Improving the safety indicators of Ukrainian railways: a study of the longitudinal stability of the railway track

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Abstract. The article considers the problem of improving safety indicators on the railways of Ukraine, in particular, with regard to the temperature-stressed jointless track, which makes up more than 75% of the total length of the main tracks. During the operation of this structure, there is a risk of dangerous failures, such as "track ejection" and "rail and sleeper grid displacement", which can lead to a rolling stock derailment. The article considers various aspects of this problem and analyses the stress state of the jointless track in the context of loss of longitudinal stability, investigating the factors that affect this risk. The purpose of the article is to propose comprehensive solutions to reduce the risk of loss of longitudinal stability of the continuous track and improve safety on Ukrainian railways. The study is based on the analysis of actual cases of rolling stock derailments due to loss of rail and sleeper grid stability. The article also examines the regulatory approach to determining the conditions of longitudinal stability of continuous track in Ukraine and the European Union and compares their approaches. Finally, the authors of the article offer proposals for improving the safety performance of railways, including the introduction of: the European approach to authorization of the subsystem "infrastructure"; modern systems for diagnostics and monitoring of the state of infrastructure; and an approach to work planning based on the assessment of the probability of the risk of loss of rail and sleeper stability. The general context of the article is to improve traffic safety on Ukrainian railways and to avoid transportation accidents associated with the loss of longitudinal stability of the rail and sleeper grid of a jointless track.

1 Identification of the problem

The temperature-stressed jointless track is the most common construction of the main tracks of Ukrainian railways. Today, it is more than 20 thousand kilometres long, which is about 75% of the total length of the main tracks. During the operation of this structure, such dangerous failures as "track ejection" and "rail and sleeper displacement" may occur, which can cause rolling stock to derail.

According to [1], if the change in the track position in the plan view occurred under the influence of longitudinal temperature compression forces without additional impact from the train and instantly, it is a "track ejection" (if the change occurred gradually, it is a "track angle"). If the change in the track position in the plan is due to the simultaneous influence of longitudinal temperature compression forces and rolling stock forces, it is a rail and sleeper displacement.

On Ukrainian railways, the number of cases of loss of stability of the continuous track is increasing annually, with the most common of them being the occurrence of such failures as "angle in plan".

It should be noted that when studying the mechanism of transport accidents, there are transport accidents in which one of the causes of rolling stock derailment is such malfunctions of the continuous track as "track ejection" and "rail and sleeper grid displacement". Unfortunately, such accidents also occur during the operation of passenger trains, which is a serious threat to railroad safety.

Compared to the European Union, the number of such incidents on Ukrainian railways is higher. Therefore, it is very important to have tools for assessing traffic safety, in particular the probability of such failures associated with the loss of longitudinal stability of the rail and sleeper grid of a continuous track.

The purpose of our study is to investigate a set of factors that affect the loss of longitudinal stability of a continuous track and to propose comprehensive solutions to reduce this risk. To achieve this goal, we have analysed actual cases of rolling stock derailments due to loss of rail and sleeper grid stability. In this study, we will present an example of one such case.

Subject of the study: temperature-stressed jointless track on Ukrainian railways.

Object of study: condition and safety of temperature-stressed jointless track on Ukrainian railways, in particular, loss of longitudinal stability of the rail and sleeper grid and incidents related to this problem.

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2 An example of a transportation event in which there was a loss of longitudinal stability of a jointless track

2.1 Characteristics of the track section at the rolling stock derailment

At picket No. 1 of the 10th km of the odd railway track of the A-B section (all parameters that identify the location of the event have been changed), six cars of an accelerated electric train derailed. Car 4 of the electric train was the first to derail.

Characteristics of the accident site: number of main tracks - 2; rise - 3.4 ‰; curve with a radius of 867 m; excavation with a depth of 1.92 m; automatic interlocking. Passed tonnage - 556 million tonnes gross. The average repair was carried out 1.5 years before the accident. The temperature of the plates' fixing is +26 °C.

Weather conditions: light, visibility 20,000 m, wind 5 m/s, air temperature +11°C. The rail temperature on the derailment section at the time of derailment was + 20 °C.

