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REQUIRED LONGITUDINAL RESTRAINT OF CWR RAIL FASTENINGS BY THE RAIL BREAK GAP CRITERION AT LOW TEMPERATURES IN KAZAKHSTAN

Batyrbek N. Kuandykov[1*], Murat M. Alimkulov[1], Baitak Apshikur[2], Kuvandik S. Lesov[3], Darkhan T. Tukenov[1], Islambek M. Kaldykarayev[1]

[1]ALT University named after M. Tynyshbayev, 050012, Almaty, Kazakhstan
[2]D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, 070004, Kazakhstan
[3]Tashkent State Transport University, 100060, Tashkent, Uzbekistan
*Corresponding author, e-mail: batyrbek.85@mail.ru

ABSTRACT

Introduction. On the network of JSC "NC Kazakhstan Temir Zholy" (KTZ), the design minimum rail temperature is below −40 °C at 38 of 68 stations. The gap that opens when a continuous welded rail (CWR) string breaks is limited to 50 mm. National rules check this gap with a fixed track resistance of 25 kN/m, whereas GOST 32698 specifies the minimum restraint of one fastening assembly; the restraint needed to meet the gap limit has not been established. **Materials and Methods.** The gap was checked for R65 rails, 1840 sleepers/km, straight track and nine stations selected to cover all amplitude groups of the codes. Two code approaches were applied: Rules No. 154-TsZ (Approach A, 25 kN/m) and SP 119.13330.2024 (Approach B, resistance derived from the GOST 32698 minimum and the sleeper density). A two-link rigid-plastic model and an inverse problem gave the required resistance per metre, the required assembly restraint, the restraint reserve and the limiting fixing temperature; the sensitivity to sleeper density, restraint and ballast resistance was assessed. **Results and Discussion.** For fixing at the upper limit of the optimum range, the calculated gap exceeds 50 mm in seven of nine scenarios (A: 54.0–74.3 mm; B: 52.4–61.2 mm). The required resistance is 22.2–37.2 kN/m and the required assembly restraint 12.1–20.2 kN. The reserve relative to the GOST minimum ranges from −22 to +14 % and is positive only for Almaty and Shymkent. At 1840 sleepers/km the GOST minimum alone does not provide the SP RK 3.03-114-2014 value for amplitudes above 100 °C. For northern stations, the limiting fixing temperature is +19.2…+32.2 °C (A) and +26.5…+33.3 °C (B); in 800 m curves the fixing window allowed by summer stability is below 10 °C at four stations. These are design scenarios with minimum code values, not the condition of track in service. **Conclusions.** The codes ignore the effect of frost on assembly restraint, so complete SKL and GK1 assemblies should be tested down to −50 °C.

KEYWORDS: continuous welded track; fixing temperature; temperature drop; sleeper spacing; frozen ballast; longitudinal resistance; GOST 32698.

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ҚАЗАҚСТАННЫҢ ТӨМЕН ТЕМПЕРАТУРАЛАРЫ ЖАҒДАЙЫНДА РЕЛЬС ТАЛШЫҒЫ СЫНҒАНДАҒЫ САҢЫЛАУ ШАРТЫ БОЙЫНША ТҮЙІССІЗ ЖОЛ БЕКІТПЕЛЕРІНІҢ ҚАЖЕТТІ БОЙЛЫҚ ҰСТАУ КҮШІ

Батырбек Н. Куандыков[1*], Мурат М. Алимкулов[1], Байтақ Апшикур[2], Кувандик С. Лесов[3], Дархан Т. Тукенов[1], Исламбек М. Қалдықараев[1]

[1]М. Тынышбаев атындағы ALT Университет, 050012, Алматы, Қазақстан
[2]Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті, Өскемен, 070004, Қазақстан
[3]Ташкент мемлекеттік көлік университеті, 100060, Ташкент, Өзбекстан
*Хат-хабар авторы, e-mail: batyrbek.85@mail.ru

АҢДАТПА

Кіріспе. «Қазақстан темір жолы» ҰК» АҚ (ҚТЖ) желісінде рельстердің есептік ең төменгі температурасы 68 станцияның 38-інде −40 °С-тан төмен. Түйіссіз жолда рельс талшығы сынғанда пайда болатын саңылау 50 мм-мен шектеледі. Ұлттық ережелер бұл саңылауды 25 кН/м тұрақты жол кедергісі бойынша тексереді. **Материалдар мен әдістер.** Саңылау Р65 рельстері, 1840 шпал/км эпюрасы, түзу учаске және нормалардағы барлық амплитуда топтарын қамтитындай таңдалған тоғыз станция үшін тексерілді. Екі нормативтік тәсіл қолданылды: № 154-ЦЗ Ережелері (А тәсілі, 25 кН/м) және СП 119.13330.2024 (Б тәсілі, кедергі ГОСТ 32698 минимумы мен шпал эпюрасы бойынша). **Нәтижелер және талқылау.** Оңтайлы аралықтың жоғарғы шегінде бекіткенде есептік саңылау тоғыз сценарийдің жетеуінде 50 мм-ден асады (А: 54,0–74,3 мм; Б: 52,4–61,2 мм). Қажетті кедергі 22,2–37,2 кН/м, тораптың қажетті ұстау күші 12,1–20,2 кН. ГОСТ минимумына қатысты қор −22-ден +14 %-ға дейін және тек Алматы мен Шымкент үшін оң. 1840 шпал/км эпюрасында ГОСТ минимумы амплитуда 100 °С-тан жоғары болғанда СП РК 3.03-114-2014 мәнін өздігінен қамтамасыз етпейді. Солтүстік станциялар үшін бекітудің шекті температурасы +19,2…+32,2 °С (А) және +26,5…+33,3 °С (Б); радиусы 800 м қисықтарда жазғы орнықтылық рұқсат ететін бекіту аралығы төрт станцияда 10 °С-тан аз. **Қорытынды.** Нормалар аяздың бекітпелердің ұстау күшіне әсерін ескермейді, сондықтан SKL және GK1 толық тораптарын −50 °С-қа дейін сынау қажет.

ТҮЙІН СӨЗДЕР: түйіссіз жол; бекіту температурасы; температура айырмасы; шпал эпюрасы; қатқан балласт; бойлық кедергі; ГОСТ 32698.

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ТРЕБУЕМОЕ ПРОДОЛЬНОЕ УДЕРЖАНИЕ СКРЕПЛЕНИЙ БЕССТЫКОВОГО ПУТИ ПО УСЛОВИЮ ЗАЗОРА ПРИ ИЗЛОМЕ ПЛЕТИ В УСЛОВИЯХ НИЗКИХ ТЕМПЕРАТУР КАЗАХСТАНА

Батырбек Н. Куандыков[1*], Мурат М. Алимкулов[1], Байтак Апшикур[2], Кувандик С. Лесов[3], Дархан Т. Тукенов[1], Исламбек М. Калдыкараев[1]

[1]ALT Университет имени М. Тынышпаева, 050012, Алматы, Казахстан
[2]Восточно-Казахстанский технический университет имени Д. Серикбаева, 070004, Усть-Каменогорск, Казахстан
[3]Ташкентский государственный транспортный университет, 100060, Ташкент, Республика Узбекистан
*Автор-корреспондент, e-mail: batyrbek.85@mail.ru

АННОТАЦИЯ

Введение. На сети АО «НК «Қазақстан темір жолы» (КТЖ) расчётная минимальная температура рельсов ниже −40 °C на 38 из 68 станций. Зазор при изломе плети бесстыкового пути ограничен 50 мм. **Материалы и методы.** Зазор проверен для рельсов Р65, эпюры 1840 шп/км, прямого участка и девяти станций, выбранных так, чтобы охватить все группы амплитуд, принятые в нормах. Правила № 154-ЦЗ (подход А, 25 кН/м) и СП 119.13330.2024 (подход Б, сопротивление по минимуму ГОСТ 32698 и эпюре шпал). **Результаты и обсуждение.** При закреплении на верхней границе оптимального интервала расчётный зазор превышает 50 мм в семи из девяти сценариев (А: 54,0–74,3 мм; Б: 52,4–61,2 мм). Требуемое сопротивление составляет 22,2–37,2 кН/м, требуемое удержание узла 12,1–20,2 кН. Резерв относительно минимума ГОСТ лежит в пределах от −22 до +14 % и положителен только для Алматы и Шымкента. При эпюре 1840 шп/км минимум ГОСТ сам по себе не обеспечивает значения СП РК 3.03-114-2014 при амплитуде более 100 °C. Для северных станций предельная температура закрепления составляет +19,2…+32,2 °C (А) и +26,5…+33,3 °C (Б); в кривых радиусом 800 м допустимый по летней устойчивости интервал закрепления на четырёх станциях меньше 10 °C. **Выводы.** Нормы не учитывают влияние мороза на удержание скреплений, поэтому полные узлы SKL и GK1 нужно испытать при температурах до −50 °C.

