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A New Procedure to Calculate the Load on the Roadway

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ABSTRACT

Presence of a developed transport and logistics system that provides year-round cargo and passenger transportation constitutes a necessary condition for intensive socio-economic development of any region.

The only type of continuum transport capable of providing year-round transportation in natural and climatic conditions of the cryolithic zone, an integral part of which is the territory of the Arctic zone of the Russian Federation, is road transport. This is due to its compactness, mobility, ease of control and maintenance, as well as to a relatively low price, both for a single vehicle and for transportation services, which in turn predetermines its use for regional and intracity transportation within the permafrost zone.

The only condition for effective use of road transport is provision of territories with year-round operated public roads, while their design and structure should correspond to the predicted load from vehicles and intensity of the traffic flow.

The Government of the Russian Federation adopted the decision to build an automobile bridge across the Lena River near Yakutsk, which is scheduled to be put into operation in 2024. Accordingly, the problem of assessing the state of the city's road network in terms of the possibility to process future traffic flows and road traffic organisation considering the design features of city roads, becomes relevant.

Calculations of basic parameters of promising cargo and passenger flows were carried out with a new author's methodology. An extended model served a basis for predictive assessment of the growth in relative intensity of transport flows and loads on the roads of Yakutsk after commissioning of the bridge across the Lena River. A variety of transport and logistics schemes for organising road traffic were considered. The condition and design features of the roads on the selected routes were assessed, and their transit capacity and maximum loads from transport flows that their structure could withstand were calculated.

It has been established that the road infrastructure of Tuymaada valley is not able to ensure the transit of promising cargo flows that will arrive to the left bank of the Lena River across the bridge.

It has been proved that the only possible solution to the vast majority of the emerging problems related to cargo traffic is construction of a federal ring road, which runs mainly outside the valley of the Lena River.

Keywords: *cryolithic zone, permafrost zone, Tuymaada valley, Yakutsk, urban street and road network, bridge, cargo transportation, traffic intensity, roadway load, transport systems, road traffic organisation.*

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INTRODUCTION

Problem Statement

A prerequisite for intensive socio-economic development of any region is the presence of a developed transport and logistics system, providing unhindered exchange between neighbouring territories with necessary goods, materials, resources, producer goods, and workforce. For administrative units (states, regions, districts), which occupy large areas and are characterised by complex climatic conditions, transportation routes constitute the most important components of transport and logistics systems. In the process of development of human civilisation, three types of technical transport systems were developed for socially significant cargo-passenger transportations for long distances, which are air, water, and land transportation systems. Each of these modes requires construction of specific transportation routes, have their own structure and engineering and technical features that are formed, first, as a function of volume and composition of the transported cargo, the technical configuration of transport systems, the natural and climatic conditions, as well as the socio-economic condition of the territory. Depending on these factors, the optimal transport and logistics scheme is being developed, which involves the most efficient use at least in the economic aspect, of certain varieties of vehicles.

By virtue of the historically formed structure of the global transport network, no mode of transport can provide on a global scale a full cycle of transportation of socially significant volumes of cargo, from the point of departure to the destination and, moreover, from the manufacturer to the consumer. The global movement of significant cargo volumes is always associated with the use of a minimum of two types of transport systems, two types of loading and unloading systems (except container shipping) and two specialised infrastructure systems of transportation routes. The most commonly used vehicle pairs are well-known: air–road, rail–road, water–road, road–road. Mandatory presence of road transport in any transport chain is associated with its compactness, mobility, simplicity in control and maintenance, as well as with a relatively low price, both on a single vehicle and transport services. These features predetermine the non-alternateness of road transport for cargo intracity transportation. On the other hand, they also provide for its attractiveness for use in interregional transportation of small batches of goods of specific configuration or composition. The only condition for the efficient use of road transport is the availability of roads within a territory, while the roads should correspond by their design to estimated load from vehicles and intensity of the transport flow.

These approaches acquire real practical importance in implementation of large infrastructure projects and require development of an appropriate methodology and procedures. This is especially true under complex physio-geographical and climatic conditions. In this regard, a characteristic example is a comprehensive project to improve the connectivity of the transport network of the Republic of Sakha (Yakutia) with a federal road network.

At the end of 2019, the Government of the Russian Federation adopted the decision to build a road bridge across the Lena River in the immediate vicinity of the city of Yalutsk, capital of the Republic of Sakha (Yakutia). The bridge is scheduled to be put into service in 2024. Its construction will lead to significant changes in the transport and logistics system of the Asian part of the Russian Federation. However, by virtue of the physio-geographical position and features of urban planning in extreme climatic conditions, these changes, from operational aspects, will be fundamental only for the road-transport network of the river valley of Tuymaada, including the city of Yakutsk, through which roads of the federal, regional, and municipal importance pass. In connection with implementation of this project, it is necessary on an example of an extended model to carry out a general analysis of the capacity of the road system of the Yakutsk city agglomeration and the adjacent territories regarding redistribution and transit of goods after commissioning of the bridge across the Lena River, to identify its prospective transit capacity (traffic intensity) and stability of structural elements of roads under the influence of the load from wheels of cars on road pavement.

The systematic study of the road infrastructure of Tuymaada valley in terms of growth in traffic intensity and loads has not been carried out. The issue of traffic intensity was considered as a secondary one in the study of the possibility of using intelligent transport systems on certain sections of the roads of Yakutsk [1]. Problems of design, physio-mechanical properties, engineering and geological processes in the soils of the road embankment, as well as behaviour at low temperatures of materials of road pavement of the roads of cryolithic zones were discussed in a number of works [2–14].

