Natural hazard impacts on transport infrastructure in Russia

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Abstract. The transport infrastructure of Russia is exposed to multiple impacts of various natural hazards and adverse weather phenomena such as heavy rains and snowfalls, river floods, earthquakes, volcanic eruptions, landslides, debris flows, snow avalanches; rock falls, ice phenomena, and others. The paper considers impacts of hazardous natural processes and phenomena on transport within the area of Russia. Using the information of the author's database, contributions of natural factors to road, railway, air, and water transport accidents and failures are assessed. The total risk of transport accidents and traffic disruptions triggered by adverse and hazardous natural impacts, as well as the risk of road and railway accidents and disruptions as the most popular modes of transport is assessed at the level of Russian federal regions. The concept of emergency situation is used to measuring risk. 838 emergency situations of various scale and severity caused by natural hazard impacts on the transport infrastructure over 1992 to 2018 are considered. The average annual number of emergencies is taken as an indicator of risk. Regional differences in the risk of transport accidents and disruptions due to natural events are analyzed. Regions most at risk are identified.

Keywords: Transport infrastructure, natural hazards, transport accident, traffic disruption, database

1. Introduction

According to the Federal Law "On Transport Security" (2019), transport infrastructure of the Russian Federation (RF) is considered as a large and complex technological system including tunnels, overpasses, and bridges; terminals and stations; river and sea ports; airports; roads, railways, and waterways, as well as other buildings, structures, and equipment ensuring the functioning of the transport system. Russia has a very extensive transportation network that is among the largest in the world. It includes 1.5 million km of public roads, more than 600,000 km of airways, 123,000 km of railway tracks, and 100,000 km of inland navigable waterways (Rosstat, 2018).

In studies on the impacts of natural hazards, transport infrastructure is most often classified by mode of transport including road, rail, water and air transport (e.g. Govorushko 2012; Mattsson and Jenelius, 2015; Voumard et al., 2018). Some researchers classify it by infrastructure asset types. For example, Kaundinya et al. (2016) select such transport assets as bridges, tunnels, embankments, cuts and centralized systems. This analysis is structured by mode of transport.

Due to the large length of the transportation network, as well as climatic, geological, geomorphologic, and other natural features of the country, transport infrastructure facilities of Russia are exposed to the undesirable impacts of adverse natural processes and phenomena, as well as natural hazards of various genesis, such as geophysical, hydro-meteorological, and others. Distribution of various natural hazards through the country area is discussed below in section 2.1. Their impacts may endanger transport safety and reliability, trigger accidents and failures, disrupt the normal operation of transport system, cause delays in delivery of passengers and goods, and lead to other negative consequences.

Natural processes and phenomena can be classified in various ways depending on the objectives of a study. Natural hazards can be typify according to their genetic features (e.g. Voumard et al., 2018), the intensity of their manifestation, the main formation and development factors, characteristics of spatial distribution and mode, etc. (Malkhazova and Chalov, 2004). Liu et al. (2016) propose a systematic natural hazard interaction classification based on the hazard-forming environment. Gill and Malamud (2016) propose a detailed classification of natural-hazard types in Guatemala, including six natural-hazard groups (geophysical, hydrological, shallow Earth processes, atmospheric, biophysical, and space), 19 hazard types, and 37 hazard sub-types.

Previously, two types of natural hazards were found by the author, based on their genesis, distribution in space and time, and the impact pattern on the technosphere and society in populated areas (Petrova, 2005). In the context of the present study, the proposed classification scheme was adapted taking into account impacts of natural hazards on the transport infrastructure (Figure 1).