КЛЮЧЕВЫЕ СЛОВА: бесстыковой путь; температура закрепления; перепад температуры; эпюра шпал; смёрзшийся балласт; погонное сопротивление; ГОСТ 32698.

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1 INTRODUCTION

The network of JSC "NC Kazakhstan Temir Zholy" (KTZ) lies in a sharply continental climate. According to Table 15 of Rules No. 154-TsZ, the design minimum rail temperature falls below −40 °C at 38 of 68 stations and reaches −53 °C at Esil [1]. In winter a continuous welded rail (CWR) string is in tension, and a rail break is then one of the most dangerous failures. The Rules limit the gap that opens at a break to 50 mm [1]. Ultrasonic inspection can detect many defects before they lead to a break [2], but the size of the gap itself is governed by how strongly the track resists longitudinal movement of the rail.

Rules No. 154-TsZ take this resistance as 25 kN/m for frozen ballast "at the normative tension of clip and fixing bolts" [1]. The value applies to the rail–sleeper panel as a whole and implicitly assumes that the fastening holds the rail at least as firmly as the ballast holds the sleeper. The reference to bolts goes back to KB-65 fastenings. Between 2017 and 2025, however, the share of clip-based SKL and GK1 systems on concrete sleepers rose from 22.9 to 53.3 %, while that of KB-65 fell to 30.6 % [3]. On the KTZ network, SKL and GK1 are anchor-type elastic fastenings without clip or fixing bolts. Their condition is checked by the clamping force, which must be at least 25 kN at installation and 17 kN in service [1].

GOST 32698-2014 requires the longitudinal rail restraint of a fastening assembly (hereafter, assembly restraint) to be at least 14.0 kN for a rail temperature amplitude $T_A \leq 110$ °C and 16.5 kN for $T_A >$ 110 °C [4]; the test is run at +25 ± 10 °C. EN 13481-2 sets a minimum of 7 kN, also at normal temperature [5]. OSJD Leaflet R 778 recommends the same 14.0 and 16.5 kN for 1520 mm track and at least 9 kN for 1435 mm track [6]. SP RK 3.03-114-2014 expresses the requirement per metre of track: 25 kN/m for T_A up to 100 °C, 30 kN/m for 100–110 °C and 33–35 kN/m above 110 °C [7]. The Russian code SP 119.13330.2024 checks the gap with the same formula as Rules No. 154-TsZ, but derives the resistance from the GOST 32698 restraint and the sleeper spacing and takes the temperature drop from the upper limit of the optimum fixing range [8]. Within the 1520 mm gauge area, one and the same design quantity is therefore defined in several different ways.

Fastening resistance may change in frost, but the available evidence is indirect. For the Spring II fastening, the slip force at −40 °C was 10–32 % lower than at normal temperature [9]; for rail anchors a drop of 22–33 % was reported [10]. Rail pad stiffness grows by 26–40 % at −40 °C [11], and the growth becomes noticeable below −10…−20 °C [12]. All of these data refer to designs other than those used by KTZ. In this paper they serve only as a qualitative indication: a loss of restraint in SKL and GK1 assemblies at low temperature has not been confirmed by tests, including the authors' own. Sleepers and fastenings also carry dynamic loads from trains [13, 14]; these loads are outside the scope of this paper.

Classical CWR theory distinguishes two mechanisms of longitudinal movement. The rail either moves together with the sleepers through the ballast or slides over the sleepers once the fastening resistance is exceeded [15]. In frozen ballast the second mechanism becomes possible, and the weaker of the two links governs [15, 16]. Field tests agree with this picture: on concrete sleepers slip occurred mainly between sleeper and ballast, whereas on timber sleepers without anchors it occurred between rail and sleeper [17]. Rules No. 154-TsZ define the resistance through the panel in the ballast, and SP 119.13330.2024 through the assembly restraint.

In the literature reviewed, we found no quantitative comparison of these approaches for Kazakhstan. Nor is it known what assembly restraint the gap limit actually requires at KTZ stations, or how this value relates to GOST 32698 and SP RK 3.03-114-2014. None of these codes accounts for a change in restraint at low temperatures.

The aim of this study is to compare the code approaches to the break gap check for KTZ stations and to find the required longitudinal restraint of an elastic fastening assembly. The tasks were:

1) to check the gap by Rules No. 154-

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TsZ and by SP 119.13330.2024 for stations with different design temperatures;

2) to find the required resistance per metre and compare it with SP RK 3.03-114-2014 and GOST 32698;

3) to find the required assembly restraint and its reserve against the code minimum;

4) to find the highest fixing temperature that meets the gap limit, with summer track stability taken into account.

2 MATERIALS AND METHODS

2.1 Input data.

One rail of CWR track is considered: heat-treated R65 rails on concrete sleepers, a sleeper density n = 1840 sleepers/km (spacing $a = 1000/n$ = 0.5435 m), crushed-stone ballast and straight track. This density follows clause 12 of Rules No. 154-TsZ and applies to lines of categories II–IV in SP RK 3.03-114-2014. For category I main lines SP RK requires 2000 sleepers/km; this case is treated separately in Section 3.6. The rail data are F = 82.65 cm², $E = 2.1\cdot10^5$ MPa and $\alpha = 1.18\cdot10^{-5}$ 1/°C [1], so that αEF = 20.48 kN/°C and $EF = 1.736\cdot10^6$ kN. The temperature force in the rail is $N_t = \alpha EF\cdot\Delta t$.

The design rail temperatures $t_{max,max}$ and $t_{min,min}$ and the amplitude T_A were taken from Table 15 of Rules No. 154-TsZ, and the optimum fixing temperature t_{opt} from Table 6 [1]. The nine stations in Table 1 were selected from the 68 stations of Table 15 by three criteria. First, every amplitude group that changes a code requirement had to be represented: $T_A > 110$ °C (16.5 kN by GOST 32698; 33–35 kN/m by SP RK 3.03-114-2014), 100 °C $< T_A \le 110$ °C (14.0 kN; 30 kN/m) and $T_A \le 100$ °C (14.0 kN; 25 kN/m). Second, all three groups of the optimum fixing temperature (30, 35 and 40 °C) had to be included. Third, the set had to span the network from the coldest station, Esil ($t_{min,min}$ = −53 °C), to the southern stations Almaty and Shymkent ($t_{min,min}$ = −28 and −26 °C), and to include the north and centre (Esil, Astana, Karaganda, Moiynty, Pavlodar), the east (Zyryanovsk), the west (Kandyagash) and the south (Almaty, Shymkent). The selected stations cover T_A from 90 to 116 °C, $t_{min,min}$ from −26 to −53 °C and all values of t_{opt}.

Table 1. Design rail temperatures and code requirements for fastenings

Station	$t_{max,max}$, °C	$t_{min,min}$, °C	T_A, °C	t_{opt}, °C	F_{GOST} by GOST 32698, kN	r by SP RK 3.03-114-2014, kN/m
Esil	63.0	−53.0	116.0	30 ± 5	16.5	33–35
Moiynty	64.0	−51.0	115.0	30 ± 5	16.5	33–35
Zyryanovsk	60.0	−51.0	111.0	30 ± 5	16.5	33–35
Kandyagash	63.0	−48.0	111.0	30 ± 5	16.5	33–35
Pavlodar	61.0	−44.4	105.4	30 ± 5	14.0	30
Astana	60.1	−43.0	103.1	30 ± 5	14.0	30
Karaganda	60.2	−40.0	100.2	30 ± 5	14.0	30
Almaty	63.0	−28.0	91.0	35 ± 5	14.0	25
Shymkent	64.0	−26.0	90.0	40 ± 5	14.0	25

2.2 Code approaches.

Three related quantities are used below and kept apart. The assembly restraint F_a, kN, is the longitudinal force at which the rail starts to slip through one fastening assembly; this is the quantity tested by GOST 32698 and ISO 22074-2, and its code minimum is denoted F_{GOST}. The longitudinal resistance of the fastenings per metre, $r_F = F_a\cdot n/1000$, kN/m, is the same restraint distributed over the sleeper spacing. The longitudinal resistance of the track per metre, r, kN/m, is the value that enters the gap formula; depending on which link governs, it equals r_F or the sleeper–ballast resistance r_b (Section 2.3).

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Both codes use the same formula for the break gap:

$$\lambda = 0.24\,\frac{\Delta t^2}{r} \le [\lambda] = 50\ \text{mm}, \qquad (1)$$

where λ is the total gap between the two rail ends, mm; Δt is the drop in rail temperature below the fixing temperature, °C; r is the longitudinal resistance of the track per metre, kN/m [1, 8]. A larger gap is considered dangerous for train passage [6].