The problem of stability of structural elements of roads in permafrost zone under the influence of loads is not considered widely in scientific sources. A similar situation has developed with scientific research on the influence of the load on the roads in more favourable climatic conditions of the so-called second-fifth road-climatic zones. It is possible to assume that the interest of the scientific community in the overall analysis of the impact of the load from vehicles on the road pavement is affected to a certain extent by constraints, which are imposed by the existing regulatory framework of the road construction industry.

In the Russian Federation, calculation of the standard load on road pavement is regulated by GOST 52748-2007 «National Standard of the Russian Federation. Automobile roads of the general using. Standard loads, loading systems and clearance approaches»[1, 2]. The analysis of basic provisions of this standard reveals, in the author's opinion, some formalisation, and to a certain extent, even inconsistency with the realities of cargo-passenger transportation and well-known physical knowledge. Parameters, stipulated om the standard, are in some part unacceptable for design and survey, construction, operational work, and, moreover, for building models and implementation of forecast estimates of cargo-passenger transportation. For example, the formula for calculating the load from passenger cars («AK load») developed on the basis of the «model chassis» with the following parameters: pressure of one axis (for the roads of category IV) is 10,2 tons (with gravitational acceleration g = 9,8 m/s^2) with a width of one wheel of 60 centimetres. Among vehicles there are no passenger cars with a weight of 20,4 tons (!). Each wheel of such a car has a load on the roadway of about 510 kilograms (5 kN). That is, all four wheels have a load of 2040 kilograms. The discrepancy between weight parameters of the model chassis and its weight load on road pavement indicates a possible incorrectness of calculations during the development of the document, which were implemented into basic parameters of the regulatory document. The standard weight of the cargo truck («NK load») according to the parameters of the same regulatory document is about 73,5 tons.

Revealed imperfection of the regulatory framework of the road construction industry in terms of the definition of loads predetermines, in the author's opinion, the need to develop a new single load calculation procedure that will allow to use the calculated data for any kind or types of road vehicles, for all classed and categories of roads. The resulting data should be adapted to a variety of transport and logistics concepts and to regulatory documentation, which will allow to build forecast models, including mathematical ones.

The main *task* of the paper is to develop a forecast estimation of the growth in traffic intensity and loads on the roads, which will be formed within the Yakutsk city district after the construction of the bridge across the Lena River.

For implementation of the calculations, it is necessary to develop an extended model of cargo-passenger transportation, which takes into account natural-climatic, engineering and geological conditions, as well as the features of the road infrastructure of Tuymaada valley, where the capital of the Republic of Sakha (Yakutia) is located.

Characteristic of the District and its Road Infrastructure

Geographically, the district is located in the southwestern part of the Central Yakut plain. Relief is plain, of erosion-accumulative type.

Yakutsk city district is located in Central Yakutia on the left bank of the Lena River. The morphology of the district is determined by its confinedness to the Tuymaada river valley (tract). From the north the valley is limited by Kangalassky Cape, and from the south by Tabaginsky Cape. The length of the valley is about 80 km. Area is of more than 300 sq. km.

The valley, with the exception for modern anthropogenic load, has been formed in the process of erosion-accumulative activities of the Lena River. It is the plain that slopes in the northern direction. River terraces are weakly marked, mainly due to intensive technogenic landscape transformation. The relief of the area is homogeneous and is formed by erosion accumulative, somewhere denudation processes, typical for river valleys of lowland rivers. Numerous oxbow lakes are found, somewhere they dry up or are overgrown in the summer, also

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[1] GOST 52748-2007 « Automobile roads of the general using. Standard loads, loading systems and clearance approaches» [Electronic resource]: https://docs.cntd.ru/document/1200057497. Last accessed 22.08.2021.

[2] English title is quoted as in the document. – *Translator's note*.

there are small frost-thaw lakes. Wetland is rare. Absolute elevation of the terrain that has not been subject to anthropogenic effects goes from 85 m to 101 m[3].

The climate is sharply continental with pronounced anticyclonal weather conditions, a sharp change of seasons, high insolation in a summer period, hot summer, very frosty dry cloudless winter. Winter continues for 204–215 days. Minimum winter temperature is 56–58°C below zero. Summer maxima is of 38–39°C above zero. The average annual temperature 9,1°C below zero. As for environmental and climatic conditions, the area refers to the northern construction and climatic zone with the most severe conditions, to climatic subsection IA[4].

Upper-quarternary deposits of Tuymaada valley are represented by two alluvial lower terraces of the Lena River: Sangyyataya and Yakutsk terraces [15]. All sediments of the area under study are in the frozen state. In the hydrological terms, they relate to alluvial sediments of the Khatasian depression of the Lena River cryoartesian basin [16; 17]. Depth of permafrost soils in Tuymaada valley is 350–400 m. According to the disparate data of the design and survey works, the depth of the seasonal thawing layer is within 3,3–4,2 m in areas not subjected to anthropogenic effects. According to field expedition observations the depth of the seasonal thawing layer within the boundaries of urban development is in the range of 6,0–9,0 m.

Within the administrative boundaries of the city of Yakutsk, there are numerous lakes, streams, as well as Shestakovka river. As long-term hydrological observations show, the levels of their water surface in the summer period are not subject to significant decrease, which indicates a high watering of the soils of the city territory. This is confirmed by the few data of laboratory studies of the physio-mechanical properties of soils. It has been established that the moisture content of most studied soils of the roadbed of the city roads of urban roads exceeds the value of humidity at the liquid limit. In addition, in certain sections of the roads laid within the first river terrace, the buried channels or branches of the Lena River are found, in which even in winter the current is preserved. Thus, it can be argued that the road infrastructure of Yakutsk is formed mostly on the soils of the first subzone of the first road-climatic zone, for which there are no regulatory construction documents. Consequently, construction, operation, repair and reconstruction of urban roads and highways is carried out in accordance with the regulatory requirements developed for the second subzone of the first road-climatic zone, which repeatedly reduces stability of their structural elements and causes an accelerated deformation process of the roadbed and destruction of road pavement [5–8].

