Assessment of contribution of human factor and factors of material-technical supply to safety risks due to poor repair and technology

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Abstract. The paper discusses the method of assessment and analysis of functional risks within the infrastructure of the railway transport network. The basis of the method is laid down in [1-4], but the risk assessment subsystem was not described due to poor repair. This paper will try to fill this gap. A general diagram of traffic safety risks by factors was developed. The method of transforming the probability function of repair rules violation into the probability of traffic safety violation due to some repair is proposed. For this purpose, the problem of minimizing the disparity in non-linear equations determining scaled factors of traffic safety violation (TSV) due to repair is solved. The calculation results at the level of linear enterprise are presented.

1. Introduction
The paper presents the diagram and main features of the algorithm to assess actual and forecast contribution of a human factor (HF) and a material-technical supply factor (MTS) to safety violation risks of railway traffic due to low-quality repair and technology violation. The developed algorithm can be used as a subsystem for factor analysis of train safety risks at different levels of track economy and artificial structures.

2. Materials and methods

2.1 Overall risk assessment and indicator factorization framework
The general risk assessment diagram is presented in [1-4] under the name “hybrid method” since it includes the general logical-and-probabilistic method [5-7] and the statistics that are used to control the overall values.

2.2 Risk assessment subsystem according to MTS and HF factors
The general diagram of risk assessment subsystem for MTS and human factors is presented in Figure 1 alongside with the main stages of its implementation.

Unlike the assessment of functional risks by risk factors of technical condition (deviations of 3, 4 degree of the Urban Planning Code of the Russian Federation, rail deficiency, deficiency of metal parts of railroad switches, railway on wooden basis), in this case the factors leading to the violation of repair rules (RR) and repair technology (RT) are on the first place (item 2 of the diagram in Figure 1 and further, in the presence of data, feasible item 3). However, this tree gives the probability function of presence or absence of RR and RT violations, and in order to estimate the appearance of risk factors...
there is a need for item 3.a – assessment of actual probability of TSV due to RR and RT (per one risk factor of technical condition) and item 4 – such scaling of previously obtained probability functions (RR and RT violations), which leads to the risk factor as a result of repair. As a result of scaling, we obtain the probability function (item 5 of the diagram) of TSV risk factors due to repair.

Further (item 6 of the diagram) – construction of the event tree leading the risk factor to TSV (at the output), giving an opportunity to determine the probability of TSV for the 1st risk factor (item 7), which makes it possible to determine the probability of TSV in the end due to causes of violations of RR and RT (item 8) and to implement the Birnbaum schemes [5-7] to define the contribution into primary factors, and then to perform item 9-10 of the diagram.

Figure 1. General diagram of factor risk analysis during repair

The diagram, on the basis of which scaling is performed, is given in Figure 2 for the assessment of risk for TSV according to deviations of 3, 4 degree of the Urban Planning Code of the Russian Federation.
Proportion of total violations (TSV)

![Diagram](image)

Figure 2. Scheme used to obtain conditions when scaling the values of the probability function arguments

Here, \( \delta_1, \delta_2, \delta_3 \) – fractions in the quantitative assessment of the risk factor of \( j \) type, which we denote as \( \lambda \).

\[
\delta_1 + \delta_2 + \delta_3 = 1
\]

Implementation of the diagram shown in Figure 1. Item 1 of the diagram is implemented on the basis of \([2]\) – method of risk factors identification during repair, factors are listed in Table 1.

### Table 1. Types of factors

| Group of factors                  | Factor                                                                 | Reference number |
|----------------------------------|------------------------------------------------------------------------|------------------|
| Poor staff training and qualification | Understaffing of track servicemen                                       | 1                |
|                                  | Understaffing of section foremen                                        | 2                |
|                                  | Understaffing of track supervisors                                      | 3                |
|                                  | Understaffing of rail detector operators                                | 4                |
|                                  | Turnover of servicemen                                                  | 5                |
|                                  | Share of workers with the length of service in a position less than 1 year | 6                |
|                                  | Lack of tools and labor saving devices                                  | 7                |
|                                  | Incomplete assembly of DBS, %                                            | 8                |
|                                  | Underperformance of material-technical resources supply plan, %          | 9                |
|                                  | Lack of equipment to measure track parameters and railroad switches      | 10               |

Item 2. The event tree is constructed according to \([8]\), the horizontal line at the branching point – yes, the vertical line – not. The enlarged diagram of the event tree is shown in Figure 3.

Item 3. On the basis of the event tree, the probability function of no violations in repair is constructed by an expression that is built using the event tree (horizontal upper line – yes, vertical line – no \([8]\)):

\[
F(x_1, x_2, x_3, \ldots, x_8, x_9) = \prod_{i=1}^{9} x_i
\]

(1)

Specific values of arguments \( x_i \) are generated by individual mathematical models \([8-10]\).