Formula (1) follows from the equilibrium of the released rail ends (Fig. 1b). Before the break, the rail carries the tensile force $N_t = \alpha EF\cdot\Delta t$ along its whole length. After the break, the force at the cut falls to zero, and each end retracts until the longitudinal resistance rebuilds the force. With r constant (rigid-plastic behaviour), the force grows linearly from zero at the break to N_t at the distance $l = N_t/r$, beyond which the rail does not move. The displacement of one end equals the free strain released over this length: $u = N_t\cdot l/(2EF) = N_t^2/(2EF\cdot r) = \alpha^2 EF\cdot\Delta t^2/(2r)$. The two ends move apart symmetrically, so the gap is $\lambda = 2u = \alpha^2 EF\cdot\Delta t^2/r$. For the R65 rail, $\alpha^2 EF = (1.18\cdot10^{-5})^2\cdot1.736\cdot10^6 = 2.417\cdot10^{-4}$ kN/°C²; with r in kN/m and λ in millimetres this gives the coefficient 0.2417, which the codes round to 0.24. The code value 0.24 is used in all calculations. The derivation assumes a uniform rail temperature along the string, a resistance r that does not depend on displacement and is the same on both sides of the break, elastic behaviour of the rail and no dynamic effects at the moment of fracture. Hence λ in (1) is the total gap between the two ends; the displacement of each end relative to its position before the break is $\lambda/2$.

The approaches differ in how r is found. In Approach A (Rules No. 154-TsZ), r = 25 kN/m. This is the code value for the rail–sleeper panel in frozen ballast with fastenings in normal condition [1]. In Approach B (SP 119.13330.2024) [8]:

$$r = \frac{F_{\text{GOST}}\,n}{1000}, \qquad (2)$$

where F_{GOST} is the minimum assembly restraint by GOST 32698, kN; n is the sleeper density, sleepers/km. With n = 1840 sleepers/km, r = 25.8 kN/m for F_{GOST} = 14.0 kN and 30.4 kN/m for F_{GOST} = 16.5 kN. Approach A thus ignores the fastening, and Approach B ignores the ballast.

2.3 Two-link model.

To relate the two approaches, the track resistance is modelled as two links in series. The first link is rail–fastening–sleeper with the ultimate restraint F_a. The second link is sleeper–ballast with the ultimate resistance r_b. Both links are rigid-plastic, and the effective resistance is set by the weaker link:

$$\begin{aligned} r_F &= \frac{F_a}{a} = \frac{F_a n}{1000}, \\ r_{\text{eff}} &= \min(r_F,\, r_b), \\ F_{\text{cr}} &= a\, r_b. \end{aligned} \qquad (3)$$

This model is our own simplification. Within it, the code approaches can be read as two limiting cases: Approach B describes the case where the fastening assembly governs ($r_F < r_b$), and Approach A the case where the panel in the ballast governs. The codes do not split the resistance into links, so 25 kN/m is treated here as a code estimate of r_b, not as a measured sleeper–ballast resistance; Rules No. 154-TsZ describe this value in the same way, as the resistance of the panel in frozen ballast [1]. At the GOST minimum, r_F is 25.8 and 30.4 kN/m, which is not less than 25 kN/m. In the model, Approach A then governs, and Approach B underestimates the gap. Approach B governs if the real panel resistance is above r_F or if the assembly restraint drops in frost. The model and the distribution of force and displacement near the break are shown in Fig. 1; the reasons for adopting it are given below.

Taking the smaller of the two ultimate resistances follows from the series arrangement of the links. The longitudinal force collected by the rail over one sleeper spacing passes first through the fastening into the sleeper and then from the sleeper into the ballast, so both links carry the same force. In a rigid-plastic description, each link transmits any force up to its ultimate value without displacement and slips at that value. The force transferred per sleeper can therefore never

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exceed $\min(F_a,\ a \cdot r_b)$. Once this force is reached, slip develops in the weaker link, while the stronger one stays below its limit and does not move. The resulting resistance per metre is $r_{eff} = \min(r_F,\ r_b)$, as in Eq. (3). Real track has elastic compliance in both links before slip, and in this stage the two displacements add up. These elastic displacements are, however, small compared with the retraction of a broken rail end, which is of the order of tens of millimetres (37 mm per end at Esil, Section 3.2). The rigid-plastic idealisation is the one adopted in classical CWR theory [15] and in the code formula (1) itself, so the model adds no assumptions beyond those already contained in the codes. Its weakest point is the case $F_a \approx a \cdot r_b$, where slip may alternate between the links; the gap is then still governed by $\min(r_F,\ r_b)$, but the actual displacement pattern is less certain.

Experimental support for the model is indirect. Field tests [17] showed that on concrete sleepers slip took place mainly between sleeper and ballast, which corresponds to the ballast-governed case ($r_b < r_F$). The review [19] reports longitudinal resistance of ballasted track of up to 30 kN/m, i.e. of the same order as the code values used here. A direct check would require measurements of both links on KTZ track at low temperature, which have not yet been made.

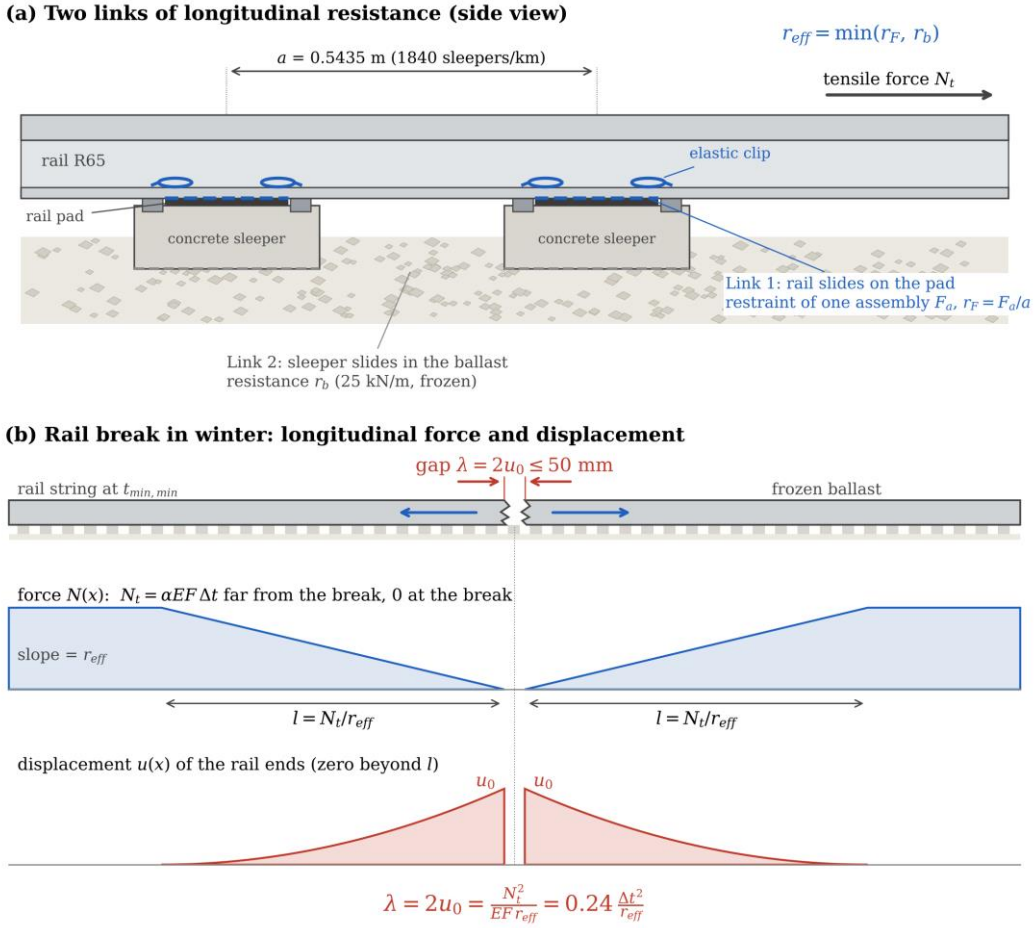


Fig. 1. Design model: (a) two links of longitudinal resistance in series (side view); (b) rail break in winter: longitudinal force and displacement of the rail ends

2.4 Inverse problem.

Setting $\lambda = [\lambda]$ gives the required resistance, the required assembly restraint and the limiting fixing temperature $t_{f,lim}$. The last value follows from the gap limit alone. It was calculated for r = 25 kN/m (Approach A) and for $r = F_{GOST} \cdot n/1000$ (Approach B):

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$$r_{\text{req}} = \frac{0.24\,\Delta t^2}{[\lambda]},$$
$$F_{\text{a,req}} = r_{\text{req}}\,a, \qquad (4)$$
$$t_{\text{f,lim}} = t_{\text{min,min}} + \sqrt{\frac{[\lambda]\,r}{0.24}}.$$

Two indicators show how well the GOST 32698 minimum covers the requirement. The safety factor η is the ratio of the code minimum F_{GOST} to the required restraint $F_{\text{a,req}}$: $\eta \geq 1$ means that an assembly with exactly the minimum restraint meets the gap limit, and $\eta < 1$ that it does not. The relative restraint reserve δ is the share of F_{GOST} by which the restraint could fall, for instance in frost, without violating the gap limit; a negative δ gives the percentage by which the restraint must exceed the minimum. The two indicators are related by $\delta = (1 - 1/\eta)\cdot 100$ %. Both are calculated values, not measured losses of restraint in frost. If the real restraint is above the minimum, the reserve is larger:

$$\eta = \frac{F_{\text{GOST}}}{F_{\text{a,req}}},$$
$$\delta = \left(1 - \frac{F_{\text{a,req}}}{F_{\text{GOST}}}\right)\cdot 100\,\%. \qquad (5)$$

The gap limit is met only if both links are strong enough: $F_{\text{a}} \geq F_{\text{a,req}}$ and $r_{\text{b}} \geq r_{\text{req}}$.