Besides Yakutsk city district, the village Zhatai is another most significant, within the framework of the topic under discussion, settlement of the Tuymaada valley, it is an independent administrative unit. It is located 17 km north of the capital.

According to the data of 2021, the population of Yakutsk was 330615 people, and population of Zhatai[5] was 10511 people.

The largest industrial facilities of the Tuymaada valley comprise Yakutsk airport, Yakutsk house-building integrated plant, Yakutsk river port, Yakutsk plant of building materials and structures, Yakutsk factory of reinforced concrete products, two thermal power plants, Yakutsk petroleum storage depot (Zhatai village), Zhatai shipbuilding plant, «Kangalassy» territory of rapid socio-economic development.

The bank of the Lena River, opposite to the city of Yakutsk, hosts several settlements, the most significant of which, in the transport and logistics plan, is the village of Nizhny Bestyakh[6], with a population of 4387 people (according to 2021 data). Its significance is explained by the fact that the village is the final destination point of the Berkakit–Tommot–Yakutsk railway connecting the Southern and Central Yakutia. The village and its surroundings host Nizhnebestyakhsky transport and logistics centre intetended for year-round processing of goods coming by rail (Pic. 1).

The Tuymaada valley with adjacent right-bank territories forms the basis of the so-called Yakutsk transport and logistics node: the most important infrastructure transport facility of Central Yakutia. This is due to the following factors:

1. The city of Yakutsk is located on the left bank of the most important water transport artery of Yakutia which is the Lena River.

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[3] Topographic map, scale 1:200000. Open access source.

[4] SP [Construction rules] 131.13330.2018 «SNIP 23-01-99* Construction climatology». [Electronic resource]: https://www.minstroyrf.gov.ru/upload/iblock/d4f/SP-131.pdf. Last accessed 22.08.2021.

[5] Respectively, website «города-россия.рф»: gorodarus.ru'zhataj.html.

[6] [Electronic resource]: bdex.ru'naselenie/respublika-saha…megino…bestyah/. Last accessed 22.08.2021.

Pic. 1. Plan of the district (without Zhatai village) with the design position of the bridge over Lena River. [Electronic resource]: https://icdn.lenta.ru/images/2019/11/29/14/20191129142456692/preview_df519b35497e2cba89f41562385e4511/. Last accessed 22.08.2021.

2. Tuymaada valley is a transit area through which the city of Yakutsk is connected to the Federal Automobile Road (FAD) A-331 «Vilyui» (Tulun, Irkutsk region–Yakutsk, 3000 km long), the Republican Automobile Road «UMNAS» (Yakutsk–Pokrovsk–Olekminsk–Daban–Chapayevo–Turukta–Lensk, 1216 km long), Republican roads «Nam» (Yakutsk–Namtsy–Bulus, 160 km long).

3. Nizhny Bestyakh (on the right bank of the Lena River) is the point of docking of FAD A-360 «Lena» (Never–Yakutsk, 1157 km long), FAD R-504 «Kolyma» (Magadan–Yakutsk, 2021 km long), Republican Automobile Road «Amga» (Nizhny Bestyakh–Amga–Ust-Maya–Eldican–Yugorenok, 702 km long) and the railway Berkakit–Tommot–Yakutsk (nearly 900 km long).

Despite the formal designation of Yakutsk as one of the final points of FAD «Lena» and «Kolyma», the roads do not reach the city. They end on the right bank of the Lena River. Transportation of goods to the right shore is carried out in summer with the help of ferries, and in the winter through ice crossing. At the same time, in the offseason periods (ice motion, ice formation) transportation of significant volumes of goods through the Lena River ceases. The duration of interruption for trucks weighing more than 20 tons can be up to three or more months.

According to the currently operating transport and logistics scheme, the overwhelming part of goods entering the Tuymaada valley for ferry and ice crossing, as well as Yakutsk river port, is transported by road through the city street network. The main destination points are warehouses, the main of which are located on the southern and western outskirts of the city of Yakutsk. A significant part of goods transit through the capital to FAD A-331 «Vilyui» (Pic. 1). The only exception is fuel and lubricants. They are transported to Yakutsk solely in a summer period by river bulk vessels. Unloading of fuel and lubricants, intended for Central Yakutia, is carried out directly from ships at the terminal of Yakutsk petroleum storage depot in Zhatai village. Only fuel and lubricants intended for the districts and uluses of the left bank of the Lena River transit through Yakutsk to FAD A-331 «Vilyui».

Mass cargo transportation in Yakutsk transport and logistics node is carried out exclusively through the territory of the city district and by city roads. At the same time, the transport network of the city of Yakutsk has only a few roads through which, according to the current standards listed in SNiP 02.07.01-89 «Urban planning»[7], heavy trucks can move. These roads include the route passing through the city from the East (hereinafter the Eastern City Corridor, ECC) along the above floodplain river terrace (second floodplain): Novoportovskoye Highway–Chernyshevskogo str.–Khabarova str.–Bogdana Chizhika str.–50 let Sovetskoi Armii str. – Vasilieva str. – Nam RAD. On the western outskirts (hereinafter referred to as the Western City Corridor, WCC) there are several scattered roads, allowing cargo transportation in the submeridional direction: Avtodorozhnaya str.–Krasilnikova str.–Lermontova str.–Keshi Alekseeva str.–Chaikovskogo str.–Vinokurova str.–Vilyuisky tract–Okruzhnoe highway–Nam RAD.