Characteristics of the track superstructure:
– rails of P65 type (longitudinal slabs of jointless track), actual lateral wear of the rail head ranged from 0 to 5.4 mm, no sharply defective rails;
– sleepers are reinforced concrete;
- there were no unserviceable sleepers in this section of the railway;
– intermediate fasteners - terminal-bolt type KB-65. In this section, the defectiveness of the fasteners was 21%, there were up to 27% of missing under-rail gaskets and some reinforced concrete sleepers were skewed (which is a sign of the theft of the right-hand plate of the jointless track). The mentioned 21% defectiveness of the fasteners relates to metal parts (KB-65 lining, terminal bolts, embedded bolts). Unsuitable rubber gaskets were not replaced during the mid-life overhaul;
– ballast is gravel;
– ballast contamination is within normal limits.

Figures 1, 2 and 3 show the technical condition of the KB-type fasteners after the derailment.

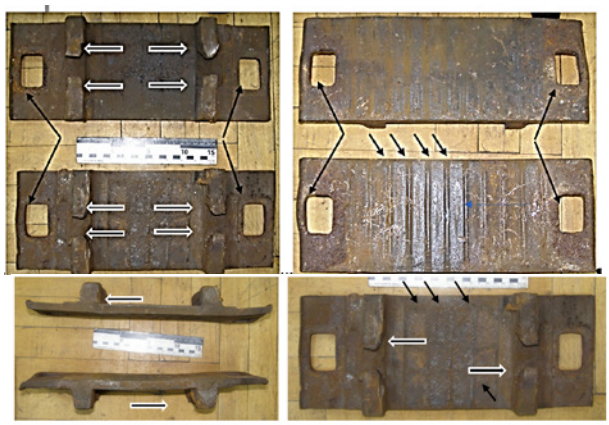

Fig. 1. Metal substrates from the train derailment area

As can be seen from these photographs, these intermediate fasteners show signs of longitudinal movement (bending) of the rail plates.

The jaws of the metal gasket under the bolt heads are deformed by torsional forces (Fig. 1; shown by double arrows). The metal gaskets are deformed in plan (Fig. 1).

Fig. 2. Underrail gaskets from the area where the derailment occurred

Both the front and back sides of the under-rail gaskets (Fig. 2) show signs of long-term operation in conjunction with the rail sole: material displacement, undiscovered cracks, material wear in the area of the recesses, and uneven fit to the rail sole plane.

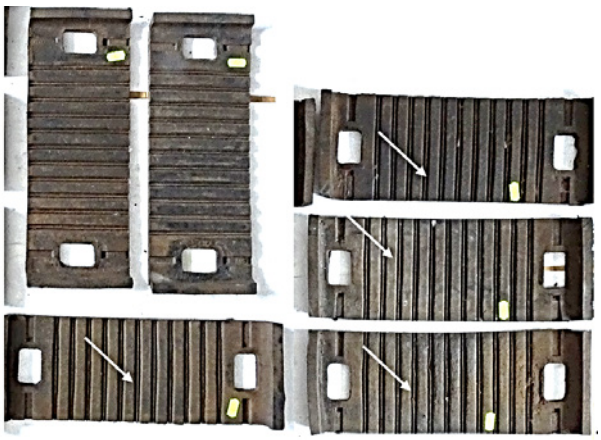

Fig. 3. Trench gaskets from the area where the derailment occurred

During the research, it was found that at the point of derailment, under-rail gaskets with markings that did not meet the requirements of the regulatory documents in force in the railway transport of Ukraine for this type of rail fastening were in use [2, 3]. In other words, the issue of the quality of these gaskets can be considered relevant in this case.

The absence of under-rail gaskets in the derailment area (up to 27 %) reduced the longitudinal stability of rail plates, since according to DSTU [2], under-rail gaskets are intended, among other things, to increase the longitudinal stability of rail plates.

During the investigation of this accident, the results of the track inspection by track measuring cars (4 months before the derailment) were analysed. As a result, it was found that at the point of the rolling stock derailment, deviations in the direction of the 3rd to 5th degree were repeatedly detected. For example, in January, a 28 mm/37 m 4th stage deviation was detected, in February, a 26 mm/37 m 4th stage deviation, in March, a 32 mm/24 m 4th stage deviation and a 36 mm/20 m 5th stage deviation, which occurred the day before the train derailment. To eliminate these track faults, track crews carried out track straightening works using hydraulic straighteners. After the track deviation was corrected, the train speed restriction was lifted 1 day before sunrise.

Figure 4 shows a freeze frame of the driver's cab video, which shows a clear deviation in the position of the rail strands in the plan at the derailment point, which can be classified as a "corner in the plan".