2.5 Scenarios.

The main case is fixing at the upper limit of the optimum range, $t_{\text{f}} = t_{\text{opt}} + 5$ °C. This follows the check in SP 119.13330.2024 [8] and gives the largest temperature drop in winter. Fixing at t_{opt} is used for comparison. The assembly restraint equals the GOST 32698 minimum of 14.0 and 16.5 kN [4]. We also show the estimate of 10 kN obtained in [3] for SKL, GK1 systems. That estimate was based only on friction between the rail foot and the pad at nominal clamping force, so it is conservative.

The fixing temperature cannot be lowered freely because of summer track stability. The lower limit of the design range is

$$\min t_{\text{f}} = t_{\text{max,max}} - [\Delta t_{\text{s}}], \qquad (6)$$

where $[\Delta t_{\text{s}}]$ is the allowed rise in rail temperature above the fixing temperature for summer stability [1]. For R65 rails, 1840 sleepers/km, crushed stone and straight track, $[\Delta t_{\text{s}}] = 54$ °C; in a curve of radius 800 m it is 44 °C (Table 12 of Rules No. 154-TsZ).

3 RESULTS AND DISCUSSION

3.1 Code values compared.

At 1840 sleepers/km and $r_{\text{b}} = 25$ kN/m, the threshold restraint is $F_{\text{cr}} = 13.59$ kN. The GOST 32698 minimum of 14.0 and 16.5 kN is 3 and 21 % above it. If the restraint equals this minimum and does not change in frost, the panel in frozen ballast is the weaker link. This agrees with Approach A. The estimate of 10 kN [3] and the EN 13481-2 minimum of 7 kN [5] are below the threshold ($r_{\text{F}} = 18.4$ and 12.9 kN/m).

Per metre of track, the GOST minimum gives 25.8 and 30.4 kN/m. This meets the SP RK 3.03-114-2014 value of 25 kN/m for T_{A} up to 100 °C. For T_{A} of 100–110 °C (30 kN/m) and above 110 °C (33–35 kN/m), meeting the GOST minimum does not guarantee the SP RK value. At 1840 sleepers/km this would need a restraint of at least 16.3 kN and 17.9–19.0 kN. Real assemblies that comply with GOST may have a higher restraint than the minimum.

3.2 Gap check.

Table 2 and Fig. 2 give the results for the main case $t_{\text{f}} = t_{\text{opt}} + 5$ °C. In Table 2, $\Delta t = t_{\text{f}} - t_{\text{min,min}}$ and $N_{\text{t}} = \alpha EF\cdot\Delta t$; the gap λ follows from Eq. (1) with $r = 25$ kN/m (Approach A) or $r = F_{\text{GOST}}\cdot n/1000$ (Approach B), and r_{req} from Eq. (4).

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Table 2. Break gap at $t_f = t_{opt} + 5$ °C (R65, 1840 sleepers/km)

Station	t_f, °C	Δt, °C	N_t, kN	λ, Approach A (r = 25 kN/m), mm	λ, Approach B ($r = F_{GOST}n/1000$), mm	r_{req}, kN/m	r by SP RK 3.03-114-2014, kN/m
Esil	35.0	88.0	1802	74.3	61.2	37.2	33–35
Moiynty	35.0	86.0	1761	71.0	58.5	35.5	33–35
Zyryanovsk	35.0	86.0	1761	71.0	58.5	35.5	33–35
Kandyagash	35.0	83.0	1700	66.1	54.5	33.1	33–35
Pavlodar	35.0	79.4	1626	60.5	58.7	30.3	30
Astana	35.0	78.0	1597	58.4	56.7	29.2	30
Karaganda	35.0	75.0	1536	54.0	52.4	27.0	30
Almaty	40.0	68.0	1393	44.4	43.1	22.2	25
Shymkent	45.0	71.0	1454	48.4	47.0	24.2	25

With minimum code values, the gap exceeds 50 mm in seven of the nine scenarios by both approaches: 54.0–74.3 mm by Approach A and 52.4–61.2 mm by Approach B. Only Almaty and Shymkent meet the limit. With the 10 kN estimate (r = 18.4 kN/m), the gap exceeds the limit at every station (60–101 mm). With fixing at t_{opt}, Approach A fails in six scenarios (51.2–66.1 mm). These are design scenarios, not an assessment of real rail strings (see Section 3.4).

The calculation sequence is illustrated for Esil. Fixing at the upper limit of the optimum range gives $t_f = t_{opt} + 5 = 35$ °C. With $t_{min,min} = -53$ °C, the temperature drop is $\Delta t = 35 - (-53) = 88.0$ °C, and the tensile force before the break is $N_t = 20.48 \cdot 88.0 = 1802$ kN (a stress of about 218 MPa). For Approach A (r = 25 kN/m) the force is rebuilt over $l = 1802/25 = 72.1$ m on each side of the break. Each end retracts by $u = 0.12 \cdot 88.0^2/25 = 37.2$ mm, and the total gap is $\lambda = 2u = 0.24 \cdot 88.0^2/25 = 74.3$ mm > 50 mm. For Approach B, $r = 16.5 \cdot 1840/1000 = 30.4$ kN/m, so that $l = 59.4$ m and $\lambda = 0.24 \cdot 7744/30.36 = 61.2$ mm. The inverse problem gives $r_{req} = 0.24 \cdot 88.0^2/50 = 37.2$ kN/m and $F_{a,req} = 37.2 \cdot 0.5435 = 20.2$ kN, hence $\eta = 16.5/20.2 = 0.82$ and $\delta = (1 - 20.2/16.5) \cdot 100 = -22$ %. The limiting fixing temperature for r = 25 kN/m is $t_{f,lim} = -53 + \sqrt{(50 \cdot 25/0.24)} = -53 + 72.2 = 19.2$ °C. The same sequence was applied to all stations in Tables 2 and 3.

The required resistance is 22.2–37.2 kN/m. At five stations it is within the SP RK 3.03-114-2014 values. At Esil, Moiynty and Zyryanovsk it reaches 35.5–37.2 kN/m, above even the upper value of 35 kN/m. At Pavlodar it nearly equals the requirement (30.3 vs 30 kN/m). So, with fixing at the upper limit of the optimum range, the SP RK value does not ensure the gap limit at all northern stations.

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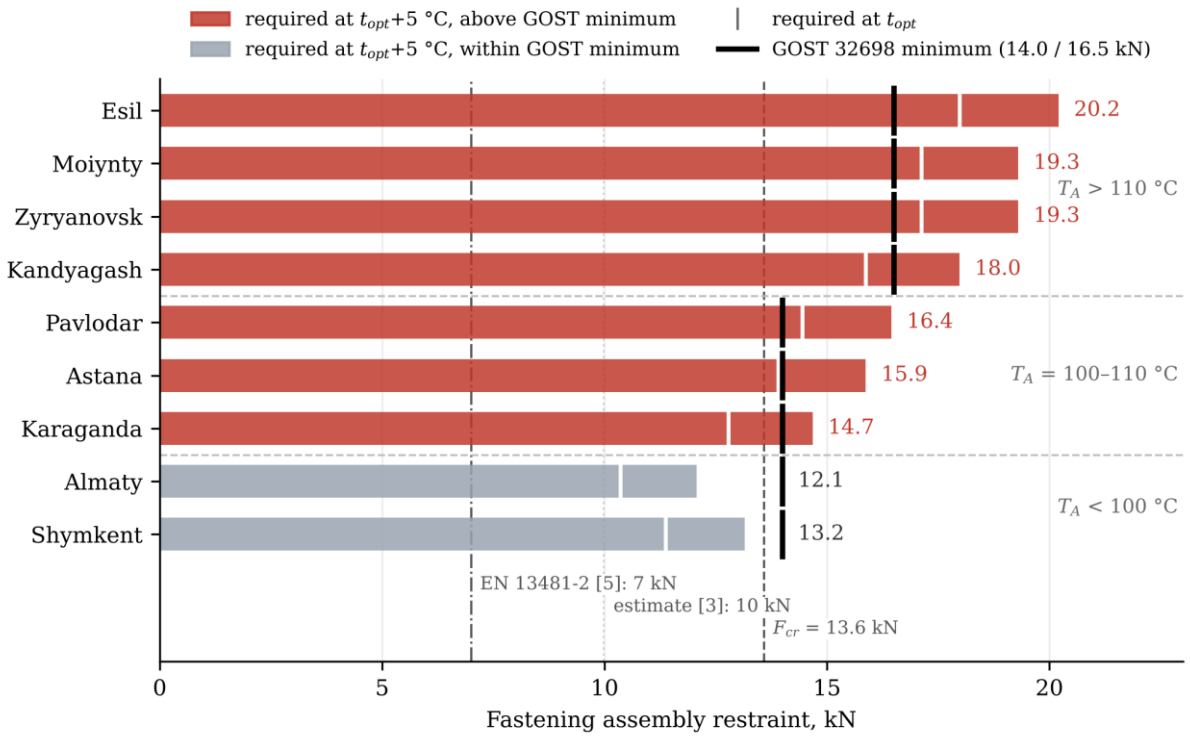


