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Point of View

Economic Assessment of Permafrost Degradation Effects on Road Infrastructure Sustainability under Climate Change in the Russian Arctic

B. N. Porfiriev[a, *], **D. O. Eliseev**[b, c, **], **and D. A. Streletskiy**[d, e, ***, #]

[a] *Institute of Economic Forecasting, Russian Academy of Sciences, Moscow, Russia*
[b] *Russian New University (RosNOU), Moscow, Russia*
[c] *Sochi Research Center, Russian Academy of Sciences, Sochi, Russia*
[d] *George Washington University, Washington, United States*
[e] *Earth Cryosphere Institute, Tyumen' Scientific Center, Siberian Branch, Russian Academy of Sciences, Tyumen', Russia*
**e-mail: b_porfiriev@mail.ru*
***e-mail: elisd@mail.ru*
****e-mail: strelets@gwu.edu*

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Abstract—Three model scenarios of changes in road infrastructure sustainability under permafrost thawing and degradation due to global climate change in nine Russian Arctic regions are considered. Until the current mid-century, economic assessment of the aftermath of climate change in these regions was physicogeographically based on six model climate assessments of cryogenic conditions, reflecting the most negative (scenario RCP8.5) option of the IPCC global climate change forecasts, which best fits the conditions of the Russian Arctic. The data of Russia's Transport Strategy until 2035, updated by the authors, serve as the basis for predicting road infrastructure development. An inertial (conservative) scenario of road infrastructure development in 2020–2050 shows that capital costs to maintain road infrastructure sustainability and reduce damage risks under permafrost thawing and degradation will average at least ₽14 bln a year and will exceed ₽21 bln and ₽28 bln, respectively, under the moderate and modernization scenarios. The maximum indicators will be relevant for the Republic of Sakha (Yakutia), Magadan oblast, and the Chukotka Autonomous Okrug. The implementation of the modernization scenario will require revision of the existing standards, technologies, and entire economy of the road infrastructure and capital construction favoring the development of innovative standards and construction technologies, as well as the improvement of the proposed methodology and methods of cost estimation for these purposes.

Keywords: Russian Arctic, permafrost, climate change, thawing, degradation, road infrastructure, investments, risks, development scenarios.

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Global climate change is manifested most in northern latitudes, especially in the Arctic regions of Russia. Studies of the past decade have shown that the intensity of climatic processes in the Russian part of the Arctic is increasing, causing economic uncertainty and risks [1]. Thus, the mean annual ground-air temperature growth of 0.5–2.5°C between 1980 and 2012 alone [2] largely predetermined a reduction in the annual ice area minimum in the Arctic Ocean (to a record value of 3.39 mln km^2 in 2012) and permafrost soil thawing and degradation [3, 4]. The latter, in turn, caused a reduction in soil stability [5–9], increasing emergencies at economic facilities [10, 11].[1] The number of buildings and structures affected by permafrost degradation has increased in recent decades [5]. By some estimations, permafrost soil thawing and degra-

RAS Academician Boris Nikolaevich Porfiriev is Director of the RAS Institute of Economic Forecasting (IEF). Dmitrii Olegovich Eliseev, Cand. Sci. (Econ.), is Head of the RosNOU Research Center and a Senior Researcher of the Sochi Research Center (SRC), RAS. Dmitry Andreevich Streletskiy, PhD, is an Associate Professor in the Department of Geography, Columbian College of Arts and Sciences, George Washington University.

[1] The bearing capacity of permafrost soils, which ensures the stability of buildings and structures, primarily depends on temperature and the mechanical characteristics of the soil. Therefore, construction in permafrost areas considers geological, climatic, and physicogeographical factors. Temperature growth in the permafrost zone triggers permafrost soil thawing and degradation, differential settlements, and deformations, which, in turn, reduce the stability of engineering facilities built on them.