Fig. 4. Location of the rolling stock derailment

This is where the derailment occurred. The first to derail was the 1st wheelset of the 4th car of the train to the left. It should be noted that approximately 50 m before the visualised fault, the driver applied external braking.

The study found that the cause of the rolling stock derailment was the displacement of the rail and fuel grid, i.e., a change in the position of the track in the plan view, which occurred under the simultaneous influence of longitudinal temperature compression forces and rolling stock forces.

The mechanism of the railway accident is not covered in this study.

2.2 Analysis of the stress state of a jointless track in the area of rolling stock derailment

After the last re-securing of the longitudinal sleeper for permanent operation (t=+26 °C), 400 m before the derailment, track works were performed that affected the change in the stress state of the continuous track, namely:
– on the right rail: December (4 months before the derailment) - temporary restoration of the rail, with the right rail moving (shortening) to increase the distance by 150 mm; February (2 months before the derailment) - replacement of the temporary restoration rail with an extended rail, additional movement (shortening) of the right rail by another 230 mm;
– on the left line: on the day of the derailment - cutting of the plate and laying of a rail 8.23 m long.

After the derailment of the electric train, the values of the change in the control sections for the placement of marks on the "lighthouse sleepers" were determined. Let's analyse the results of the control cross-sectional movements:
– right track: at the point of temporary restoration rail installation, the mark was displaced by 390 mm. This displacement occurred within the breathing end of the slab, for which it is not possible to analyse changes in the temperature regime of slabs along "lighthouse" sleepers [4]. The value of the displacement of the marks on the neighbouring "lighthouse" sleepers towards the place of derailment is 30 mm, 0 mm and 5 mm. Further, at the point of derailment, it is impossible to determine the value of the displacement of the marks on the neighbouring lighthouse sleepers, since the upper track structure was destroyed as a result of the train derailment. Based on the obtained values of changes in the displacement of the risks on the neighbouring lighthouse sleepers, in accordance with clause 7.4.4 of the Technical Guidelines [4], the change in the temperature of the plate fixing from the place of installation of the temporary restoration rail towards the derailment point was determined, namely: decreased by 24 °C; not changed; decreased by 4 °C (values taken between the "lighthouse sleepers"). The values obtained for the displacement of the slab towards the derailment site and the drop in the setting temperature at the initial section of the slab indicate that the track works were performed at a temperature lower than the setting temperature; the slab displacement occurred as the longitudinal resistance to longitudinal movement was overcome. The gaps between the rail of temporary restoration on the right track after derailment were 3 mm and 10 mm. The gaps were within normal limits.
– left track: at the point of cutting of the tie - the displacement of the mark was 15 mm (breathing end of the tie); the value of the displacement of the marks on the neighbouring lighthouse sleepers is: 3 mm, 8 mm, 2 mm; further, the upper track structure was destroyed as a result of a train derailment. The gaps in the joints were 34 mm and 22 mm. The gap before the short rail is larger than normal, and the gap after the short rail in the direction of increasing kilometres is within normal limits.

It should be noted that the difference in the movements of the control sections between the right and left tracks was caused by the fact that track works were performed on the right and left tracks at different actual rail temperatures.

The cutting of the left rail on the day of the derailment was due to the fact that the day before on the left line (in the place where the derailment occurred) there was a deviation of the rail strands in the plan of 5 degrees. And in accordance with the requirements of paragraph 7.8.3 of the Technical Guidelines [4], it is stated that "in some cases, in case of urgent need for complete stress relief,

long strands should be cut into short ones and temperature stresses should be discharged using conventional technology". On the day of the derailment, between 9am and 2pm, work was carried out to cut the left-hand rail and lay a temporary 8.23m long rail.

No work was carried out on the right rail after the temporary restoration rail was laid to completely restore the right rail. During this period of operation, the breathing end of the plate was displaced by 390 mm. This amount of movement occurred due to the following reasons. At the standard longitudinal resistance to longitudinal movement of 25 kN/m, in the event of a plate fracture, a gap is formed, the size of which depends on the temperature drop of the rail plate compared to the fixing temperature. With a permissible temperature drop of 72 °C for P65 rails, a gap of up to 50 mm is formed [4]. However, for fasteners of the KB type, the established longitudinal displacement resistance is 20.8 kN/m at a test pattern of 1840 pcs/km and tight terminal tightening, and 14.7 kN/m at a test pattern of 1840 pcs/km and medium terminal tightening [1]. During the temporary restoration work 4 months before the derailment, a gap of 150 mm was formed when the plate was cut, which is more than the standard 50 mm. The increase in the gap is due to the reduced linear resistance for this type of fastener compared to the standard value in the calculation, which was formed when the plate was broken.