Fig. 2. Required assembly restraint by station at $t_f = t_{opt} + 5$ °C and code restraint levels (calculated by the authors from Tables 6 and 15 of Rules No. 154-TsZ, GOST 32698-2014 and EN 13481-2)

3.3 Required restraint and reserve.

Table 3 and Figs. 3 and 4 give the required restraint, the reserve and the fixing temperature limits. In Table 3, $F_{a,req} = r_{req} \cdot a$ is the required assembly restraint from Eq. (4); $\eta = F_{GOST}/F_{a,req}$ is the safety factor and $\delta = (1 - F_{a,req}/F_{GOST}) \cdot 100$ % the relative restraint reserve from Eq. (5). A positive δ shows by how much the restraint may fall below the GOST minimum before the gap exceeds 50 mm; a negative δ shows by how much it must exceed the minimum.

Table 3. Required assembly restraint, reserve and fixing temperature limits

Station	F_{GOST}, kN	$F_{a,req}$ at t_{opt} / t_{opt} + 5, kN	η at t_{opt} + 5	δ at t_{opt} / t_{opt} + 5, %	$t_{f,lim}$ by Approach A / B, °C	min t_f by stability, °C
Esil	16.5	18.0 / 20.2	0.82	−9 / −22	19.2 / 26.5	9.0
Moiynty	16.5	17.1 / 19.3	0.86	−4 / −17	21.2 / 28.5	10.0
Zyryanovsk	16.5	17.1 / 19.3	0.86	−4 / −17	21.2 / 28.5	6.0
Kandyagash	16.5	15.9 / 18.0	0.92	4 / −9	24.2 / 31.5	9.0
Pavlodar	14.0	14.4 / 16.4	0.85	−3 / −17	27.8 / 28.9	7.0
Astana	14.0	13.9 / 15.9	0.88	1 / −13	29.2 / 30.3	6.1
Karaganda	14.0	12.8 / 14.7	0.95	9 / −5	32.2 / 33.3	6.2
Almaty	14.0	10.4 / 12.1	1.16	26 / 14	44.2 / 45.3	9.0
Shymkent	14.0	11.4 / 13.2	1.06	19 / 6	46.2 / 47.3	10.0

For fixing at the upper limit, the required restraint is 12.1–20.2 kN. The GOST 32698 minimum covers it only at Almaty and Shymkent (η = 1.16 and 1.06; reserve 14 and 6 %). At the other seven stations the reserve is negative, from −5 % at Karaganda to −22 % at

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Esil. For fixing at t_{opt}, five stations have a positive reserve of 1–26 % (Fig. 3).

A negative reserve means that the assembly restraint must exceed the GOST 32698 minimum even at normal temperature. Where r_{req} > 25 kN/m, the gap limit also requires a panel resistance in frozen ballast above the 25 kN/m of Rules No. 154-TsZ.

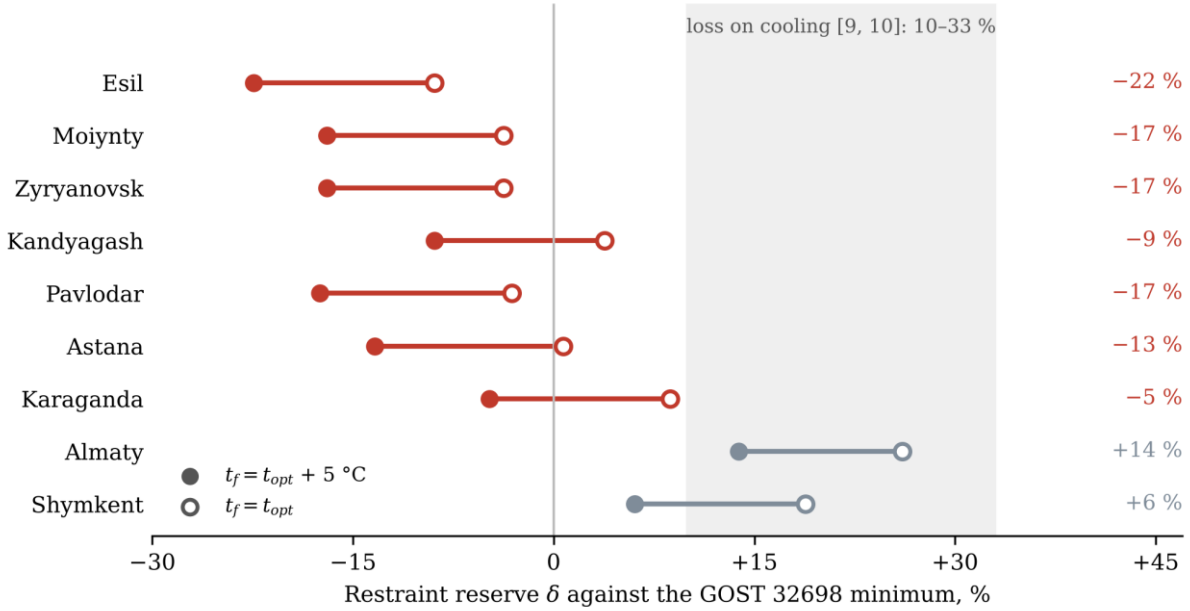


Fig. 3. Restraint reserve against the GOST 32698 minimum by station (calculated by the authors; the range of resistance loss on cooling is taken from [9, 10])

For the northern stations, the limiting fixing temperature is +19.2…+32.2 °C by Approach A and +26.5…+33.3 °C by Approach B (Fig. 4), while Table 6 of Rules No. 154-TsZ gives +35 °C. In the two-link model at the GOST minimum, Approach A governs. The Approach B values are therefore an upper estimate: they hold only if the panel resistance in frozen ballast is at least r_F. Both values consider the gap only and are not a code requirement. On straight track the lower limit for stability is +6…+10 °C, so the interval between the two limits is not less than 10.2 °C (Esil, Approach A). In curves the allowed temperature rise is lower, for example $[\Delta t_s]$ = 44 °C for a radius of 800 m [1]. The interval then becomes shorter than the 10 °C minimum fixing range of Rules No. 154-TsZ. By Approach A this happens at Esil (0.2 °C), Moiynty (1.2 °C), Zyryanovsk and Kandyagash (5.2 °C); by Approach B, at Esil (7.5 °C) and Moiynty (8.5 °C).

