processes accompanying the motion of trains [7, 9-11]. Derailment factors can include characteristics and parameters of the technical state of the rolling stock, the wagons of which are derailed, track maintenance condition in the area of derailment, scheme of the train set and operating conditions, etc. Identification of the most compelling reasons is one of the components of the provision of running safety and prevention of similar accidents in the future. Where an internal investigation found no violation of „limit values" for any of the controlled factors of the accident, or, conversely, combined violations for several factors were found, the degree of reliability of the conclusion about the main reasons for the accident is reduced.

It should be noted that the determination of the importance of derailment factors is the inverse problem with respect to the prediction of safety running parameters. Models of the dynamics of the rolling stock focused on the investigation of traffic accident have some differences from models designed for prediction of dynamic performances [2, 4, 5]. The characteristic feature of computer simulation technology for investigation of the rolling stock derailment is a significant amount of research (computing) options, and this is due to the necessity of adequate representation of circumstances of the traffic accident. These features do not cause complications due to modern development of computer facilities. In determination of importance of derailment factors the lack of information (uncertainty) in respect of certain elements of the examined mechanical system is the most significant one. Furthermore, the investigation of derailment is complicated by the fact that the reasons for derailment can include not only parameters, but also characteristics, circumstances, conditions, that is, data diverse in their structure, for example, scheme of the train set and operating conditions.

Combined computer model of the train dynamics was proposed to investigate the reasons for derailment of freight cars in the train set [6]. This model, which describes the longitudinal dynamics of trains

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in a traditional way, includes a group of three cars, each of which is represented by a spatial system of 19 rigid bodies and 114 degrees of freedom [1, 3]. The location of a train with the specified model of coupling as the sub-system in a general system is determined by the sequence number of the car that derailed first. This car is located at a central spot of the coupling scheme. Parameters of coupling cars required for the computer experiment including the car that derailed first, as well as other vehicle in the train set, are determined by the actual data of the official investigation.

In case of cars derailment in traction mode the appropriate traction characteristic of the train locomotive is formed in the model. If the derailment happened when braking, then the appropriate braking characteristics are formed. Characteristics of primary and secondary specific resistance to movement for each locomotive and car of the train are set according to the prescribed track layout at the area of derailment.

2. Simulation modeling

Difficulties in the use of technologies of simulation modeling for the assessment of the most possible reasons for derailment of the railway vehicle of any type are caused by several factors, most important of which are the following: computer model of the dynamics of the vehicle includes many components and connections with stochastic characteristics; the process of derailment is insufficiently formally defined; large amount of data obtained as a results of simulation experiment causes the need for development of the special approach to their analysis. The proposed general procedure of simulation experiment concerning the reasons for the rolling stock derailment can be summed up in the sequence of stages:

- determination of certain reliable factors of derailment in accordance with the result of investigation,
- structuring and ranking of undetermined factors,
- plan for the experiment,
- calculation of dynamic parameters of vehicle safety against derailment under the conditions of rerailing of the wheel flange on the top of rail,
- analysis and establishment of the degree of influence of undetermined factors according to the safety against derailment indexes.

It is necessary to set the actual technical characteristics and values of parameters of both car and track in order to carry out the investigation by means of computer simulation to identify possible reasons for derailment. Only in this way one can expect to increase the degree of reliability of the simulation of dynamic processes accompanying emergency situation and this will promote the efficiency of clarification of the circumstances that led to the derailment.

Of all the factors (conditions, characteristics, parameters) that may led to the derailment, one part of them is a priori probable, i.e. before the derailment, and the other part is a posteriori probable, i.e. after the traffic accident. The initial data available for the reliable determination include the general technical characteristics of the vehicle. These data are established according to the appropriate technical documentation and form the basis of parameters for simulation of dynamics of the railway vehicle of different types. Characteristics of the track maintenance conditions in the area of the derailment can be obtained according to the data of track recording car run nearest in time to the accident under investigation.