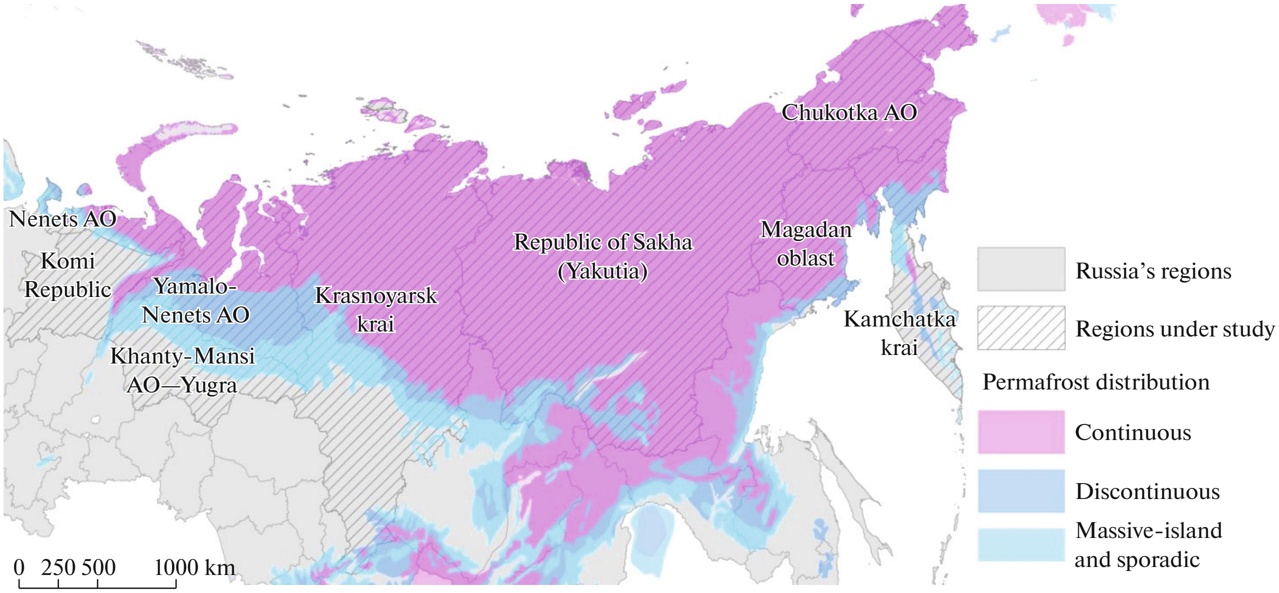

Fig. 1. Distribution of the permafrost considered across the territory of Russia's regions.

dation at oilfields of Western Siberia have caused, on average, 7400 emergencies a year, including about 1900 in the Khanty-Mansi Autonomous Okrug (AO).

Despite the severity of this problem for the economic development of the Russian Arctic and the country in general (which is predetermined, on the one hand, by the prevalence of permafrost in Russia: about two-thirds of the country's territory, and, on the other, by a considerable contribution of the microregion under consideration to the national economy, exceeding 13% of the GDP and 40% of the exports), economic assessments of permafrost degradation effects are obviously insufficient. There are rather limited macroeconomic valuations (by one of which, the average annual perennial damage caused by permafrost degradation is about ₽150 bln [12], or 0.16% of the GDP), or cost estimations to reduce this damage to individual economic units, e.g., pipelines (by one of the estimations, up to ₽55 bln are spent annually to maintain pipeline working capacity and eliminate mechanical deformations related to permafrost soil disturbance [13]), or cost estimations of individual fixed assets in permafrost-affected risk zones [14].

Obviously, more detailed assessments of actual and expected damages caused by permafrost thawing and degradation are necessary for specific territories, production facilities, and infrastructure complexes. The transport (road) infrastructure, including the branching network of motor roads and man-made facilities (bridges, road ramps, tunnels, etc.), is especially important for the Russian economy and, at the same time, vulnerable to the above effects of climate change. This article attempts to give an economic assessment of the sustainability of road infrastructure under various climate change scenarios in the aftermath of permafrost thawing and degradation.

The role of transport and road infrastructure in the economy of permafrost-affected territories. The permafrost zone encompasses 28 regions of Russia, which occupy about 65% of its territory, the permafrost distribution being extremely variable. In the European part, permafrost can be detected in Murmansk oblast, the Nenets AO, and the Komi Republic, as well as fragmentarily in Perm' krai and Sverdlovsk oblast. To the east of the Urals, the permafrost is located in the Yamalo-Nenets AO, the Khanty-Mansi AO, Krasnoyarsk krai, the Republic of Sakha (Yakutia), Magadan oblast, Kamchatka krai, the Chukotka AO, and partially the republics of Buryatia and Tyva, Zabaikalskii and Primorski krais, and Amur, Irkutsk, and Sakhalin oblasts. However, permafrost occupies the larger part of economically developed territories of only nine regions in the Russian North (the Komi Republic; Yakutia; the Nenets, Yamalo-Nenets, Khanty-Mansi, and Chukotka AOs; Krasnoyarsk krai; Magadan oblast; and Kamchatka krai); the remaining regions have permafrost fragments.[2] Below, the economic assessment of permafrost thawing and degradation will cover only these nine regions (Fig. 1).