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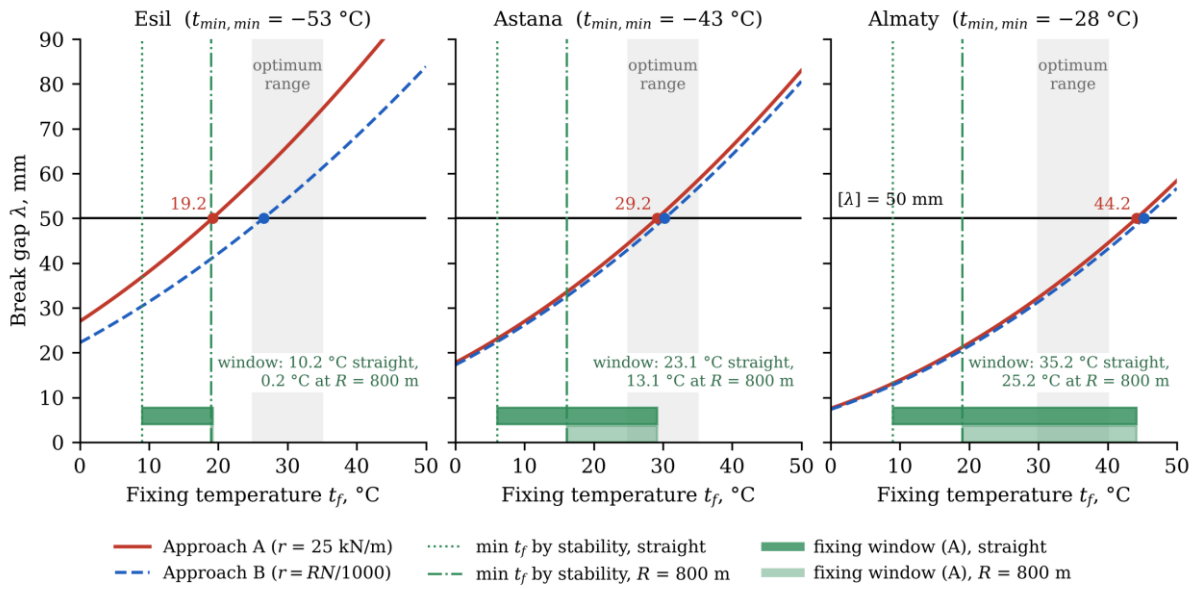


Fig. 4. Break gap versus fixing temperature at Esil, Astana and Almaty: limiting fixing temperature by Approaches A and B and fixing windows on straight track and in curves of radius 800 m (calculated by the authors)

Fig. 5 brings the two constraints together for all nine stations. The lower end of each bar is the stability limit min t_f from Eq. (6), with $[\Delta t_s]$ = 54 °C on straight track and 44 °C in 800 m curves; the upper end is the gap limit $t_{f,lim}$ from Eq. (4). The length of the bar is thus the range of fixing temperatures in which both the summer stability check and the winter break-gap check are satisfied. By Approach A, at Esil, Moiynty, Zyryanovsk and Kandyagash the whole optimum range $t_{opt} \pm 5$ °C lies above the gap limit. At Pavlodar, Astana and Karaganda only its lower part, from +25 °C to +27.8…+32.2 °C, satisfies both conditions, and at Almaty and Shymkent the optimum range lies entirely within the permissible window. In 800 m curves every window becomes 10 °C shorter, and at the four coldest stations it falls below the 10 °C minimum fixing range. The comparison shows that in the north the binding constraint is the winter gap, not summer stability, as long as the minimum code resistance is assumed.

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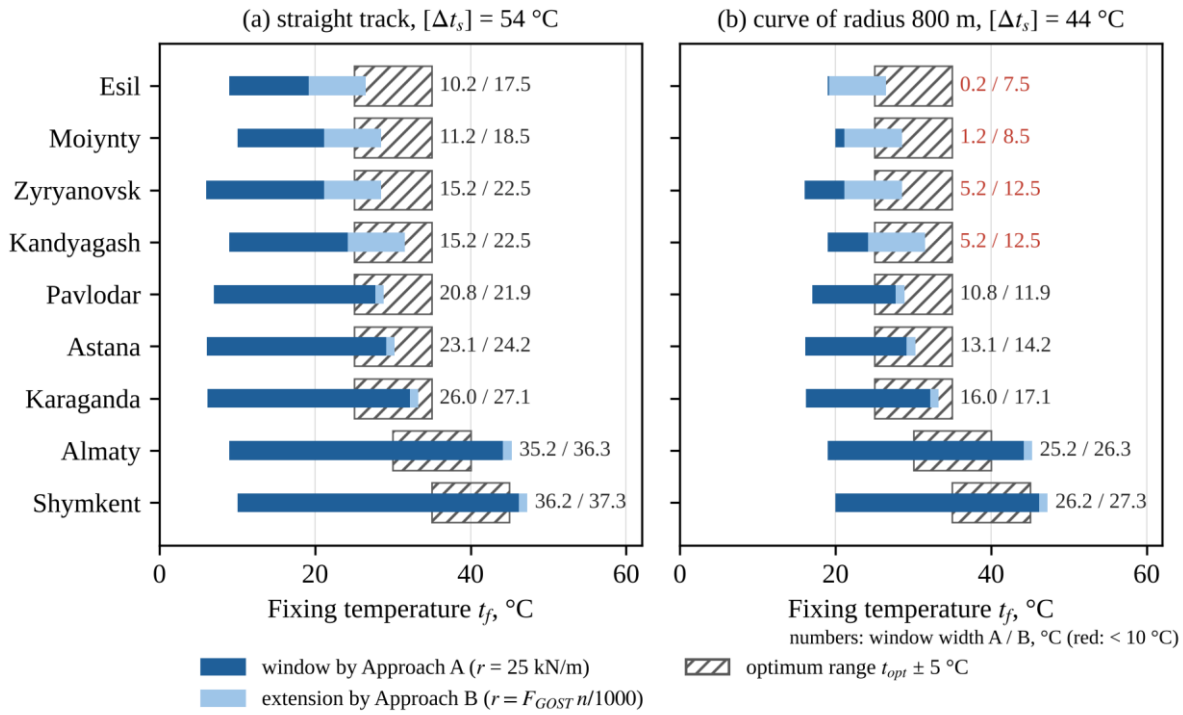


Fig. 5. Permissible fixing temperature range from the summer stability limit (Eq. (6)) and the break gap limit (Eq. (4)): (a) straight track; (b) curve of radius 800 m (calculated by the authors)

3.4 Interpretation of results.

The check estimates the gap after a break has already occurred. It does not predict whether a break will occur. According to the OSJD catalogue of rail defects [18], a full transverse break usually develops from a fatigue crack caused by a metallurgical flaw, from a contact-fatigue crack in the head or from a crack in a weld. The catalogue also lists brittle breaks without visible defects and relates them to high tensile stress in continuous welded rail and to cold brittleness of the steel, especially in the cold season [18]. Breaks therefore tend to occur in winter, when the tensile force is close to its maximum. This is the condition assumed in the gap check. For regions with amplitudes above 110 °C, OSJD recommends rails of low-temperature reliability [6]. The tensile stress at Δt = 88 °C is about 218 MPa, below the strength of heat-treated rails, so a break needs a defect or brittle steel. The causes of breaks are outside the scope of this study. The scenario is conservative by design: fixing at the upper limit of the optimum range, the absolute minimum rail temperature and the minimum code resistance are combined. Even so, Rules No. 154-TsZ with their own values give a gap of 74.3 mm at Esil. Gaps of this size are not common in KTZ practice. This suggests that the actual winter resistance of the track and the actual assembly restraint are higher than the code minima of 25 kN/m and 14.0–16.5 kN. Measuring them at low temperatures is therefore the next step.

The results should therefore be read as a check of the design assumptions, not as a diagnosis of the track in service. A calculated gap above 50 mm means that the minimum code values of resistance, combined with the most adverse temperature conditions, are not enough to guarantee the limit. It does not mean that the existing rail strings are in an unsatisfactory condition. Whether a particular section is at risk depends on its actual assembly restraint and ballast resistance, which the codes do not provide and which have to be measured.

3.5 Novelty. The novelty of this work is applied. For nine KTZ stations, the code

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approaches to the break gap check were compared quantitatively: Rules No. 154-TsZ, SP 119.13330.2024 and SP RK 3.03-114-2014. With a two-link model, the approaches of Rules No. 154-TsZ and SP 119.13330.2024 were read as two limiting cases. The required resistance and assembly restraint were found. At 1840 sleepers/km, the GOST 32698 minimum does not by itself meet the SP RK value for amplitudes above 100 °C. The restraint reserve and the limiting fixing temperature were calculated for the northern stations. The formulas themselves are known. The contribution is a quantitative comparison of the codes and the resulting design values for Kazakhstan.

3.6 How the codes relate.

The four documents set related but different values. GOST 32698 sets the restraint of one assembly at +25 °C [4]. SP RK 3.03-114-2014 sets the fastening resistance per metre depending on the amplitude [7]. Rules No. 154-TsZ use a constant r = 25 kN/m [1], and SP 119.13330.2024 converts the assembly restraint into resistance per metre using the sleeper spacing [8]. Table 4 brings these values together for the three amplitude groups and for the two sleeper densities of SP RK: 1840 sleepers/km (categories II–IV) and 2000 sleepers/km (category I).