That is, in the course of operation at the study site, the right and left strands of the jointless track changed their stress state by the time of derailment. At the same time, the hardening temperature of the right and left end parts of the plate decreased. During the track works, longitudinal deformations of the rail plate occurred at the end section of the plate when the temperature changed by a certain number of degrees. The longitudinal deformations of the end part of the right-hand slab (150 mm and 230 mm) at a decrease in the hardening temperature were taken into account by laying temporary rails of the design length (from 8.06 m to 8.29 m). Smaller longitudinal displacements were observed on the left slab, since the works were performed at temperatures close to the actual temperature of the left slab fixing for permanent operation (+26 °C).

As a result of the above conditions of operation of long-length slabs, an uneven change in the temperature of slab fixation was formed in the study area (400 m to the site of the east). At the same time, in accordance with clause 7.4.4 of the Technical Guidelines [4], the temperature of the plate consolidation from PK8 to PK9 decreased by 24 °C and amounted to +2°C. Within the next pickets, the difference in the offset of the lines between adjacent "lighthouse" sleepers was up to 5 mm. Accordingly, the setting temperature on PK9...PK10 was +26°C, PK10...PK1 +22 °C.

The unevenness of the tie temperature along the length of 400 m to the derailment point and between the left and right rail strands contributed to the development of deviations of the rail strands in the plan. To stabilise the position of the rail ties, it was necessary to carry out the final restoration of the ties as soon as possible [4]. However, the terms themselves are not specified in the regulatory document.

The change in the longitudinal displacements of the control sections in the study area (excluding the breathing end of the girder) did not exceed 30 mm, so the established speed was limited to 60 km/h in accordance with the requirements of 4.1.4. No technical guidelines [4] were required, i.e. the rail slabs of the jointless track on the section of 400 m to the derailment point were in good condition.

It is not possible to establish whether there was a need to limit the speed of trains at the point of derailment, since this part of the track was destroyed as a result of the derailment.

During the investigation of the case file, it was found that the rail and sleeper grid had been displaced in the derailment area.

3 Normative approach to determining the conditions of longitudinal stability of a jointless track

Let's look at the requirements of regulatory documents in Ukraine and the EU regarding longitudinal track stability and compare approaches.

According to paragraph 4.2.6.2.1 TSI INF [5], it is established that: «The track, including switches and crossings, shall be designed to withstand longitudinal forces equivalent to the force arising from braking of 2,5 m/s^2 for the performance parameters chosen in accordance with point 4.2.1.

According to paragraph 4.2.6.2.2 TSI INF [5], it is established that: «The track, including switches and crossings, shall be designed to be compatible with the use of magnetic braking systems for emergency braking».

According to paragraph 4.2.4.5.1 TSI LOC&PAS [5], it is established that: «The maximum average deceleration developed with all brakes in use, including the brake independent of wheel/rail adhesion, shall be lower than 2,5 m/s2; this requirement is linked to the longitudinal resistance of the track».

According to [1], to ensure the longitudinal stability of the track, it is necessary that:

1) the longitudinal forces acting on the rail plate do not exceed the forces of resistance to the movement of sleepers in the ballast;

2) the same forces do not exceed the resistance forces provided by rail fasteners.

In other words, the longitudinal stability of the track will be ensured if there is no joint longitudinal movement of the rails with the supports and no longitudinal slippage of the rail sole on the supports.

The first condition (which should be called the longitudinal stability of the rail and sleeper grid) will be met if the elastic longitudinal response of each support does not exceed the permissible resistance to movement of that support along the track, i.e. the inequality must be met:

$$\max(p_{зг}^{пр} + p_{гальм}^{ср}) \cdot l_ш + p_t^{роз} \cdot l_ш \leq \frac{[W_0^{пр}]}{K_з} \qquad (1)$$

- $p_{зг}^{пр}$ - is the longitudinal force due to elastic bending of the rail, *kN/m*;
- $p_{гальм}^{ср}$ - is the distributed braking force transmitted from the wheels of a moving train to the rail thread, *kN/m*;
- $l_{ш}$ - is the distance between the sleeper axes (width of the 1st sleeper span), *m*;
- $p_t^{роз}$ - is the distributed longitudinal temperature force acting on the rail (in case of a link track) or on the rail plate (in case of a jointless track), *kN/m*;
- $[W_0^{пр}]$ - is the permissible resistance to movement of the sleeper along the track (attributed to one rail thread), *kN*;
- $K_з$ - factor of safety for longitudinal stability (assumed to be $K_з$ =1,15).