[2] According to the International Permafrost Association's methodology, the following permafrost types are distinguished by areal extent: continuous (90–100% of territory coverage), discontinuous (50–90%), massive-island (10–50%), and sporadic or island (less than 10%); by the ice content in permafrost: high, medium, and low. Thus, in Murmansk oblast, the Middle Urals (Perm' krai, Sverdlovsk oblast), Southern Siberia (Irkutsk oblast, Altai krai, the Republic of Tyva, Kemerovo oblast), and the Far East (Amur oblast, Sakhalin), permafrost, as a rule, is located either in hard-to-reach mountain regions or in spots with no substantial risk for economic activity.

Table 1. Cargo transportation in regions of the Russian North

Region	Cargo transportation, mln tons (2017)		
	motor	rail	inland waterway
Komi Republic	28.4	13.7	0.19
Nenets AO	3	0	0.064
Khanty-Mansi AO—Yugra	135.1	13.9	4.24
Yamalo-Nenets AO	29.9	11.9	1.72
Krasnoyarsk krai	78.2	53.3	11.38
Republic of Sakha (Yakutia)	16.4	13.6	4.73
Magadan oblast	2.2	0	0.04
Kamchatka krai	1	0	0.006
Chukotka AO	1.5	0	0.33

Source: Data of the Russian Federal Agency of Maritime and River Transport, the Russian Federal Road Agency, and Rosstat.

Table 2. Length of surfaced roads in regions of the Russian North in 2018, km

Region	Roads			Engineering facilities
	Total	Hard-surface	Improved hard-surface	
Komi Republic	7534.30	6479.9	4447.7	389
Nenets AO	350.70	248.7	86.7	42
Khanty-Mansi AO—Yugra	6945.70	5739.1	5215.9	270
Yamalo-Nenets AO	2504.40	2327.2	2027.9	246
Krasnoyarsk krai	32595.10	27540.4	12081.5	928
Republic of Sakha (Yakutia)	30424.46	11899.7	1989.7	503
Magadan oblast	2168.19	2039.6	678.7	166
Kamchatka krai	2803.61	2565.7	484.7	213
Chukotka AO	3354.35	850.5	49.6	82
Total	88680.81	59690.8	27062.4	2839

Source: Rosstat data.

The extractive industry dominates the economies of the above regions: the extraction of raw materials and mineral resources is 44% of the total gross regional product (GRP), the value of which in 2017 exceeded ₽10 trillion, or 10.91% of the country's GDP. Most mineral resources are exported outside the extraction territory and abroad (primarily, oil, gas, various metals, coal, and diamonds). At the same time, the extraction of mineral resources requires massive imports of necessary materials, machines and equipment, and labor (rotation workers). Therefore, it is hard to overstate the importance of the transportation system, the contribution of which to the total gross regional product is about 7%. The system includes subsystems of railroad, motor, aircraft, water, and pipeline transport. The leading role among them belongs to motor transport, which serves 69% of the regional freight traffic (except for pipelines) (Table 1). Hence, the strategic relevance of road network development and the quality of the road infrastructure for the economy of the regions of the Russian North is hard to overstate . The length of motor roads is about 88000 km; the number of engineering facilities (bridges, overhead roads, etc.) exceeds 2800. Hard-surface (asphalt, cohesive soil) roads comprise 67% of the total length, high-quality roadbeds of categories II and III comprising only 30% of the roads. In the Yamalo-Nenets and Khanty-Mansi AOs, over 90% of the roads are paved, while in Krasnoyarsk krai, the share of asphalt and asphalt—concrete roads does not exceed 30%, and in Yakutia, Magadan oblast, and the Chukotka AO, most roads are not paved at all (Table 2).

According to data of the Russian Ministry of Transportation (Mintrans), the construction cost of 1 km of new roads (per one traffic lane) net of VAT is ₽11.73—₽52.28 mln; the motor road reconstruction cost is ₽10.32—₽46.03 mln; the cost of roadbed capital repairs is ₽9.71—₽20.62 mln; and the maintenance

Table 3. Average cost of roadwork in Russia in 2017

Work activities	Average cost of work, mln rubles				
	For 1 km of motor roadbed of a corresponding category				For unit of engineering facilities
	II	III	IV	V	
Construction	42.53	37.1	14.09	11.73	1382.24
Reconstruction	28.41	32.93	13.73	10.32	
Capital repairs	17.88	17.21	9.74	9.71	557.78
Maintenance	7.13	6.69	6.49	3.89	

Source: Russian Mintrans data.

cost is ₽3.89–₽7.29 mln. The price depends on the roadbed quality, road category, and construction region.[3] Most expensive are roads of category I with an improved roadbed (asphalt–concrete, cement concrete), and the cheapest roads are of category V, including dirt roads and improved firm-ground roads (Table 3).