Table 4. Assembly restraint and resistance per metre by GOST 32698-2014, SP RK 3.03-114-2014 and the gap limit ($t_f = t_{opt} + 5$ °C)

Group of T_A (stations)	**F_{GOST}, kN**	**r_F at F_{GOST}, kN/m, n = 1840 / 2000**	**r by SP RK, kN/m**	**F_a to meet SP RK, kN, n = 1840 / 2000**	**r_{req} by gap limit, kN/m**	**$F_{a,req}$ by gap limit, kN, n = 1840 / 2000**
$T_A \le 100$ °C (Almaty, Shymkent)	14.0	25.8 / 28.0	25	13.6 / 12.5	22.2–24.2	12.1–13.2 / 11.1–12.1
100 °C < $T_A \le 110$ °C (Pavlodar, Astana, Karaganda)	14.0	25.8 / 28.0	30	16.3 / 15.0	27.0–30.3	14.7–16.4 / 13.5–15.1
$T_A > 110$ °C (Esil, Moiynty, Zyryanovsk, Kandyagash)	16.5	30.4 / 33.0	33–35	17.9–19.0 / 16.5–17.5	33.1–37.2	18.0–20.2 / 16.5–18.6

At 1840 sleepers/km the GOST minimum is below the SP RK value in both groups with T_A above 100 °C, by 4.2 kN/m and by 2.6–4.6 kN/m. At 2000 sleepers/km it gives 28.0 and 33.0 kN/m: the requirement is then met for $T_A > 110$ °C at its lower bound of 33 kN/m, but not for T_A of 100–110 °C (30 kN/m). The denser spacing also lowers the restraint required by the gap limit in the ratio 1840/2000, i.e. by 8 %. For the coldest group it falls to 16.5–18.6 kN, which is still equal to or above the GOST minimum of 16.5 kN at all four stations. In Approach B the gap at Esil decreases from 61.2 to 56.3 mm. In Approach A, where 25 kN/m is a fixed panel value, the code gives no rule for the effect of sleeper density, and the gap does not change. The summer stability limit for 2000 sleepers/km was not recalculated.

This is not a conflict between the codes, because real assemblies may exceed the GOST minimum. A design check based on minimum values, however, does not guarantee this margin. For anchor-type elastic fastenings, the bolt condition of Rules No. 154-TsZ cannot be applied literally; in practice, the winter value r = 25 kN/m relies on the clamping force of the clips [1].

3.7 Northern stations.

In seven scenarios, meeting the gap limit requires 27.0–37.2 kN/m, which is above the 25 kN/m of the Rules. A review [19] reports longitudinal resistance of ballasted track up to 30 kN/m. Such resistance in winter is therefore partly achievable. The actual value depends on the frost depth, which is large in northern Kazakhstan [20], and on the state of the track

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bed [21]. The higher panel resistance can only work if the assembly restraint is at least 14.7–20.2 kN. Otherwise the fastening assembly becomes the weaker link, as in Approach B.

3.8 Fastenings at low temperature.

Both codes use the restraint measured at normal temperature, whereas a break occurs near $t_{min,min}$. Table 5 summarises the published data on the low-temperature behaviour of fastening components and separates measured relationships from the assumptions of this study. The measured data [9–12] concern the Spring II fastening, rail anchors and rail pads. None of them refers to the SKL or GK1 assemblies used by KTZ, which differ in clip type, pad material and the way the clamping force is produced. These data can therefore support only a qualitative conclusion: a reduction of restraint on cooling is physically plausible and, for other designs, has been of the order of 10–30 %. A reduction of restraint in the SKL and GK1 assemblies themselves has not been confirmed, and the authors have not yet carried out their own low-temperature tests.

Table 5. Published data on the low-temperature behaviour of fastening components and their use in this study

Component	Quantity	Test temperature	Change against normal temperature	Basis	Use in this study
Spring II fastening (Qinghai–Tibet railway)	longitudinal slip force	−40 °C	−10…−32 %	measured [9]	qualitative indication only
Rail anchors	slip force	-	−22…−33 %	measured [10]	qualitative indication only
Rail pads	stiffness	−40 °C	+26…+40 %	measured [11]	indirect; not converted into restraint
Rail pads	static and dynamic stiffness	below −10…−20 °C	noticeable increase begins	measured [12]	indirect; not converted into restraint
SKL and GK1 assemblies (KTZ)	assembly restraint F_a	+25 ± 10 °C (GOST 32698 test)	not determined at low temperature	code minimum [4]	assumption: $F_a = F_{GOST}$, no change in frost
SKL and GK1 assemblies (KTZ)	assembly restraint, estimate	–	–	calculated from rail foot–pad friction at nominal clamping force [3]	lower-bound scenario, F_a = 10 kN

For the southern stations the reserve in the main case is 6–14 % (Fig. 3), which is about equal to or smaller than the losses measured for other designs on cooling. The northern stations have no reserve at all. The behaviour of elastic fastening assemblies at −40…−50 °C therefore decides whether the gap limit is met. The sign and size of this effect should be found by testing complete assemblies to ISO 22074-2 [22] at temperatures down to −50 °C.

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3.9 Sensitivity of the results.

The base case uses fixed inputs: 1840 sleepers/km, the GOST 32698 minimum restraint, r_b = 25 kN/m and $t_f = t_{opt}$ + 5 °C. Table 6 shows how the gap changes when each input is varied separately within the two-link model, $r_{eff} = \min(F_a \cdot n/1000, r_b)$, for three stations that represent the three amplitude groups: Esil, Astana and Almaty. The variation of F_a by −10 to −30 % covers the range of losses reported for other designs on cooling [9, 10]. The range r_b = 20–35 kN/m extends from a loosened or fouled ballast prism to values somewhat above those reported for ballasted track in [19]. In this analysis r_b is treated as a per-metre value that does not depend on the sleeper density.

Table 6. Sensitivity of the break gap to sleeper density, assembly restraint, ballast resistance and fixing temperature (two-link model; values are r_{eff}, kN/m / λ, mm)

Factor	Value	Esil	Astana	Almaty
Base case	n = 1840 sleepers/km, $F_a = F_{GOST}$, r_b = 25 kN/m, $t_f = t_{opt}$ + 5 °C	25.0 / 74.3	25.0 / 58.4	25.0 / 44.4
Sleeper density n	1600 sleepers/km	25.0 / 74.3	22.4 / 65.2	22.4 / 49.5
	2000 sleepers/km	25.0 / 74.3	25.0 / 58.4	25.0 / 44.4
Assembly restraint F_a	−30 % of F_{GOST}	21.3 / 87.5	18.0 / 81.0	18.0 / 61.5
	−20 % of F_{GOST}	24.3 / 76.5	20.6 / 70.9	20.6 / 53.9
	−10 % of F_{GOST}	25.0 / 74.3	23.2 / 63.0	23.2 / 47.9
	+20 % of F_{GOST}	25.0 / 74.3	25.0 / 58.4	25.0 / 44.4
Ballast resistance r_b	20 kN/m	20.0 / 92.9	20.0 / 73.0	20.0 / 55.5
	30 kN/m	30.0 / 62.0	25.8 / 56.7	25.8 / 43.1
	35 kN/m	30.4 / 61.2	25.8 / 56.7	25.8 / 43.1
Fixing temperature t_f	t_{opt}	25.0 / 66.1	25.0 / 51.2	25.0 / 38.1
	t_{opt} − 5 °C	25.0 / 58.4	25.0 / 44.4	25.0 / 32.3

The response of the gap is strongly asymmetric, which follows directly from the weaker-link model. At the GOST minimum the ballast link governs at all three stations, so a higher sleeper density or a higher assembly restraint does not change the gap at all, while their decrease matters only once r_F falls below r_b. At Esil, where F_{GOST} = 16.5 kN gives r_F = 30.4 kN/m, the restraint may drop by about 18 % before the fastening becomes the weaker link; a 30 % loss raises the gap from 74.3 to 87.5 mm. At Astana and Almaty (F_{GOST} = 14.0 kN, r_F = 25.8 kN/m) the margin is only 3 %. A 20 % loss of restraint then increases the gap by 21 %, and at Almaty it pushes the gap above 50 mm (53.9 mm). A lower density of 1600 sleepers/km has a similar effect (+12 %).

The ballast resistance acts in both directions. A drop of r_b to 20 kN/m raises the gap by 25 % at every station, whereas an increase to 30–35 kN/m reduces it only until the fastening link takes over: by 17–18 % at Esil and by 3 % at Astana and Almaty. The fixing temperature is the most effective single factor. Since λ is proportional to Δt^2, lowering t_f by 5 °C reduces the gap by 11–14 %, and by 10 °C, by 21–27 %. Fig. 6a shows the gap at Esil as a continuous function of F_a for several values of r_b. With fixing at +35 °C, no combination of restraint and ballast resistance up to 35 kN/m keeps the gap below 50 mm; this would need $r_{eff} \geq 37.2$ kN/m, i.e. $F_a \geq 20.2$ kN together with $r_b \geq 37.2$ kN/m. Fig. 6b shows the restraint required by the gap limit as

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a function of the fixing temperature. At 1840 sleepers/km the GOST minimum is sufficient at Esil only for $t_f \leq +26.5$ °C, at Astana for $t_f \leq +30.3$ °C and at Almaty up to +45.3 °C; at 2000 sleepers/km these limits rise to +29.9, +33.4 and +48.4 °C.