Due to the objective circumstances caused by the consequences of the accident some characteristics of running gears cannot be identified by the available means. Thus, obtaining of comprehensive data about the controlled sizes using regular measurement tools becomes impossible because of significant damages of wheelsets as a result of derailment. In such cases it is necessary to use methods of parameters identification to restore the required data using incomplete information.

At the stage of development of a computer model of the dynamics of the rolling stock its structural features should be considered and also it is necessary to provide the ability to display in the model all the factors that will be used in the computer experiment. The development of computer models of the dynamics of freight cars is made using the approach of the system of rigid bodies according to which the studied mechanical system is represented as a set of perfectly rigid bodies connected by joints and load-bearing elements.

Computer models of the dynamics of the rolling stock developed to assess the risks of derailment have some differences compared to models being developed for another purpose, for example, models for choosing rational parameters in the design of the rolling stock. Orientation of computer models towards the assessment of risks of the rolling stock derailment determines their specific feature and this feature is the formation of elements of the mechanical system according to parameters reflecting the actual technical condition of running gears. At the same time, following the experimental and computational concepts based on empirical data obtained according to the analysis of technical condition of railway vehicles using modern measuring methods, in addition to the simulation of main parameters the set of appropriate parameters and characteristics separately formed in the model. Models made in this way make it possible to find the reasons for derailment and to set limit values of parameters of the technical condition translating the formation of requirements to the system of the rolling stock maintenance into the demonstrative dynamics.

According to the method of computational mechanics, the numerical integration of motion equations in the time domain, which operate on specific numeric values, is the calculation tool that allows receiving solutions by means of mathematical description. Therefore, the development of specialized models of the dynamics and development of research methods based on the theory of experiments planning are the prerequisite for the assessment of risks of derailment. The reliability of the simulation results depends on the adequacy of the computer models of the dynamics of the rolling stock and formation of a plurality of factors of derailment.

3. Decomposition of factors of derailment

Due to the diversity of circumstances of derailment it was proposed to use decomposition of factors according to four groups substantially separated from each other in order to form generalized plan of the computer experiment. Group F_1 includes factors that show technical condition of the car that derailed first; group F_2 includes factors that show track maintenance condition in the area of derailment; group F_3 includes factors that characterize the scheme of the train set; group F_4 includes factors that relates to the train operation conditions. General set of factors of the accident F is the combination of factors from the following groups $F = F_1 \cup F_2 \cup F_3 \cup F_4$.

To develop the plan of the experiment it was proposed to represent diverse factors of the derailment as characteristics. At the same time, any characteristic can take two values: 1 for calculation according to the actual „value" of the relevant factor; 0 for calculation according to the nominal „value" or those that improves the circumstances of derailment.

Group F_1 consists of factors that characterize technical condition of the car that derailed first. The inclusion of factors to the group F_1 should be selective. It may happen that certain parameters of technical condition of the car coincide with the nominal ones when using information about the actual derailment, in this case the number of elements of the group F_1 decreases, consequently, the number of research options N_1 reduces.

Group F_2 consists of factors that characterize track maintenance condition and defects in the working surfaces of the rails: $F_2 = \{n_k, n_{rl}, n_{rr}\}$, where n_k is the characteristic of the track maintenance condition; n_{rl} is the characteristic of the working surfaces of the rails on the left side and n_{rr} – on the right side of the track in the direction of the train running on the area of derailment. If $n_k = 1$, data on the actual track condition are used in calculations; if $n_k = 0$, data representing track maintenance condition with deviations of the second degree (satisfactory condition) are used. Characteristics of the condition of the working surfaces of the rails n_{rl} and n_{rr} are used when the information on the wear of rails on the area of derailment is known. If n_{rl} (n_{rr}) = 1, data on the actual worn condition of the working surfaces of the rails are used; if n_{rl} (n_{rr}) = 0, data that describe working surfaces of the new rails are used, these data correspond to the type of rails in the area of derailment. If there is no information on worn condition of the rails, the number of options in this group is $N_2 = 2$, generally the number of options equals to $N_2 = 2^3$.