The regions considered do not have roads of category I; therefore, they are excluded from the calculations. In addition, road maintenance was not assessed, since permafrost degradation conditions imply that roadbed maintenance is not enough to keep the road network fully functional.

Methodological approaches to the economic assessment of permafrost thawing and degradation risks for road infrastructure sustainability. The following indicators appear to be key for the economic assessment of permafrost thawing and degradation effects on the sustainability of motor road infrastructure and road system functionality in general. First, there is the cost of fixed assets at risk, which reflects maximum potential damages caused by reduced bearing capacity of permafrost soils and the subsequent destruction of facilities built on them. Second, there is the length of motor roads and the number of engineering facilities at risk, which helps assess the scale of the problem in physical units, which, in turn, makes it possible subsequently to update cost assessments. Third, there is the cost of reconstruction, new construction, or possible repairs of fixed assets at risk; in fact, there is the assessment of the costs of a corresponding economic agent to reduce the risk of losing road infrastructure sustainability when implementing a specific scenario of permafrost thawing and degradation effects.

At present, the Russian Statistics Agency (Rosstat) accounts annually for fixed assets using the following cost indicators: the industrial structure of fixed assets (the extraction of raw materials, agriculture, industry, transport, etc.); the specific structure of fixed assets (buildings, structures, machines and equipment, means of transportation, other assets); the regional cost of fixed assets (by the subjects of the Russian Federation); the structure of fixed assets by type of property (public, municipal, private, etc.). The corresponding Rosstat data at the regional level were used as a statistical basis to assess the cost of the fixed assets of the road infrastructure. Statistical data on the full cost of fixed assets at the end of 2017 were used assuming that about 40% of the fixed assets in the regions under study had practically been fully depreciated and, consequently, statistics does not always reflect the real picture [15].

Considering the choice of statistical indicators, it was assumed that the fixed assets of the road infrastructure belong to the category "transport" (roads) and "structures" (engineering facilities), and with respect to property rights, to the category of federal, regional, and municipal property [15].[4] Note that regional statistical indicators prevent us from understanding fully the cost of the road infrastructure at specific locations. Therefore, the total cost data on the fixed assets at the regional level (FA_{reg}) isolating the share of public fixed assets (FA_{pub}) from them were used for calculations. At the final stage, statistical data on the share of the fixed assets of the transport industry were taken at the regional level using the Rosstat accounting methodology (FA_{trans}), isolating the road infrastructure from them, which corresponded to the category "structures" (FS_{road}). In a general form, the formula to calculate the cost of the fixed assets of motor roads in a specific region is like this:

$$FA = FA_{reg} * FA'_{pub} * FA'_{trans} * FA'_{road}, \qquad (1)$$

where FA is the cost of the fixed assets of the road infrastructure in a region; FA_{reg} is the total cost of the fixed assets in a region; FA'_{pub} is the share of public and municipal fixed assets; FA'_{trans} is the share of the fixed

[3] A report by the Russian Mintrans shows that the cost was assessed using a comparable regional sample of facilities and varied from 256 to 4000 facilities across all of Russia.

[4] This study does not assess private motor roads, which exist in several regions of Russia (e.g., in the Yamalo-Nenets and Khanty-Mansi AOs), because this is largely a special case of a specific territory and the actual facts of the quality and quantity of these roads are not statistically accounted for.

Table 4. Scenarios of road infrastructure development in predominantly permafrost regions of the Russian North*

Scenario	Increased length of motor roads by 2030, % (2018 = 100%)	Share of hard asphalt motor roads, %	
		2018	2030
Conservative	100.00	30.6	30.60
Moderate	102.52	59.6	60.55
Modernization	107.71	59.6	98.30

* Continuous, discontinuous, and massive-island permafrost.

assets of the regional transport industry; and $FA'_{\rm road}$ is the share of the road infrastructure in the structure of a region's transport industry.