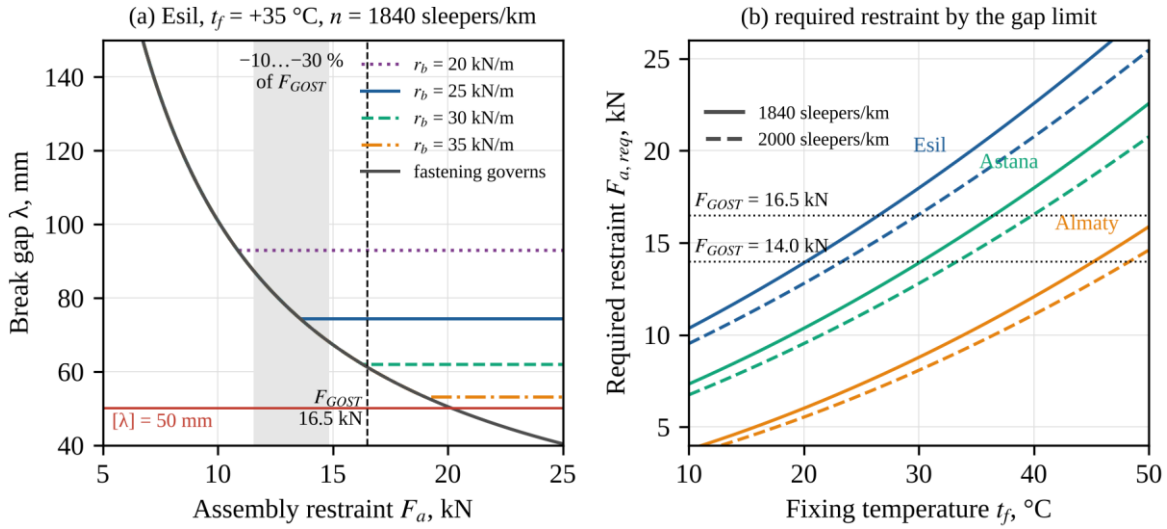


Fig. 6. Sensitivity of the results: (a) break gap at Esil versus assembly restraint for different sleeper–ballast resistances r_b; (b) restraint required by the gap limit versus fixing temperature for 1840 and 2000 sleepers/km (calculated by the authors)

3.10 Practical use and limitations.

The results indicate at which stations the gap limit needs attention when the fixing temperature is set and fastenings are selected. They lead to several practical recommendations, which supplement, but do not replace, the code checks.

– Monitoring of fastenings. On sections with T_A above 100 °C, the clamping force of SKL and GK1 clips should be checked against the service limit of 17 kN [1] before the winter period, with priority given to Esil, Moiynty, Zyryanovsk and Kandyagash, where the calculated reserve is the smallest. Where possible, the longitudinal restraint of complete assemblies should be measured on samples taken from track.

– Condition of the ballast prism. Because the panel in frozen ballast is the governing link at the GOST minimum, the shoulder width, crib filling and compaction of the ballast should be restored before freezing on these sections. Fouled or loosened ballast lowers r_b; a 20 % loss of r_b raises the calculated gap at Esil by 25 % (Table 6).

– Selection of the fixing temperature. At the northern stations, rail strings should preferably be fixed in the lower part of the optimum range rather than at its upper limit, within the window shown in Fig. 5. In curves of radius 800 m and less, the window should be checked individually, because the stability and gap limits may leave less than 10 °C.

– Acceptance of fastenings. For regions with T_A above 100 °C, the SP RK 3.03-114-2014 requirement at 1840 sleepers/km corresponds to an assembly restraint of 16.3–19.0 kN, which can serve as a target value when assemblies are accepted.

The limiting fixing temperature for the northern stations (+19.2…+32.2 °C by Approach A and +26.5…+33.3 °C by Approach B) is a reference value, not a design rule. Before use it must be checked for strength, stability and the width of the optimum range, including curves.

The study has limitations. The two-link model is rigid-plastic. It ignores link compliance before slip and the nonlinear force–displacement behaviour, and the code values are assigned to the links by assumption. The restraint was taken from code minima and

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an estimate, not from tests of specific assemblies. Only straight track and uniform temperature along the string were considered. Break dynamics and train loads [14] were not included. The sensitivity analysis varied one factor at a time. The stations were chosen to cover the code groups, not drawn statistically from the network. SP 119.13330.2024 is not a code of the Republic of Kazakhstan and is used only for comparison. The results describe design scenarios, not the state of particular rail strings.

4 CONCLUSION

The main conclusions are as follows.

1. Rules No. 154-TsZ and SP 119.13330.2024 use the same gap formula with different resistance values; in the two-link model they correspond to the ballast-governed and the fastening-governed limiting cases. For fixing at the upper limit of the optimum range and minimum code values, the gap exceeds 50 mm in seven of nine scenarios: 54.0–74.3 mm by Rules No. 154-TsZ and 52.4–61.2 mm by SP 119.13330.2024. Only Almaty and Shymkent meet the limit. These are design scenarios and do not describe the condition of track in service.

2. Meeting the gap limit requires a resistance of 22.2–37.2 kN/m. At five stations this is within SP RK 3.03-114-2014; at Esil, Moiynty and Zyryanovsk it is above 35 kN/m. At 1840 sleepers/km, the GOST 32698 minimum (25.8 and 30.4 kN/m) does not by itself meet the SP RK value for amplitudes above 100 °C; that would need a restraint of 16.3 kN and 17.9–19.0 kN. At 2000 sleepers/km (category I lines) the shortfall remains only for amplitudes of 100–110 °C (28.0 against 30 kN/m).

3. The required assembly restraint is 12.1–20.2 kN. The reserve against the GOST minimum is between −22 and +14 % and is positive only at Almaty and Shymkent. At the GOST minimum the gap is governed by the ballast link: a 20 % loss of ballast resistance increases the gap by 25 %, a loss of assembly restraint matters once it exceeds about 3 % (14.0 kN) or 18 % (16.5 kN), and lowering the fixing temperature by 5 °C reduces the gap by 11–14 %.

4. For the northern stations, the limiting fixing temperature is +19.2…+32.2 °C by Rules No. 154-TsZ and +26.5…+33.3 °C by SP 119.13330.2024, against +35 °C in the Rules. On straight track the interval to the stability limit is not less than 10.2 °C (Esil, Approach A). In 800 m curves it is shorter than 10 °C: 0.2–5.2 °C at Esil, Moiynty, Zyryanovsk and Kandyagash by Approach A, and 7.5–8.5 °C at Esil and Moiynty by Approach B. At these stations the gap limit requires a panel resistance above 25 kN/m and an assembly restraint above the GOST 32698 minimum. These values need a full code check before use.

5. The codes do not consider the change in restraint at low temperatures, and published data on other fastening designs cannot be transferred to SKL and GK1 assemblies without tests. For the northern part of the network, complete elastic fastening assemblies with R65 rails should be tested down to −50 °C to find the limit restraint $F_{slip}(T)$.

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INFORMATION ABOUT THE AUTHORS
Kuandykov Batyrbek Nurumovich – doctoral student, Department of Transport Construction, ALT University named after M. Tynyshbayev, Almaty, Kazakhstan, batyrbek.85@mail.ru, https://orcid.org/0009-0001-1560-2413
Alimkulov Murat Mametkulovich – Candidate of Technical Sciences, Associate Professor, Department of Transport Construction, ALT University named after M. Tynyshbayev, Almaty, Kazakhstan, m.alimkulov@alt.edu.kz, https://orcid.org/0000-0002-1882-760X
Apshikur Baitak – Candidate of Technical Sciences, Professor, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan, bapshikur@edu.ektu.kz, https://orcid.org/0000-0003-2103-9513
Lesov Kuvandik Saginovich – Candidate of Technical Sciences, Professor, Head of the Department of Railway Engineering, Tashkent State Transport University, Tashkent, Republic of Uzbekistan, kuvandikl@mail.ru, https://orcid.org/0000-0002-9434-0713
Tukenov Darkhan Toktarovich – doctoral student, Department of Transport Construction, ALT University named after M. Tynyshbayev, Almaty, Kazakhstan, tukenov.darkan@gmail.com, https://orcid.org/0009-0001-8726-8389
Kaldykarayev Islambek Mandibekovich – doctoral student, Department of Transport Construction, ALT University named after M. Tynyshbayev, Almaty, Kazakhstan, islamkaz91@mail.ru, https://orcid.org/0009-0004-3830-8577

AUTHORS CONTRIBUTION
Kuandykov B.N. – conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing – original draft.
Alimkulov M.M. – supervision, methodology, validation, writing – review & editing.
Apshikur B. – validation, analysis of regulatory requirements, interpretation of results, and writing – review and editing.
Lesov K. – methodology, validation of the theoretical model, interpretation of the results, and writing – review and editing.
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