Research options for the experiment plan with the use of the third group are formed in accordance with the characteristics describing the loading of the rolling stock cars. The number of cars, models of cars and their sequence in the train remain unchanged. Group $F_3 = \{n_{1v}, n_{2v}\}$ includes two characteristics: n_{1v} is the characteristic of the loading of cars standing before the car that derailed first; n_{2v} is the characteristic of the loading of cars running behind the car that derailed first. Each characteristic n_{1v} and n_{2v} can take two values: 0 and 1. If $n_{1v} = 1$, the actual loading of the rolling stock cars standing before the car that derailed first is considered; if $n_{1v} = 0$, these cars are modeled in an empty state provided that the car that derailed first is also in an empty state; if the car that derailed first was in loaded condition, all cars that preceded it are considered as loaded. If $n_{2v} = 1$, the actual loading of the rolling stock cars standing behind the car that derailed first is considered; if $n_{2v} = 0$, these cars displayed in empty state provided that the car that derailed first is also in an empty state, or in loaded condition in opposite case. Consequently, the number of research options for this group is $N_3 = 2^2$. In case of derailment of the first or the last car of the train, the number of options reduced to $N_3 = 2$, if it is the study of the derailment of passenger train, $N_3 = 1$.

Research options for the experiment plan with the use of the F_4 are formed in accordance with the train operating conditions in the area of the derailment. This group includes the following characteristics $F_4 = \{n_{Vn}, n_{tr}, n_r, n_{tE}\}$, where n_{Vn} is the characteristic of the speed of movement V_n at the beginning of the derailment area; n_{tr} is the characteristic of time of change τ_r of train operating conditions measured from the moment when the first locomotive of the train run into the area of derailment; n_r is the characteristic of the applied braking mode or the controller notches of the driver for traction mode; n_{tE} is the characteristic of time of application of locomotive brakes. If derailment occurred in the stopping regime, group F_4 reduced to one element n_{Vn} that characterizes the speed of movement V_n: n_{Vn} = 1 means the actual speed of movement V_n determined in the investigation of the derailment; n_{Vn} = 0 – defined speed of movement is lower than the actual one (for example, 5 m/s lower). In this case the number of options is $N_4 = 2$.

Since it is known that the considerable forces provoking adverse dynamic processes may occur in intercar joints in the braking mode, especially when it is emergency braking, and sometimes in traction mode in combination with certain track layout in the area of derailment with a certain train set, then the calculations options of the group F_4 have to answer the question whether the derailment might occur at the actual mode of running of the train. The full group of characteristics of the group F_4 allows generating several scenarios of the train running including transitional modes of running. Besides, it is possible to override characteristics depending on the circumstances of the derailment. For example, if the derailment occurred in braking mode (traction), characteristics n_{tr} and n_r received the following values: 1 for actual running mode of the train; 0 for the mode that "softens" dynamic behavior.

Thus, obtained total number of research options, according to which the computer experiment is carried out, is $N = N_1 \cdot N_2 \cdot N_3 \cdot N_4$. In addition to the above, decomposition of factors of derailment allows, first, to structure them and, secondly, to reduce the number of groups and number of factors in each group, reducing the amount of calculation options, in case of known circumstances of derailment.

4. Organization of computer experiment

As demonstrated by the carried out researches, it is sufficient to take the total track length L_d = 300 m to perform computer experiment for determination of the influence of factors on derailment of freight cars. At the same time, it is also necessary to replicate all the track features in regards to the characteristics and geometry of rail profiles and maintenance condition at the L_d section. To show the track maintenance conditions based on data from the track measurement car rails irregularities on the left and right sides in the horizontal and vertical directions are formed in accordance with the developed algorithm. At the same time, the „synchronization" of irregularities according to the area of the derailment and place of the derailment accident is of fundamental importance.

Evaluation of running safety parameters, i.e. extreme value selection, is carried out in accordance with the derailment area just before the point of the derailment. The evaluation of extreme values of calculated running safety parameters and comparing them with corresponding acceptable values provides information on the possibility of the derailment under certain factors, but does not allow drawing conclusions about the significance of factors that influenced the accident. This fact determines the need for purposeful computer experiment on the conditions of the derailment accident, this experiment consists of N experiments with the change of factors which influence and selected for the set F.