Based on the foregoing, it is possible to discuss only two schemes for moving goods, coming by the railway, within the Tuymaada valley (Pic. 1):

Scheme 1. Approach to the bridge across the Lena River (4,2 km) – Umnas RAD (about 30 km) – border of the Yakutsk City district – WCC – industrial zone and warehouse terminals of the western outskirts of Yakutsk–transit cargoes on FAD A-331 «Vilyui».

Scheme 2. Approach to the bridge across the Lena River (4,2 km) – Umnas RAD (about 30 km) – border of the Yakutsk city district – ECC – Nam RAD – Yakutsk petroleum storage depot (village Zhatai).

Both schemes include the same section of the road with a length of about 35 km: approach to the bridge across the Lena River (4,2 km) – Umnas

[7] [Electronic resource]: https://files.stroyinf.ru/Data2/1/4294854/4294854799.pdf/. Last accessed 22.08.2021.

RAD, which is associated with its non-alternateness within the current road infrastructure of the Tuymaada valley.

METHODOLOGY

Following the problem of the lack of correct regulatory documentation for determining the load on road pavement from the flow of cars and for development of forecasts on the dynamics of its change, the author developed its own load assessment system. Its foundation is the principle of calculating the axial load of any motor vehicle reduced to the axial load of the so-called «standard private car» (the regulatory requirement of the road construction industry). The standard axial load from the given passenger car is determined based on the category of the road or its section (Table 1). The category of the road is indicated in the passport of the road (stored materials) or regulatory documents. Next, an estimate of an existing or promising cargo-passenger flow is made. The total volume of cargo-passenger traffic is estimated. The technical characteristics of vehicles that will be involved in transportation are determined. The real axial load of an existing or promising transport flow, considering the types of cargo transported (bulk, overall, food, fertilizers, etc.) and passengers are calculated. The data obtained are normalised being reduced to the standard axial load of the standard passenger car.

In an extended model/cargo model scheme, it is assumed that the structure of goods for each of the city corridors has its own specifics. Only fuel, lubricants and petroleum products are transported along ECC in transit to Yakutsk petroleum storage depot (village Zhatai). All other goods are transported along WCC. These include cargoes, following in transit to FAD A-331 «Vilyui», as well as intended for stockage in the warehouse areas of Khatyng-Yuryakhsky and Okruzhnoe Highways. According to the classification of city streets and roads (SNIP 02.07.01-89 «Urban planning») all the roads of ECC and WCC refer to the category II («Main Streets»). In accordance with the technical classification (Table 1), which is established depending on traffic intensity, all parts of the roads of both corridors belong to the category IV. The real estimated traffic intensity on the roads of the IV category reduced to the car, according to which the design of the road is made, is 200–2000 normalised passenger cars per day in both directions.

At the same time, in accordance with the peculiarities of the regulatory framework, the roads of the category IV and city main roads are built, mainly, for the axial load of up to six tons.

Table 1

Identification of the road category per traffic intensity*

Road category	Estimated traffic intensity, car/day	
	in transport units	reduced to a passenger car
1-a	Above 7000	Above 14000
1-b	Above 7000	Above 14000
II	3000–7000	6000–14000
III	1000–3000	2000–6000
IV	100–1000	200–2000
V	Below 100	Below 200

*According to SP 34.13330.2012 «Automobile roads». [Electronic resource]: docs.cntd.ru'document/1200095524/. Last accessed 22.08.2021.

The main problem that needs to be solved in the simulation process is to determine the probable capacity of urban traffic infrastructure to ensure the unhindered passage of cargo that will come to the left bank of the Lena River after construction of the bridge, considering also possible developments within next 20 years. To build and calculate the extended model, it is necessary to determine its basic parameters, including:

1. Cargo transportation channels through urban infrastructure and their technical capabilities (intensity and load) to ensure cargo transportation.
2. Assessment of the growth of the volume of cargo turnover after construction of the bridge across the Lena River for certain types of goods.
3. The choice of technical systems involved in transportation of goods and calculation of the standard growth in traffic intensity, as well as the physical exertion to the city roads.

The results obtained regarding the growth of traffic intensity and load on city roads when compared with the actual technical capacity of the city road infrastructure will allow to evaluate promising areas of modernisation or reconstruction of the road infrastructure of the Tuymaada valley.

As shown above, due to the features of historical urban development, transportation of goods is possible only through the urban territory and exclusively on two routes: Eastern and Western city corridors (respectively, ECC and WCC). Cargo transportation can be carried out according to two schemes. Both schemes have a common section: an approach to a bridge across the Lena River (4,2 km) – Umnas RAD (about 30 km) – the border of the Yakutsk City district. Through the Eastern corridor, it is supposed to transport exclusively fuels, and through the

Western – all other goods. All roads included in the scheme belong to the category IV with the standard maximum permissible axial load of six tons.

We shall carry out the close-to-realty calculation of the load on the road pavement from the standard passenger car, which is laid in the basis of the extended model. Parameters for calculation:

• Weight of a standard car – 1500 kg (14715 N when $g = 9{,}81$ m/s²).

• Number of axes – 2.

• Number of wheels – 4.

• Width of one tire – 0,145 m.

• Length of the area of the contact of a tire with road pavement along the axis of the movement of a car – 0,1 m.

The assumed width of the tire of 145 mm corresponds to the minimum width of the tires produced by the domestic industry for economy-class cars, which allows determining the maximum possible load from the wheel of the given vehicle on the road structure.