The probability function of repair and technology violations:

\[
P(x_1, x_2, x_3, \ldots, x_8, x_9) = 1 - \prod_{i=1}^{9} x_i
\]

(2)
Figure 3. Enlarged event tree of violations during repair

For a specific situation at a linear enterprise, the number of repairs with the violation of repair technology or rules is calculated according to formulas:

\[ Q = N \cdot P(q_1, q_2, q_3, \ldots, q_8, q_9) \]  \hspace{1cm} (3)

\[ P(q_1, q_2, q_3, \ldots, q_8, q_9) = 1 - \prod_{k=1}^{9} q_k \]

where \( q_1, q_2, q_3, \ldots, q_8, q_9 \) – specific values of arguments derived from material supply data and the state of the “human factor”,

\( N \) – number of repairs;
\( x_i \) – variables \((0 \leq x_i \leq 1)\) determining a condition of all repair components;
\( \Pi \) – product sign;
\( I = 1 - 9 \) – whole index.

Here, in the time period of the task, there are clear values of the above variables, indicated respectively as \( q_1, q_2, q_3, \ldots, q_8, q_9 \)

\[ F(q_1, q_2, q_3, \ldots, q_8, q_9) = \prod_{k=1}^{9} q_k . \]  \hspace{1cm} (4)

Item 4. The scaling of variables is based on the fact that the topology of the event tree leading to the risk factor is the same as in Figure 3, and therefore the probability function of no risk factors in repair is represented by the same expression, but the value of variables is different. Let us define them as follows:

\[ q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^* \]  \hspace{1cm} (5)
and value of function:  
\[ F(q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^*) = \prod_{k=1}^{9} q_k^* \]  

The value of this function at such values of variables is known (usually from AS of TSM for infrastructure), but \( q_i^* \) is not known.

In factor analysis the problem is to determine the values (5) based on statistically known value \( Q = (\delta_1 + \delta_2) \cdot \lambda \) or

\[ N \cdot P(q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^*) = (\delta_1 + \delta_2) \cdot \lambda \]  

where \( \lambda \) – current intensity of risk factor of type \( j = 1-7 \);  
\( N \) – total number of repairs aimed at elimination and prevention of risk factors of \( j \) type;  
\( P(q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^*) \) – value of the probability function of risk factor due to violation of technology or repair rules.

\[ P(q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^*) = 1 - \prod_{k=1}^{9} q_k^* \]

The mathematical formulation of this task is as follows:

to construct the conversion of numbers \( q_1, q_2, q_3, \ldots, q_8, q_9 \) into numbers \( q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^* \), where:

\[ F(q_1^*, q_2^*, q_3^*, \ldots, q_9^*) = C \]

where \( C \) – constant obtained from calculations and fuzzy ratios expressed by terms:

Term 1: if \( q_i = 1 \), then \( q_i^* = 1 \) (if the state of the factor is complete, it does not contribute to the occurrence of risk factors).

Term 2. The closer \( q_i \) to 1, the smaller the change in it when converted into \( q_i^* \).

Term 3: if \( q_i = q_0 \), then \( q_i^* = q_0^* \) (equally imperfect factors contribute equally to risk occurrence).

Term 4: if \( q_i < q_0 \), then \( q_i^* < q_0^* \).

Calculation of factors \( q_i^* \) is based on the solution of a problem of minimizing the difference:

\[ (\prod_{k=1}^{9} q_k^* - C) \rightarrow \min. \]  

In this case \( q_i^* \) (\( i = 1-n \)) should lie in the interval \((\delta, 1)\), \( \delta > 0 \), and meet the above specified requirements (10)-(14).

After scaling, taking into account the implementation of items 5-6 and using the probability of TSV for 1 risk factor, we come to the conclusion that the probability of TSV due to repair is calculated according to the formula:

\[ P_{TSV}(q_1^*, q_2^*, q_3^*, \ldots, q_8^*, q_9^*) = (\delta_1 + \delta_2) \cdot (\lambda/N) \cdot p \]

where \( p \) – TSV probability per 1 risk factor by technical component calculated using the event tree and the probability function, which is described in detail in [3-4].

The contribution of factor \( i \) according to Birnbaum [5-6] is calculated as follows:

\[ P_{TSV}(x_i) = P_{TSV}(x_i = 1) \cdot P_{TSV}(x_i = q_i^* ) \]

Accordingly, the factor risk in a single economic equivalent is calculated by the formula:

\[ R(x_i) = P_{TSV}(x_i) \cdot W \]

where \( W \) – given average damage from the type of TSV whose risk is analyzed;  
\( R(x_i) \) – contribution to the risk of TSV factor with number \( i \).
With this approach, it is possible to obtain contributions from human and MTS factors by summing up all types of repairs in the main area of activities of a linear enterprise, regional and central management offices, i.e. in fact, in the railway network as a whole.