As there are no data on the presence or absence of permafrost under a specific road throughout its length or under a specific engineering facility of the road infrastructure in the territories under consideration, to assess the length of roads and/or the number of engineering facilities of the road infrastructure located on permafrost, a previously tested methodology [14], based on the criteria of the International Permafrost Association, was used. According to these criteria, 90% of the length of roads (or the number of facilities) in the permafrost zone are considered to be built on perennially frozen soils. The corresponding criteria for the zones of continuous, and massive-island, and island permafrost are 90, 50, 10, and 0% (i.e., the facilities were built outside the zone of permafrost soils). In a general form, the calculation formula is the following:

$$L = 0.9L_c + 0.5L_d + 0.1L_f, \qquad (2)$$

where L is the total length of motor roads built on permafrost; L_c is the length of roads built in the zone of continuous permafrost; L_d is the length of roads built in the zone of discontinuous permafrost; L_f is the length of roads built in the zone of massive-island (fragmentary) permafrost.

To assess the cost of the fixed assets of the road infrastructure (roads and engineering facilities) built on permafrost soils, the same criteria were used as in formula (2). In addition, to calculate the cost of construction, reconstruction, or capital repairs of the road infrastructure, the Russian Mintrans data on the current cost of these operations were used, as well as those on the roadbed length calculated according to formula (2). As a result, the cost of the fixed assets of the road infrastructure located in the permafrost zone can be calculated by the following formula:

$$FA^* = 0.9FA_c^* + 0.5FA_d^* + 0.1FA_m^*. \qquad (3)$$

At the final stage, the expected damage from permafrost thawing and degradation for the road infrastructure is given under various climate change scenarios, as well as maintenance and modernization costs until 2060. The assessment is based on modeling, where the basic scenario provides for permafrost soil degradation at a designated date and the need for corresponding costs to maintain the road infrastructure operational. In addition, it was taken into account that these costs were additional to the maintenance costs of the infrastructure in question because they were not due to roadbed depreciation (wear and tear) but due to the effects of permafrost thawing and degradation.

The forecast of road infrastructure development and functional dynamics net of the climatic factor, its effect on the bearing capacity of permafrost, and their effects on road infrastructure sustainability includes three scenarios (Table 4). The scenarios are based on the indicators of Russia's Transport Strategy until 2030. [16], approved by the Russian government in 2008 as amended in 2016. The Strategy has no clear-cut criteria of defining qualitative changes in the roadbed condition in its implementation. It just states that by 2030, a corresponding share of roads in Russia will meet transport operation requirements. Since the Russian Mintrans's documents lack explanations on the criteria of standard requirements [17], the calculations use the assumption that roadbed quality improvement implies improvements by road category.

The *conservative (inertial) scenario* assumes maintenance of the current condition of the road infrastructure proceeding from its existing quality and length. The total cost of capital outlay is assumed to be distributed proportionately by year over the entire period 2019–2030.

The *moderate scenario* assumes that the road infrastructure will develop, but the growth rates of road length and quality improvement will be small until 2030, meeting the Strategy's target indicators and the approved federal, regional, and municipal transport system development programs; namely, the length of motor roads will increase by 2.52% by 2030, and the share of paved roads will be 60.55% of the total motor road length in the same year (see Table 4).

The *modernization scenario* assumes the construction of new road infrastructure facilities along with the maintenance and upkeep of the existing roadbed and engineering facilities, as well as their stage-by-stage reconstruction and quality improvement. According to this scenario, the length of motor roads in 2030 will grow by 7.71%, and the share of paved roads will reach 98.3% of the total length of motor roads (see Table 4).

Table 5. Cost of the fixed assets of the road infrastructure in regions of the Russian North in 2018

Region	Cost of fixed assets, bln rubles		
	Total	Including fixed assets federally, regionally, and municipally owned	Fixed assets federally, regionally, and municipally owned in the permafrost zone
Komi Republic	3207.3	122.4	3.6
Nenets AO	887.4	2.7	1.7
Khanty-Mansi AO—Yugra	12543.0	245.1	5.9
Yamalo-Nenets AO	11279.8	292.9	142.9
Krasnoyarsk krai	3604.5	41.0	2.4
Republic of Sakha (Yakutia)	2208.1	51.1	43.8
Magadan oblast	540.8	3.9	0.3
Kamchatka krai	281.0	3.4	2.8
Chukotka AO	170.4	0.7	0.7
Total	34722.3	763.2	204.0

Source: Rosstat data processed by the authors.