The area (S) of the tire contact with the road is 0,0145 m². A wheel accounts for 375 kg of the distributed weight of the car, which is 3678,75 N (P_{car}). We determine the load (P), created by one wheel of the standard passenger car on road pavement as:

$P = P_{car.}/S = 3678{,}75$ N$/0{,}0145$ m² $= 253706{,}89655$ Pa $\approx 253{,}707$ kPa.

For comparison, let us determine the pressure of a «model chassis's» wheel (P_n) given in GOST 52748–2007[8] on the contact area of 0,0145 m²:

$P = P_{n.}/S = 500$ N$/0{,}0145$ m² $= 34482{,}75862$ Pa $\approx 34{,}482$ kPa.

Thus, the pressure on the road of a wheel of GOST «model chassis» is more than seven times less than the pressure of the wheel of the standard car. Accordingly, the application of the recommendations of this regulatory document in practical calculations will lead to unpredictable results in terms of sustainability and safety of highways.

It should be emphasised that the expression of the axial load in Newtons, adopted in the regulatory documentation, has a very small significance for practical calculations of the load on road pavement. The axial load expressed in Newtons is recorded only by special equipment during a sufficiently cumbersome procedure and only to standardise measurement data (for example, under the influence of static or dynamic stamps) when checking the quality of road pavement. The values of the axial pressure, expressed in Newtons, do not change in variations of gravity acceleration at different points of the earth's surface. In this aspect, the measured axial pressure reflects the effect of the axis of the car on the rod of the measuring instrument and is in no way associated with the impact of the car on the roadway. The impact of the weight of the car on road pavement is transmitted by wheels through the contact area and should be expressed in Pascals (N/m²). In real conditions, when receiving data of operational control over the road traffic, determining the parameters of the contact area of each wheel of all cars is impossible. The factors affecting the size of the contact area are the vehicle type, type and quality of tires, their width and working pressure, cargo, air temperature, etc. Accordingly, kilograms are used in the practice of road control of the load from cars on the structural elements of highways everywhere. This value reflects the weight of the car and is easily fixed at the posts of weight control even for moving cars. Accordingly, when calculating loads within the extended model, a kilogram is used as a unit of measurement.

For the roads of II–V categories the upper limit of the permissible traffic intensity is indicated. It is assumed that the construction of a certain category of the road is designed for traffic of precisely this maximum of cars per day. Data on traffic intensity in transport units (vehicles) does not allow to identify the weight of each unit. Let's recall essential parameters of standard passenger car:

• Weight – 1500 kg.

• And number of axes – 2.

Let's calculate:

1. General standard normalised daily load on road pavement (P1), which is a product of the maximum daily standard intensity of the normalised passenger cars and a mass of one given car.

For roads of the category IV:

P1(IV) = 2000 car/day × 1500 kg = 3 000 000 kg/day = 3 000 t/day.

2. Single standard axial load from the normalised car (P2), obtained by dividing the mass of one car by the number of axes.

For roads of any category:

P2 = 1500 kg/2 = 750 kg.

[8] GOST 52748-2007 «National standard of the Russian Federation. Automobile roads of public use. Regulatory loads, calculation schemes of loading and dimensions of approximation». [Electronic resource]: https://docs.cntd.ru/document/1200057497/. Last accessed 22.08.2021.

3. The number of standard axial exposure (N1), which is determined by multiplying the number of standard normalised cars by the number of axes.

For roads of the category IV:
N1 = 2000 car/day × 2 = 4000.

This indicator is dimensionless. It can be used when determining additional loads on road pavement arising from the action of a force pulse on irregularities or potholes, as well as from centrifugal forces and shear efforts in the materials of road pavement in turns.

Indicated parameters are regulatory ones, i.e., calculated according to the regulatory requirements for traffic intensity. At the same time, similar calculations can be made for model or real vehicles. Calculating the average axial load (P3) of the vehicle according to the P2 technique, it is necessary to determine the coefficient of reduction (M1) of the average axial load of the vehicle to a single standard axial load from the normalised car according to the formula:

M1 = P3/P2. (1)

The reduction coefficient shows, what number of single standard axial loads from the normalised standard vehicle corresponds to the average axial load of the considered vehicle, and makes it possible to conduct a comparative analysis of relative changes in the load relative to the standard one. For any wheeled vehicle, as well as for the normalised one, a total daily load on road pavement (P4) and the amount of axial effects (N2) are calculated. N2 can be reduced to a standard passenger car according to the formula N1 = N2 × M1. The proposed units of measurement allow within the framework of the current regulatory documentation to quantitatively estimate the load intensity and its temporary fluctuations for any entire road, its individual sections or arbitrary transverse profiles. At the same time, it is possible to assess the impact of any types of vehicles, including motorcycles, bicycles, etc.

Based on the standard traffic intensity for roads of the category IV (200–2000 car/day) and the weight of the standard car (1500 kg), we determine the maximum allowable overall normalise daily load on the road pavement.

$P1_{max}$ = 2000 car/day × 2×750 kg = 3 000 000 kg/day = 3 000 t/day.

The standard normalised axial load (both general and single) shows which axial pressure is implied by a standard vehicle or a flow of cars on road pavement, both in static condition and along the entire distance of its movement. The impact on road pavement is carried out by wheels through the contact area. At the same time, the bulk share of the load falls on a running track within the road lane.

RESULTS

After commissioning of the bridge across the Lena River transport flow of Yakutsk will be composed of three components: currently existing, redirected from winter ice roads and summer ferries, as well as of vehicles carrying cargo coming by rail (main flow).

It is believed that the existing traffic intensity does not exceed the standard one and amounts to 2000 normalised cars per day. Standard axial load on road pavement, including transport flows through ice and ferry crossing is of 3000 tons per day. The number of daily standard axial exposures (N1) – 4000.