Based on the research objective and significant amount of necessary calculation options arising in the mathematical description of the task of investigation of the derailment, picking out of factors from the set $F = \{f_1, f_2, ..., f_K\}$ should be ordered and based on the theory of experiments planning in order to ensure the maximum amount of information in conducting the fewest number of experiments.

The plan of full factorial experiment is developed when conducting computer experiment [7, 8]. The main requirements that apply to the plan of the experiment are their orthogonality and rotatability. The paired orthogonality condition of matrix columns of the planning is implemented in orthogonal plan. The use of rotatable plan for any direction from the center of the experiment provides the equivalence of accuracy of the estimation of the response function at equidistance from the center of the experiment. Based on the extreme values of running safety parameters determined in the area of derailment for each experiment the processing is carried out in relation to construction of the function of multiple regression depending on factors by the method of least squares.

The equation of multiple regression was chosen considering the major linear effects of factors and their interaction equal to or less than second order in the following form:

$$y = Y(f_1, f_2, ..., f_K) =$$
$$= b_0 + b_1 f_1 + ... + b_K f_K + b_{1,1} f_1 f_1 + b_{1,2} f_1 f_2 + ... b_{K,K} f_K f_K \quad (1)$$

where:

b_0 – absolute term of an equation,
b_k $(k = \overline{1,K})$ – main (linear) effect of k factor,
$b_{k1,k2}$ $(k1 = \overline{1,K}, k2 = \overline{1,K})$ – effects of interaction of factors and quadratic effects.

Desired coefficients b_0, b_k, $b_{k1,k2}$ of the equation (1) are determined as a result of solving the system of equations of the following form:

$$y_i = b_0 + b_1 f_{1i} + ... + b_K f_{Ki} +$$
$$+ b_{1,1} f_{1i} f_{1i} + b_{1,2} f_{1i} f_{2i} + ... b_{K,K} f_{Ki} f_{Ki}, \ (i = \overline{1,N}), \quad (2)$$

where:
f_{ki} is the value of k factor during the i experiment;
y_i are extreme values of running safety parameter determined in the area of a derailment accident.

The said task is solved according to the principle of maximum likelihood, which allows to calculate coefficients b_0, b_k, $b_{k1,k2}$ using the least squares method. At the same time, function $\Phi(b_0,b_1,...,b_{K,K})$ which is formed on the basis of:

$$\Phi(b_0,b_1,...,b_{K,K}) = \sum_{i=1}^{n}[(y_i - Y(f_i,b_0,b_1,...,b_K,b_{1,1}...,b_{K,K})]^2 \tag{3}$$

is minimized.

Thus, this task is reduced to a system of equations obtained as the first derivative of the function Φ according to every parameter b_0, b_k, $b_{k1,k2}$:

$$\begin{cases} \dfrac{\partial\Phi}{\partial b_0} = 0 \\ \dfrac{\partial\Phi}{\partial b_1} = 0 \\ ... \\ \dfrac{\partial\Phi}{\partial b_{K,K}} = 0 \end{cases} . \tag{4}$$

After recording the system of equations (4) considering (3) one obtains a system of linear equations to determine the parameters b_0, b_k, $b_{k1,k2}$:

$$\begin{cases} \sum_{i=1}^{n}\left[y_i - Y(f_i,b_m)\right]\cdot Y'_{b_0}(f,b_1,b_2,...,b_{K,K}) = 0 \\ \sum_{i=1}^{n}\left[y_i - Y(f_i,b_m)\right]\cdot Y'_{b_1}(f,b_0,b_1,...,b_{K,K}) = 0 \\ ... \\ \sum_{i=1}^{n}\left[y_i - Y(f_i,b_m)\right]\cdot Y'_{b_m}(f,b_0,b_1,...,b_{K,K}) = 0 \end{cases} . \tag{5}$$

Solving the system of equations (5) with respect to the parameters b_0, …, b_K, $b_{1,1}$, …, $b_{K,K}$, one finds all coefficients and, therefore, the specific form desired regression function. To calculate coefficient the Gauss-Newton numerical method was used. The computer program in Mathcad system, which was tested during the processing of data of the computer experiment on the possibility of the derailment of gondola car in empty state, has been developed according to the abovementioned method.