To assess the effect of the bearing capacity of permafrost reduced by climate warming on road infrastructure sustainability, the climate change forecasts should be superimposed on the above scenarios. There are six global climate change models,[5] used by the Intergovernmental Panel on Climate Change (IPCC) during the preparation of the V Assessment Report on Climate Change (CMIP-5) for the period until the mid-21st century. The above models allow high-quality predictions of surface-air temperature in Russia's northern regions [1, 13]. The results of surface temperature and precipitation modeling were averaged over time intervals of 2006—2015 and 2050—2059.

Scenario RCP8.5, the worst-case (most radical) scenario of the global climate change forecasts, was used for the basic assessment of climate change effects in the regions under consideration until the middle of the current century. It appears to reflect in the best way the dynamics of the most probable climate change in the northern, primarily Arctic, regions of Russia, delivering maximum risks (expected damages) from these changes. In addition, the forecast is based on the assumption that permafrost degradation occurs gradually under the effect of an increase in the surface air temperature. Therefore, the assumed stage-by-stage reduction in permafrost soil thickness will occur over the course of the next 30 years within the basic scenario. Considering the impossibility of the predicted permafrost thawing and degradation levels and their effect on sustainability of the road infrastructure on specific year, the expected total damage is assumed to spread evenly between 2015 and 2050.

The most dangerous long-term consequences of permafrost degradation are the reduced bearing capacity of permafrost and soil subsidence during thawing. Considering this study, the results obtained previously and based on the authors' geotechnical models of permafrost changes were used as the methodological basis for assessing such phenomena [14, 18]. The specific values of the changes were calculated according to the following formula:

$$S = dZ * I, \tag{4}$$

where S is the depth (amount) of soil subsidence, mm; dZ is the time difference in the thickness of the seasonally thawed layer of permafrost soils in 2005—2015 and 2050; and I is the ice content in soils, %.

Assessing the cost of reducing the risk (expected damage) of permafrost thawing and degradation under climate warming for the road infrastructure. According to the above methodology, let us assess the *cost of the fixed assets of the road infrastructure at risk*. To this end, it is necessary to make calculations and define the values of the elements on the right-hand side of formulas (2) and (3).

According to the Rosstat data, in 2018, the total cost of fixed assets in the nine regions under consideration was ₽34.72 trillion, or 17% of the total cost of Russia's fixed assets. The share of transport is about 30%, or ₽10.29 trillion of the fixed assets' coast of the regions above. The share of federal, regional, and municipal property, to which motor roads belong, is about 27% of the total cost of transport's fixed assets. One-third of them, or ₽763.2 bln, falls on the road infrastructure (motor roads and engineering facilities: bridges, overhead roads, etc.) (Table 5).

The cost of the fixed assets of the road infrastructure varies by region: the highest values are typical of the Komi Republic, the Yamalo-Nenets and Khanty-Mansi AOs with almost 90% of paved motor roads, as

[5] They include CanESM2, CSIRO-Mk3-6-0, GFDL-CM3, HadGEM2-ES, IPSLCM5A-LR, and NorESM1-M.

Table 6. Length of motor roads located in the permafrost zone in regions of the Russian North, 2018

Region	Total length, km	Including roads by category, km				Engineering facilities
		II	III	IV	V	
Komi Republic	449.40	0.00	44.59	184.87	219.94	24
Nenets AO	216.95	0.00	13.78	40.73	162.43	26
Khanty-Mansi AO—Yugra	166.61	3.15	33.63	97.53	32.30	7
Yamalo-Nenets AO	1222.08	0.00	192.86	771.43	257.79	121
Krasnoyarsk krai	1871.50	0.00	185.08	499.14	1187.27	50
Republic of Sakha (Yakutia)	26 028.19	0.00	306.71	3284.29	22 437.19	433
Magadan oblast	187.61	0.29	11.33	43.47	132.52	15
Kamchatka krai	2322.36	125.86	116.36	624.14	1456.00	159
Chukotka AO	3006.95	0.00	0.00	57.67	2949.28	74
Total	35 471.64	129.30	904.34	5603.28	28 834.72	909

Source: calculated by the authors.

well as of Krasnoyarsk krai and the Republic of Sakha (Yakutia), where the motor road network is lengthy (see Table 2). Similar differences exist in the cost of the above assets located in the permafrost zone. In eastern regions of Russia's North, practically 100% of motor roads were built on permafrost, but in the Komi Republic, the roads on permafrost comprise only about 25%.