Assessment of intensity of the redistributed flow, with the prospect till the year 2044, was produced by the Research and design institution of territorial development and transport infrastructure[9]. This assessment is presented in Table 2, which is expanded by the author's calculated data on the standard normalised intensity and the standard normalised axial load.

The entire redistributed flow in the calculated model runs along the route of scheme No. 1.

Calculation of the forecast of movement conducted by Research and Design Institute for Territorial Development and Transport Infrastructure[9], in accordance with the tasks assigned to it, was focused exclusively on determining the flow intensity. It does not contain any forecasts or data on changes in the load on road pavement. Accordingly, the amount of cargo/passengers in transport units is not taken into account.

In this regard, the author presents the basic parameters for calculating the normalised axial load for various types of vehicles presented in Table 2:

• Cars. The characteristics correspond to the parameters of the standard normalised car – the mass of 1500 kg, two axes.

• The calculation of the axial load of the buses was carried out for the most common brand that

[9] Transport model of the project of construction of the bridge across the Lena River near the city of Yakutsk. Stage 1. LLC Research and Design Institute for Territorial Development and Transport Infrastructure. St.Petersburg, 2018, 93 p.

Table 2

Intensity of the redistributed transport flow and its standard daily normalised axial load with the outlook for 2044 [Table is compiled by the author using the data* in column 2]

Transport type	Traffic intensity car/day, units/ normalised	Curb weight, kg	Weight with cargo or passengers, kg	Number of axes, pcs	P4 / N2, t/quantity	M1 / N1
1	2	3	4	5	6	7
Passenger cars	4550*/4550	1500	1500	2	6750/9100	1/9100
Buses	185*/629	17930	23130	2	4279/370	15,42/5705
Cargo transportation trucks with bearing capacity:						
up to 5 tons	445*/890	2500	7500	2	3338/890	5/4450
from 5 t to 12 t	450*/1080	6000	18000	3	8100/1350	8/10800
from 12 t to 20 t	275*/715	7000	24000	4	6600/1100	8/8800
above 20 t	495*/1485	7000	30000	5	14850/2475	8/19880
Total	6400*/9349	–	–	–	43917/15285	-/58735

* Data of LLC Research and Design Institute for Territorial Development and Transport Infrastructure[9].

operates on suburban routes. Brand – LiAZ 525657. Curb weight – 17930 kg. The number of axes – 2. The maximum number of passengers – 104. The calculations assume that the population of the bus is 50 % with the standard weight of one conventional passenger assumed to be 100 kg.

• Trucks have a load capacity of up to 5 tons. Curb weight – 2500 kg. Total weight of 7500 kg. The number of axes – 2.

• For vehicles with a load capacity of more than five tons, characteristics were determined based on the maximum allowable axial pressure for the roads of the accepted category (6000 kg) and the number of axes. The mass of the equipped car was determined according to standard maximum load capacity for cars with a load capacity from 12 to 20 tons and above 20 tons, considering curb weight of a possible chassis. For a redistributed flow, only the full mass of the vehicle has a fundamental importance.

• Trucks with a load capacity from 5 to 12 tons. Axes – 3. Maximum permissible total weight of 18000 kg. Curb weight 6000 kg.

• Trucks with a load capacity from 12 to 20 tons. Axes – 4. Maximum permissible total weight of 24000 kg. Curb weight 7000 kg.

• Trucks with a load capacity of more than 20 tons. Axes – 5. Maximum permissible total weight of 30000 kg. Curb weight 7000 kg.

In the main flow of cargo turnover between the point of departure and the city of Yakutsk, two fundamentally different traffic vectors will be formed. From cargo terminals of the station of Nizhny Bestyakh to destination cars move with full load, and from Tuymaada valley to terminals – mainly with curb weigh (empty cars). Accordingly, for calculating traffic intensity and the normalised axial load when driving to the station Nizhny Bestyakh, specific data on weight of vehicles in the equipped state is necessary.

To calculate the parameters of the main flow, the chassis of type KAMAZ 65201-63 is selected. The number of axes – 4. Curb weight of 11250 kg.

Transportation of oil products is carried out by a tank truck type «Sespel» with a total weight of 35400 kg. Curb weight 10400 kg. Useful cargo – 25000 kg. The number of axes – 3.

Calculation characteristics of a vehicle with tank truck for transportation of oil products: the number of axes – 7. Full weight – 47650 kg. Curb weight – 21650 kg. Useful cargo – 26000 kg.

All other goods are transported by the corresponding rigid trucks with a three-axes chassis. The full mass of the body device is 30750 kg, the estimated curb weight of 8000 kg. Useful cargo – 22750 kg.

The estimated characteristics of the vehicle for transportation of «dry» cargo: the number of axes – 7. Full weight – 42000 kg. Curb weight – 19250 kg. Useful cargo – 22750 kg.

Let us estimate the volume and structure of the main transport flow. In accordance with the data of the press service of the Joint Stock company «Railways of Yakutia»[10], the first stage of Tommot–Nizhny Bestyakh transport and logistics hub was built based on estimated capacity of six million tons per year. We assume that two million tons are sent in the eastern and south-eastern directions through the roads R-504

[10] Official website of Joint-stock company «Railways of Yakutia». [Electronic resource]: https://rw-y.ru/. Last accessed 22.08.2021.

«Kolyma» and «Amga». Four million tons will go to the left bank through the bridge.