It was found that the inclusion of additional components, which consider the interaction of factors above the second order, overcomplicate the regression model and does not provide additional information on evaluation of the impact of the derailment factors on running safety parameters [8, 12].

As a result of calculation of coefficients b_0, …, b_K, $b_{1,1}$, …, $b_{K,K,}$ the analytical description of functional connection of running safety parameters and factors of dynamic system is determined based on the results of the experiment allowing to evaluate the impact of these factors on the level of parameters. Thus, coefficients b_0, …, b_K, $b_{1,1}$, …, $b_{K,K}$ describe the contribution of each factor and their interaction to the value of running safety parameter of the car in the area of derailment. The process of transferring origin of coordinates to the center of the space of factors with coordinates is very important in the processing of data of any experiments which are described by the model in the form of hyperplane, because it allows getting the average value for b_0.

5. Evaluation of risks of derailment

In addition to a multicriterion approach in evaluation of risks of derailment, the tasks of identification of sources of risks of mechanical origin relating to changes in the characteristics of a technical condition of the rolling stock and track during operation require thorough study. The task of identification of possible changes is solved based on empirical approach according to statistics obtained during operation. Next, the integrated indicator of risk of derailment allowing classification of the degree of dangerous changes in technical condition of the rolling stock and track is calculated by means of computer experiment and calculation of levels of running safety parameters according to the set of standard operating conditions.

After the computer tests, it is also appropriate to present the results of each of them in the form of characteristics: 1 – the derailment occurred; 0 – it did not occur. If information on the mechanism of derailment is available, the recognition of the fact that the accident has occurred is performed based on the criteria applied in relation to the appropriate mechanism of derailment. In case when the mechanism of derailment is unknown, the recognition of the accident is carried out in accordance with the vector criterion:

$$z = \begin{bmatrix} z_1 & z_2 & z_3 & z_4 & z_5 \end{bmatrix}, \tag{6}$$

where each element z_j is the characteristic of the safety parameter of typical mechanism of derailment:
z_1 – in the event of wheel running over the top of rail,
z_2 – in the event of the car displacement,
z_3 – due to overturning of car,
z_4 – due to displacement of assembled rails and sleepers,
z_5 – due to spreading of the rail track.

If the derailment mechanism was found during the investigation, the evaluation of calculation options of the computer experiment involves the use of only one element of vector z, other elements are considered as limitations. Moreover, if the wheelset that derailed first was found, the accident recognition is carried out according to this wheelset.

The experimental results presented in such a way in binary system are used to calculate probabilities q_0 of the derailment accident Z and p_0 the opposite accident (derailment did not occur), and conditional probabilities q_i^+, q_i^-, p_i^+, p_i^- in the presence of F_i and absence of $\overline{F_i}$ characteristics of factors of i group ($i = \overline{1,4}$):

$q_i^+ = P(Z|F_i)$ i $q_i^- = P(Z|\overline{F_i})$ – accident Z in the presence of F_i and absence of $\overline{F_i}$,

$p_i^+ = P(\overline{Z}|F_i)$ i $p_i^- = P(\overline{Z}|\overline{F_i})$ – accident $\overline{Z}$ in the presence of F_i and absence of $\overline{F_i}$.