According to the authors' estimates, the total cost of the fixed assets of the road infrastructure in the permafrost zone is ₽204 bln, ₽143 bln (70%) of which falls on the Yamalo-Nenets AO. This is associated with the region's natural and geographical characteristics (practically all its territory is located on permafrost), as well as with the length of its road network and the quality of its road infrastructure. Permafrost also prevail in the eastern regions of Siberia (Yakutia, the Chukotka AO, and Magadan oblast), but most motor roads are dirt roads, and engineering facilities (e.g., bridges) are wooden or metallic; therefore, the cost of the existent fixed assets of the road infrastructure is much smaller. In addition, the indicator of the current cost of the fixed assets of the road infrastructure is largely conventional, considering the fact that the depreciation life of most fixed assets expired long ago. Thus, the cost of motor roads in the regions considered is about ₽760 bln according to the Rosstat data, their total length being 88 000 km, which is practically 2.5–3 times less than the cost of building similar facilities.

More accurate assessments of the scope of the problem were obtained on the basis of physical terms of the road infrastructure condition. The motor roads laid in the permafrost zone comprise 35 471 km and 909 bridge crossings (Table 6). They include 2.9% of paved roads of categories II and III and 97.1% of dirt roads of improved and technical categories. Note Yakutia here, which has almost three-fourths of permafrost motor roads: over 90% of them are dirt roads.

According to the adopted methodology, let us consider the above scenarios (see Table 4) of the effect of permafrost thawing and degradation on the sustainability of the road infrastructure built on permafrost and the estimate risk (expected damage) reduction costs for 2020–2050 (Table 7).

The *conservative scenario* assumes that the existing road infrastructure on permafrost, including over 35 000 km of the road network, will need constant additional capital investment to repair and maintain sustainable functioning due to permafrost degradation and the reduction of soil bearing capacity, as well as surface deformation due to thaw subsidence of ice-rich soils. Proceeding from the data in Table 3, these costs in the nine regions considered will amount to ₽422.68 bln over the entire stated period, including ₽252.83 bln (59.8%) for Yakutia. Thus, the additional costs will amount to ₽14.07 bln, on average, per year, or 0.14% of the total gross regional product of all nine regions in 2018. The highest indicators will be in Yakutia, Krasnoyarsk krai, Magadan oblast, and Chukotka (see Table 7).

The *moderate scenario* assumed in accordance with the Strategy that, by 2030, 17460 km of motor roads on permafrost in the regions considered will be reconstructed bringing their quality to 60.55% of category V roads (with a hard asphalt top) (see Table 4). In addition, 2234.75 km of roads and 56 engineering facilities will be built (proportionately by region). In 2020–2050, ₽304.24 bln will have to be additionally spent on capital repairs of the roadbed and engineering facilities due to the effects of permafrost degradation. The reconstruction of part of the road network with improved quality in 2020–2030 and the subsequent maintenance and upkeep of this infrastructure in 2030–2050 are estimated at ₽272.9 bln. The cost of expanding the motor road network in 2020–2030 and its subsequent operating costs will amount to ₽67.34 bln. In addition, road construction and reconstruction

Table 7. Predicted cost of the reconstruction and maintenance of the regional road infrastructure due to thawing and permafrost degradation risks, bln rubles in 2018 prices

Region	GRP	Infrastructure at risk, %*	Conservative		Moderate		Modernization	
			2020–2050	annually	2020–2050	annually	2020–2050	annually
Komi Republic	574.38	89.1	20.05	0.67	27.70	0.92	32.55	1.09
Nenets AO	276.49	40.0	7.59	0.25	9.55	0.32	10.53	0.35
Khanty-Mansi AO—Yugra	3511.1	27.2	2.05	0.07	2.62	0.09	3.42	0.11
Yamalo-Nenets AO	2461.4	27.6	25.91	0.86	31.43	1.05	35.74	1.19
Krasnoyarsk krai	1882.3	63.1	42.49	1.42	62.51	2.08	81.41	2.71
Republic of Sakha (Yakutia)	916.58	33.6	252.83	8.43	409.43	13.65	566.12	18.87
Magadan oblast	201.64	5.8	0.71	0.02	0.98	0.03	1.10	0.04
Kamchatka krai	157.63	25.8	35.55	1.19	45.80	1.53	55.15	1.84
Chukotka AO	68.729	35.7	35.5	1.18	54.46	1.82	78.81	2.63
Total	10050	18.8	422.68	14.09	644.48	21.48	864.81	28.83

* The authors used calculations from their previous work [14].
Source: the authors' calculations.

costs in 2020–2030 are also accounted for as their renewal costs due to permafrost degradation.