In accordance with the official documents of the Government of the Republic of Sakha (Yakutia), in particular with the decree of the Government of the Republic of Sakha (Yakutia) of March 29, 2019 No. 322-r «On organisation of delivery of goods to the Republic of Sakha (Yakutia) during navigation period 2019 (as updated on October 3, 2019)» (as amended by the order of the Government of the Republic of Sakha (Yakutia) dated 03.10.2019 No. 1264-r)[11], the volume of «Northern Supply Delivery» of oil products to the Republic of Sakha (Yakutia) during navigation period 2019 was about 500 thousand tons. The need of Central Yakutia in fuel and lubricants is also about 500 thousand tons. Thus, in the flow of goods transported to the left bank, petroleum products, fuel and lubricants will make one million tons, and three million tons will consist of other goods.

Based on the structure and volume of goods, let us calculate the need for vehicles (N, in pieces) for their transportation based on the formula:

N = cargo volume/carrying capacity of a transport unit. (2)

Petroleum products and fuel and lubricants (N4):

N4 = 1 000 000 000 кг/25000 kg = 40 000 cars.

Average annual average daily intensity (I_{avdoil}) of tank trunks:

I4 = 40 000 cars × 2/365 days = 109,59 × 2 cars/day ~110 × 2 cars/day = 220 cars/day.

Other goods (N5):

N5 = 3 000 000 000 kg/22750 kg = 131 868,13 cars ~131 869 cars.

Average annual average daily intensity ($I_{avdtruck}$) of trucks:

I5 = 131 869 cars × 2/365 day = 361,28 × 2 cars/day ~ 362 × 2 cars/day = 724 cars/day.

When calculating the intensity, multiplication by two takes into account transport flow in both directions.

The intensity of the main transport flow and its standard daily normalised axial load are presented in Table 3.

Before starting the analysis of the growth in traffic intensity and load on the roadway, it is necessary to highlight in the calculated cargo transportation schemes the sections with homogeneous density of traffic.

[11] Official website of the Government of the Republic Sakha (Yakutia). [Electronic resource]: http://docs.cntd.ru/document/561407665. Last accessed 22.08.2021.

Both schemes have one common section: Umnas RAD – border of the Yakutsk city district nearly 30 km long (hereinafter «Umnas section»). All goods arriving to the left bank from the bridge will be transported along it.

On the border of the city (at the traffic circle Umnas RAD, Avtodorozhnaya str., Krasilnikova str.) a single transport flow is divided into two, running respectively through the Western (WCC) and Eastern (ECC) city corridors.

In accordance with the extended model under consideration, only oil products, fuel and lubricants are transported along the Eastern corridor to Yakutsk petroleum storage depot in Zhatai village (scheme 2). All other goods and passengers follow the Western corridor (scheme 1). The estimated characteristics of promising transport flows on separate sections are presented in Table 4.

As can be seen from the data given in Table 4, the most problematic situation will be on Umnas section. The estimated traffic intensity on the section, considering the existing transport flow, will reach 16354 normalised cars per day, which corresponds to traffic intensity of roads of category I, more precisely I-b (general-purpose main roads). At the same time, total daily load and the number of standard axial daily impacts on road pavement will increase by about 32 times. It should be recalled that design of the road pavement and the main body of the earth embankment of Umnas section was calculated based on the standards for roads of category IV, considering outlook for the next 20 years. However, in the future, only the transport flow of the left bank was considered together with, most likely, an increase in the cargo flow associated with completion of construction of the Umnas republican year-round road (Yakutsk–Lensk, 1216 km).

Based on the calculations within the extended model of cargo-passenger transportation and considering the current state of the road on Umnas section, it can be argued that after the bridge across the Lena River will be commissioned this section will not be able to ensure transit of the transport flow from the right bank. The increase in traffic intensity by 7,17 times will lead to blocking of traffic in both directions due to the occurrence of traffic jams, first, at the traffic circle Umnas–Novopokrovskoe highway–Avtodorozhnaya. At the same time, the total daily load on road pavement will reach 98885 tons compared to the normative value of 3000 tons. Wear rate of asphalt concrete coating and intensity of the rut formation

Table 3

Intensity of the promising main transport flow and its standard daily normalised axial load on the Umnas section [compiled by the author]

Transport type	Traffic intensity cars/day, units/normalised	Load	Weight of one transport unit, kg	Number of axes	P4/N2, t/quantity	M1/N1
1	2	3	4	5	6	7
KamAZ 65201-63 with tank truck type «Sespel»	110/330	Full	47650	7	5241,5/770	9,1/6989
	110/330	Empty	21650	7	2381,5/770	4,1/3175
KamAZ 65201-63 with body device	724/2172	Full	42000	7	30408/5068	8/40544
	724/2172	Empty	19250	7	13937/5068	3,7/18752
Total	1668/5004	–	–	–	51968/11676	-/69460

Table 4

Characteristics of the promising transport flow in separate areas of Tuymaada valley roads [compiled by the author]

Section	Traffic intensity in normalised cars ($I_{normalised}$), car/day	Growth over the maximum permissible standard (existing),%	Total daily load on road pavement (P), t	Growth over the maximum permissible standard (existing),%	Number of standard axial daily impacts (N1), pcs	Growth over the maximum permissible standard (existing),%
1	2	3	4	5	6	7
Umnas	14354	717,8	95885	3196,17	128195	3205
WCC	13694	684,7	88262	2942,07	118031	2951
ECC	660	33	7623	254,1	10164	255
Nam–Yakutsk petroleum storage depot	660	33	7623	254,1	10164	255

during the summer period will increase approximately by 32 times. In the autumn-spring periods during saturation of the body of the earth embankment with water (up to 100 %), under such a load, the processes of its deformation and subsidence are inevitable. In winter, which lasts more than seven months, when the asphalt concrete roads acquire increased fragility [5], the growth of standard axial daily effects by 3205 % (Table 4, column 7) will cause intensive destruction of the asphalt concrete coating. It will be destroyed during single winter season or will require an annual overhaul on the entire length of the section, while the normative period is once every 12 years.