3. Results

Below is the example of calculation of contributions to the risk of MTS factors for one linear enterprise of the North Caucasus Office of Infrastructure and the influence of factors on contributions to risk.

The dynamics of risk factors (technical condition of track superstructure (TSS), MTS, staffing) in 2015 -2018 is presented in Table 2.

| Table 2. Risk data |
|-------------------|
| year | Deficiency of railway facility | Deviations in TSS maintenance | Deviations from maintenance standards of continuous welded rail | Staff | MTS factors |
|------|-------------------------------|------------------------------|---------------------------------------------------------------|------|----------------|
|      | Number of flawed rails in a main trunk route | Number of defective metal elements of railroad switches | Length of a route with unsatisfactory appraisal by points, km | Number of failures of a route of III, IV degrees per 100 km route | Number of repeated failures of a route of III, IV degrees per 100 km route | Length of track sections with excess operating time stress-free temperature | Understaffing of section foremen | Understaffing of track supervisors | Understaffing of track servicemen | Turnover of servicemen, % | Share of workers with the length of service in a position less than 1 year, % | Lack of tools and labor-saving devices | Lack of equipment to measure track parameters and railroad switches |
| 2015 | 112 | 14 | 10 | 29 | 183 | 61 | 2.7 | 189 | 78 | 98 | 100 | 100 | 3.8 | 4 | 18.3 | 27 | 57 | 71 |
| 2016 | 157 | 52 | 12 | 28 | 280 | 93 | 2.7 | 237 | 196 | 100 | 100 | 100 | 100 | 0.0 | 0 | 18.3 | 29 | 57 | 71 |
| 2017 | 268 | 146 | 0 | 10 | 107 | 36 | 2.7 | 235 | 294 | 96 | 95 | 100 | 88 | 2.2 | 2 | 18.3 | 32.8 | 57 | 71 |
| 2018 | 298 | 52 | 22 | 4 | 165 | 22 | 28.3 | 417 | 1 | 98 | 98 | 100 | 85 | 2.0 | 2 | 37.2 | 100 | 65 | 95 |

**DBS – distance-based stock**

There is an increase of indicators “Number of failures of a route of III, IV degrees per 100 km”, “Number of places of temporary repair of continuous welded rail strings per 100 km of a main trunk route”.

4. Discussion

There is positive dynamics of the factor within 2017-2018:

- DBS from 62% to 100%,
- feasibility of the MTS plan,
- availability of route measuring tools and railroad switches.
- understaffing of track servicemen,
  - understaffing of track servicemen,
  - staffing of rail detector operators.

5. Risk calculation and risk dynamics.
One of the calculation steps is to calculate the risk matrix parameters according to [9, 10].
For this enterprise, the boundaries of risk levels are given in Table 3.

| Category, color | Unacceptable | Unfavorable | Acceptable (Admissible) | Negligible |
|----------------|--------------|-------------|------------------------|------------|
| Category boundaries | 73.01 < R    | 12.17 < R < 73.01 | 2.03 < R < 12.17       | R < 2.03   |

The results of risk calculation and assessment by factors are presented in Table 4.

| Main factors | Poor staff training and qualification | MTS level |
|--------------|--------------------------------------|-----------|
| Indicators defining the level of risk development | Understaffing of track servicemen | Understaffing of track servicemen | Understaffing of track servicemen | Understaffing of track servicemen | Understaffing of track servicemen | Understaffing of track servicemen | Understaffing of track servicemen |
| 2017         | 90  93  0.0  150 247 82 69 73 69 18 482 |
| 2018         | 32.6 32.4 0.0 64.4 92.4 28.1 28.6 29.0 28.6 9.2 212 |

* The total risk level was determined taking into account factors of technical condition, the calculation diagram of which is specified in [3-4].

Due to measures taken, the total risk level has decreased by 2.5 times, but is in the category of “unacceptable”.

6. Conclusion.
The calculations showed that the objective consideration of the impact of MTS completeness, staffing and staff turnover allowed adding the list of measures with measures positively affecting the risk dynamics towards reduction.

The calculations also show a significant non-linear degree of risk reduction with positive factors (improvement of conditions) of MTS and human factors. At the same time, even some deterioration of the condition of factors of “technical condition” and the increase of risks associated with it are more than compensated for through the improvement of MTS and human factor.
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