Values of permissible resistance to movement of an unloaded sleeper along the track $[W_0^{пр}]$attributed to one rail thread, are given in Table 19 [1].

The second condition (which should be called the longitudinal stability of the rail track) will be met if the total longitudinal rail bending forces (together with the temperature longitudinal forces) do not exceed the longitudinal movement resistance forces provided by the rail fasteners:

$$\sum p_{угон+темп} = \max(p_{зг}^{пр} + p_{гальм}^{ср}) + p_t^{роз} \leq [r_{скр}^{пог}] + + \frac{2 \cdot R_н^{'}}{K_з \cdot l_{бп}}, \quad (2)$$

- $[r_{скр}^{пог}] = \frac{r}{K_з}$ - is the permissible longitudinal resistance of the rail thread provided by the fastener (*kN/m)*. The values of *r* - the calculated longitudinal resistance to the longitudinal movement of the rail sole along the base for modern types of fasteners are given in Table 20 [1];
- $R_н^{'}$ - length of the buttless plate, *m*;
- $l_{бп}$ - is the value of resistance to longitudinal movement of the rail plate in the joint lining, *kN*.

In other words, the national requirements consider two main conditions for ensuring the longitudinal stability of a temperature-stressed jointless track. The first condition requires that the longitudinal forces acting on the rail plate do not exceed the forces of resistance to movement of the sleepers in the ballast. This means that the longitudinal forces due to elastic bending of the rail, the distributed braking force and the thermal force must not exceed the permissible resistance to movement of the sleeper along the track, which is defined by the standards. The second condition requires that the total longitudinal rail bending forces, including thermal longitudinal forces, do not exceed the longitudinal movement resistance forces provided by the rail fasteners. This means that the rail track must be able to withstand rail runout and temperature loads without exceeding the permissible longitudinal resistance, which is determined by the calculated longitudinal resistance to longitudinal movement, considering the length of the jointless plate and the resistance in the joint linings.

According to the European requirements, the longitudinal stability of a jointless track must consider such requirements as resistance to longitudinal forces during braking, compatibility with magnetic braking systems for emergency braking and maximum average deceleration due to braking. The overall objective of these requirements is to ensure the safety and stability of the track during braking and other similar operations.

Thus, the approaches to ensuring longitudinal continuous track in the EU and Ukraine have significant differences in the requirements and criteria for assessing track stability.

4 Proposals for improving the safety performance of Ukrainian railways in the context of ensuring the longitudinal stability of jointless track

In order to ensure the required level of railway traffic safety in the event of possible dangerous failures associated with the loss of stability of the rail and sleeper grid of a jointless track, the following tasks must be solved in operational practice:

1. *Determination of the probability of ejection and displacement in a particular section of the railway track*. This is a focused study and analysis of the factors that can lead to a derailment and displacement of the rail and sleeper gauge of a continuous track.
2. *Evaluation of the obtained values of the probability of ejection and derailment from the point of view of traffic safety*. This is the determination of the risk and safety of railway traffic based on the obtained data on the probability of derailment and derailment, taking into account the potential consequences of such events for the safety of passengers and personnel.
3. *Development of measures aimed at reducing the level of risk to the minimum established level*. This includes the development and implementation of specific technical, organisational, and preventive measures aimed at preventing rail and sleeper derailments, improving railway safety, and ensuring compliance with minimum risk levels.

These tasks are aimed at ensuring the safety and reliability of railway transport and require joint efforts of engineers, researchers, and railway traffic system operators. In particular, the issue of ensuring the functional safety of the railway track under the influence of rolling stock is considered in [6].

Proposals for improving safety performance on Ukrainian railways include several measures and recommendations. First, it is recommended to introduce effective modern systems for diagnosing and monitoring the condition of the continuous track, which would allow to constantly monitor its stability and detect deviations from the norm in time.

It is also important to improve the quality of maintenance and regularly check the condition of railway infrastructure. This includes systematic inspections and inspections of the continuous track, including the condition of the fasteners and rail track, as well as timely repair work to eliminate identified defects.