A similar situation will also be formed in the Western City Corridor. Considering the existing urban traffic flow, traffic intensity will be of 16694 normalised cars per day, which also corresponds to the category I-b. When changing the basic parameters of the model in a part of uniform distribution of passenger cars of a redistributed flow between WCC, ECC and the route Avtodorozhnaya str. – Oiunskogo str. (Table 2), as well as of the directions of travel of buses on Avtodorozhnaya str. – Oiunskogo str. – Bus station section, intensity in the section Krasilnikova str. – FAD A-331 «Vilyui» will be of 13031 normalised cars per day. The resulting intensity corresponds to the category II of roads.

The Eastern city corridor as for traffic intensity and loads on the roadway seems, at first glance, to have a fairly favourable situation. If design and construction of roads of the corridor considers estimated promising flows, then there are no technical problems with the passage of cargo transport. However, in accordance with the model, this cargo flow is represented exclusively by tank trucks carrying petroleum products, fuel, and lubricants. WCC and ECC pass exclusively through the territory of urban residential buildings. The estimated annual volume of transported petroleum products and fuel and lubricants is one million tons. This type of cargo refers to particularly dangerous, and mass transportation of such goods through residential sectors of cities is prohibited. Thus, delivery of extremely dangerous goods from the railway station to Zhatai village through the city road infrastructure is not possible at all.

There is a formal solution regarding transiting through the city infrastructure of about three million tons of different goods (without oil products). Considering current problems of the city road infrastructure [1], one of the most familiar paths seems to reconstruct a set of roads that are included in the scheme 1, and bring them in terms of transit capacity and permissible axial load to the state of the category of roads of category I-b. However, the peculiarities of the historically inherited scheme of residential building and the road scheme of the city of Yakutsk, the quality of soils of grounds and standard requirements for urban roads and highways exclude the possibility of implementing this project even in the distant future.

At the same time, an important problem that creates an almost insurmountable barrier to solve the obvious transport and logistics tasks is that the discussed cargo transportation schemes include roads, whose construction, repair, and maintenance are carried out at the expense of the budgets of three different levels. Approach to the bridge in the left bank of the Lena River of about 4,2 km, refers to the federal level. The Umnas section to the border of the Yakutsk city district (about 30 km) and a section of the Nam road from the city border to the border of municipal district «village Zhatai» (about 17 km) refer to the republican budget. Financing of road works within the city of Yakutsk and municipal district «village Zhatai» is carried out from municipal budgets. Considering the standard volumes of funds for road construction in various budgets and the requirements for execution of budget legislation, it does not seem possible to find the solution of the above problems of the transport infrastructure of the Tuymaada valley.

CONCLUSION

Approbation of a new procedure to calculate the load on the roadway has revealed its practical applicability when evaluating existing and promising transport flows with regard to the traffic intensity and the load on road pavement. The developed technique allows calculating the real load on the structure of the motor road for a transport flow consisting of any type of vehicles. The obtained data is reduced to the load of the standard normalised passenger car. The parameters of the normalised car can be selected in relation to the situation on a specific road or their network. First, it concerns its total weight and number of virtual passengers. At the same time, when developing a methodology, the determination of a real load from vehicles was not the main task. The main objective was to obtain an algorithm for calculating, which makes it possible to associate the data of transport and logistics origin-destination matrices, which, at its base, have exclusively economic evaluation criteria (economic feasibility), with construction features of roads, which are not considered in origin-destination matrices. For example, if in the built origin-destination matrix an economically reasonable transport artery is identified, which will transport some amount of cargo with specific types of vehicles, the proposed method allows determining the conformity of the design of the road or roads in the transport corridor to cargo flow and type of vehicles predicted in the origin-destination matrix. Based on the obtained calculations, it is possible to offer substantiated recommendations regarding amendments to the logistics routes or overhaul/reconstruction of the selected transport routes, construction technologies. The technique also allows making recommendations on the necessary changes and optimisation of the structure of the current and promising fleet of vehicles (regarding load capacity, the number of axes, routes, etc.), organisation of transport flows, depending on the structural features of roads, organisation and location of transport and logistics centres or warehouses (warehousing, weight control, loading and unloading, service station, filling stations, parking, campgrounds, etc.). An important property of the technique is the possibility of producing an independent automated calculation and digital modelling of the destinations and volumes of cargo-passenger transportation within the urban street road network, considering its design features.

Based on the approbation of the developed technique when calculating the prospective load on the street-road network of the Yakutsk city district, which will arise after construction of the bridge across the Lena River, it is possible to draw the following conclusions.

1. The road infrastructure of the Tuymaada valley is not able to ensure the passage of prospective cargo flows that will go to the left bank of the Lena River through the bridge.

2. Reconstruction of basic roads and bringing their condition, transit capacity and permissible loads to the level of category I-b roads, primarily within the boundaries of the Yakutsk city district and municipal district «village Zhatai», are impossible because of a number of objective reasons.

3. The only possible solution to the overwhelming part of the problems arising is construction of a federal circle highway passing mainly outside the Tuymaada valley. As the most promising route, the highway is proposed to be

built at the so-called «main shore»: bridge area at the left bank–FAD «Vilyui»–Magansky highway–Nam RAD–Yakutsk petroleum storage depot (Zhatai village).

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Editorial note. The published article offers opportunity for scientific discussion, particularly considering author's opinion on the need to develop and / or clarify a number of parameters of regulatory documents in terms of road construction, his proposals on calculation of the load on the roadway. Publications on this topic can be continued upon receipt of opinions that support those expressed by the author or, on the contrary, are alternative to them.