Thus, the total costs are to comprise the cost of capital repairs and general additional costs of road infrastructure maintenance, including new motor roads, reconstructed sections, and the remaining road network. Until 2050, these costs will amount to ₽644.48 bln (₽21.46 bln a year), which is equivalent to 0.21% of the total GRP in 2018 of all nine regions. As in the previous scenario, the highest indicators will be typical of Yakutia, Magadan oblast, and Chukotka (see Table 7).

The *modernization scenario* assumed in accordance with the Strategy taking the share of the qualitative roadbed in the considered regions to 98.3% by 2030, or the actual reconstruction of 28 344.53 km of roads, as well as the additional construction of 6837.29 km of new roads and 171 engineering facilities. For 2020–2030, the costs of reconstructing motor roads located in the permafrost zone will be ₽426.65 bln, and the costs of maintaining the sustainability of the existent road infrastructure for 2020–2050 will amount to ₽230.39 bln. The costs of construction of new motor roads and engineering facilities for 2020–2030 and their maintenance costs for 2030–2050 are estimated at ₽207.75 bln. Thus, the total costs for the entire period until 2050 will reach ₽864.81 bln, or ₽28.83 bln in average annual terms, which is equivalent to 0.29% of the total GRP of all nine regions in 2018. The maximum indicators will be typical of the Chukotka AO, Yakutia, and Magadan oblast (see Table 7).

* * *

Permafrost is a major natural characteristic of the Russian Arctic that predetermines the design specifics and construction economy of practically all capital structures (buildings, fuel-and-energy facilities, runways, roads, etc.), which have been built over almost a century of Arctic exploration. In recent decades, global climate change, primarily the accelerated growth of surface air temperature, has substantially changed natural conditions, especially the integrity and stability of permafrost, triggering near-surface permafrost thawing and degradation, and, consequently, the reduction of their bearing capacity and thaw subsidence. This has turned a vast territory into a zone of increased investment risks, including the construction and maintenance of the transport infrastructure, the development of which is of critical importance of the modern redevelopment of this strategic macroregion.

The calculations based on the methodology of assessing the effects of permafrost thawing and degradation under climate change on the sustainability of the road infrastructure in the Russian Arctic, proposed in this paper, show that the risks of disturbing and destroying the sustainability of the road infrastructure under permafrost thawing and degradation are very high even under the conservative scenario of the development of the transport infrastructure in general and the road infrastructure in particular. The expected direct damage (net of indirect losses due to delays in delivery and clearance deadlines, emergency response costs, etc.) to road infrastructure sustainability in the nine Arctic regions will amount to at least ₽14 bln. Thus, additional (to the current maintenance expenses) costs to repair and maintain infrastructure sustainability will amount to 0.14% of the total GRP cost of these regions in 2018. This indicator will be much higher in Yakutia, Krasnoyarsk krai, Magadan oblast, and Chukotka, the economies of which are most vulnerable to permafrost degradation risks. Under the modernization scenario, which includes the construction of new motor roads and engineering facilities and the improvement of the quality of roads already built (increasing their capacity and reducing the above risks), the costs of maintaining road infrastructure sustainability will double, the maximum indicators being typical of the Chukotka AO, Yakutia, and Magadan oblast.

The implementation of the modernization scenario requires revision of the existing standards and technologies, and the entire economy of road infrastructure and capital construction in general, favoring the development of innovative (including resource-efficient and ecological "green") standards and construction technologies [15], and the improvement of the proposed methodology and methods of assessing these costs. In particular, they should be supplemented with an analysis of a scenario that accounts for longer terms thawing, degradation, and near-surface disappearance of permafrost, which will tell substantially on the total cost, distribution, and, consequently, risks of investments. In addition, to assess correctly the emerging additional load on the economies of the regions of the Russian Arctic, it should be correlated with economic dynamics. To this end, in turn, it is necessary to make not only long-term (until 2030–2035) but also extended (until 2050) economic growth forecasts.

The above imperatives should be considered in detail by the new Strategy of Russian Arctic Development until 2035, the elaboration of which was announced by the Russian President at the V International Arctic Forum in St. Petersburg on April 9, 2019. The Strategy should combine national projects and government programs, investment plans of infrastructure companies, and development programs for Arctic cities and regions, paying special attention to transport and support infrastructure development [19].

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