The significance of the impact of risk of the derailment factors is calculated as a difference of conditional probabilities of presence and absence of factors $P(F_i|Z)$ i $P(\overline{F_i}|Z)$ using the formula:

$$R(F_i) = P(F_i|Z) - P(\overline{F_i}|Z) = \\ = \frac{q_0 \cdot q_i^+}{q_0 \cdot q_i^+ + p_0 \cdot p_i^+} - \frac{q_0 \cdot q_i^-}{q_0 \cdot q_i^- + p_0 \cdot p_i^-}. \tag{7}$$

$R(F_k) = 0$ for factors F_k the presence or absence of which has the same effect on the probability of derailment. According to the results of classification, potentially dangerous areas with a high risk of derailment are identified. Further, these results are used to prevent accidents associated with the rolling stock derailment, in particular, for identification of reasonable terms and scope of repair work, which in turn will affect the cost of maintenance of the rolling stock.

6. Conclusions

The concept of the assessment of risks of the rolling stock derailment was developed. It combines identification of mechanical risks of derailment and technology of computer simulation of the dynamics of the rolling stock. Basic models of the rolling stock, which are focused on the assessment of derailment risks, together with an adequate display of design features of units of the rolling stock reflect the full range of features of technical condition of the rolling stock.

This article proposed the decomposition of factors of derailment into four groups: factors that show technical condition of the car that derailed first; factors that show track maintenance condition in the area of derailment; factors that characterize the scheme of the train set; factors that relates to the train operation conditions. The presentation of factors from each group is made in the form of characteristics which allows the formation of the plan of computer experiment not only by parameters but also by circumstances of the derailment accident. Initial data processing lies in recognition of probability of the accident for every experiment, presentation of the results as a vector with elements presented in binary system, and calculation of the significance of factors of derailment risks based on conditional probabilities.

The proposed approach to the assessment of risk of the rolling stock derailment is recommended for quick determination of significance of derailment factors and formation of reasonable regulatory requirements that provide guaranteed level of train running safety.

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Wykorzystanie środków symulacji komputerowej do oceny ryzyka wykolejenia

Streszczenie
Artykuł przedstawia metodę oceny czynników ryzyka wykolejenia się taboru, wykorzystującą symulację komputerową. Celem opracowania tej metody jest identyfikacja najważniejszych przyczyn wykolejenia spowodowanego czynnikami mechanicznymi, tzn. takich, bez których wykolejenie byłoby niemożliwe. Metoda ta polega na użyciu komputerowej symulacji dynamiki ruchu poszczególnych części taboru i pociągów. Modele dynamiczne, specjalnie do tego celu zaprojektowane, zawierają odpowiednie parametry przedstawiające stan taboru w trakcie eksploatacji. Zgodnie z ilościowymi zmianami parametrów bezpieczeństwa, proponowana metoda może być zastosowana do analizy tendencji pojazdu do wykolejenia. Zastosowanie tej metody daje możliwości znalezienia takich obszarów dalszej poprawy bezpieczeństwa ruchu związanego z utrzymaniem wagonów towarowych, torów i warunków ich eksploatacji, które zapewnią akceptowany poziom bezpieczeństwa ruchu.

Słowa kluczowe: tabor, bezpieczeństwo ruchu, wykolejenie, dynamika ruchu, symulacja komputerowa czynników wykolejenia

Использование средств компьютерного моделирования для оценки риска схода с рельсов

Резюме
В статье представлен метод оценки факторов схода с рельсов подвижного состава при использовании компьютерного моделирования. Целью этого метода является идентификация самых главных причин схода с рельсов из-за механических факторов, т.е. таких, без которых сход с рельсов является невозможным. Этот метод заключается в употреблении компьютерного моделирования динамики движения отдельных частей подвижного состава и поездов вообще. Динамические модели, разработанные специально с этой целью, содержают подходящие параметры представляющие состояние подвижного состава во время эксплуатации. Предлагаемый метод может быть использован для анализа тенденций единицы для схода с рельсов, согласно количественным изменениям параметров безопасности. Использование предлагаемого метода дает возможность найти такие области дальнейшего улучшения требований безопасностьи движения связанного с техническим обслуживанием грузовых вагонов, путей и условий для их рациональной эксплуатации для того, чтобы возможно было обеспечить приемлемый (подходящий) уровень безопасности движения.

Ключевые слова: подвижной состав, безопасность движения, сход с рельсов, динамика движения, компьютерное моделирование факторов схода с рельсов