In addition, it is recommended to improve the regulatory documents governing the longitudinal stability of the continuous track, in particular by adapting them to

European safety standards and norms, which will help reduce the risk of transport incidents.

Finally, effective coordination between different levels of management and cooperation between different railway departments, as well as training and professional development of personnel responsible for the technical condition of infrastructure, play an important role in ensuring safety on the Ukrainian railways.

The structural diagram of ensuring the longitudinal stability of a continuous track is shown in Figure 5.

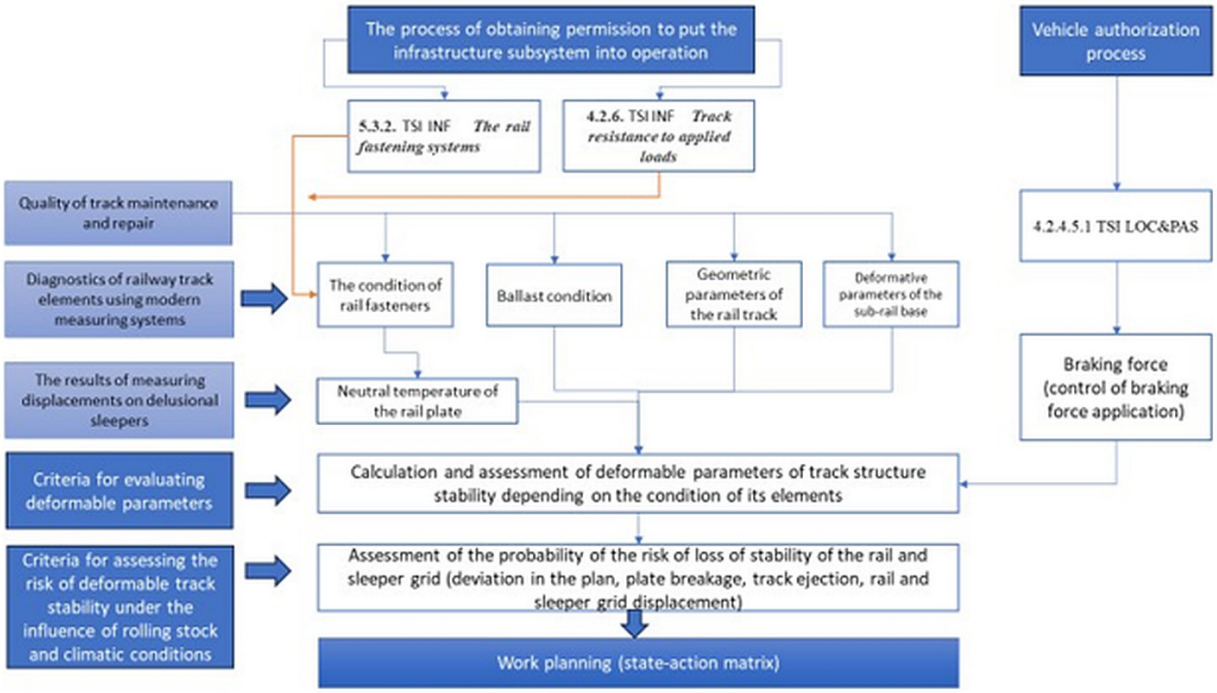

Fig. 5. Structural diagram of ensuring longitudinal stability of continuous track

Infrastructure control is a continuous process that determines the current state of railway infrastructure elements and changes in this state over time. As a result of inspections and checks, after weighing up various possible options, decisions are made on the necessary measures (repairs). The correct solution to the maintenance tasks is determined depending on the technical condition. A condition-based strategy requires collecting a huge amount of data, storing and processing it. This qualitative and quantitative data characterises the geometric and structural condition of the railway infrastructure. At the same time, an important task is to control and assess the quality of work. This structure and diagnostic system contribute to the rational use of funds for infrastructure needs. Avoiding the assignment of repairs according to aggregate standards in favour of planning repairs using diagnostic systems can help reduce track maintenance costs.

5. Conclusion

Ensuring safety and reliability in railway transport in Ukraine requires solving a number of tasks, including determining the probability of occurrence of such dangerous failures as "track ejection" and "rail and sleeper displacement", risk assessment and development of risk mitigation measures: improving diagnostics and monitoring of the condition of the jointless track , as well as improving the quality of maintenance.

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