Solar and geomagnetic disturbances (space weather), geodynamics, geophysical and astrophysical field variations, and other global processes belong to the first group. They have global scale in space and cyclic development in time. Natural processes of this type may influence the transport infrastructure both

directly, causing electronics error and automatic machinery failure, as well as indirectly, by affecting the nervous system of operators, drivers or pilots and thereby leading to a decrease in their reliability. Natural hazards of the second type are of more "earthly" origin, i.e. from the atmosphere, lithosphere, hydrosphere or biosphere. They vary greatly in their spatial scale and geographical location. This type of natural hazards includes earthquakes, volcanic eruptions, landslides, snow avalanches, hurricanes, windstorms, heavy rains, hail, lightning, snow and ice storms, temperature extremes, wild fires, floods, droughts, etc. Natural hazards belonging to this group cause a direct destructive effect leading to accidents and disruptions.

A transport accident is any accident that occurs when people and goods are transported. With over 1.2 million people killed each year, road accidents are among the world's leading causes of death; another 20–50 million people are injured each year on the world's roads (WHO, 2017). Transport accidents of other types including air, rail, and water transport are not as numerous as road crashes, but the severity of their consequences is much higher because of the higher number of people killed and injured per accident. Shipwrecks with a large number of passengers have the highest number of casualties.

Traffic interruptions and disruptions cause multiple social problems because our societies are highly dependent on the transport system for people's daily mobility and for goods transport (Mattsson and Jenelius, 2015). In the case of emergency situation, transport network serves as a life-line system. Thus, ensuring the robustness and reliability of the transport system is one of the most important and pressing problems of the socio-economic development of any country. In May 2018, the Ministry of Transport of the RF has developed a new version of the Transport Strategy up to 2030 (Ministry of Transport of the Russian Federation, 2018). Among the key priorities, the Transport Strategy includes requirements to cope with the modern challenges, such as climate change and a need for increasing the safety of the transport system.

Since the early 1950's (Tanner 1952), it has been recognized that weather conditions affect many road (un-)safety aspects such as driver's attention and behavior, vehicle's operation, road surface condition, etc. A large number of studies devoted to the influence of weather factors on the accident rates were published over the last decades. All the authors agree that the adverse weather is a major factor affecting road situation (e.g. Edwards 1996; Rakha et al 2007; Andrey 2010; Andersson and Chapman 2011; Bergel-Hayat et al 2013; Chakrabarty and Gupta 2013). Many authors connect the maximum number of road accidents with precipitations (Jaroszweski and McNamara 2014; Spasova and Dimitrov 2015). Aron et al (2007) revealed that 14% of all injury accidents in Normandy (France) took place during rainy weather and 1% during fog, frost or snow / hail. Satterthwaite (1976) found the rainy weather to be a major factor affecting accident numbers on the State Highways of California: on very wet days the number of accidents was often double comparing to dry days. Brodsky & Hakkert (1988) with data from Israel and the USA did indicate that the added risk of an injury accident in rainy conditions can be two to three times greater than in dry weather; when a rain follows a dry spell, the hazard could be even greater. Among other weather factors, bright sunlight was identified as a cause of accidents (Shiryaeva 2016). Redelmeier and Raza (2017) investigated visual illusions created by bright sunlight that lead to driver error, including fallible distance judgment from aerial perspective. According to their results, the risk of a life-threatening crash was 16% higher during bright sunlight than normal weather.

Some authors consider other natural hazards, such as landslides (Bíl et al., 2014; Schlögl et al., 2019), flash floods (Shabou et al., 2017) or rock falls (Bunce et al., 1997; Budetta and Nappi, 2013).

As for railway transport, most papers also focus on specific hazards, considering impacts of adverse weather and hydro-meteorological extremes (Ludvigsen and Klæboe, 2014; Nogal et al., 2016), landsliding (Jaiswal et al., 2011), flooding (Hong et al., 2015; Kellermann et al., 2016), snowfall (Ludvigsen and Klæboe, 2014) or tree falls (Nyberg and Johansson, 2013; Bil et al., 2017) as triggers of accidents.

Some studies combine all types of natural hazards affecting road and rail infrastructure (Govorushko 2012; Petrova, 2015; Kaundinya et al., 2016). Voumard et al. (2018) examine small events like earth flow, debris flow, rock fall, flood, snow avalanche, and others, which represent three-quarters of the total direct costs of all natural hazard impacts on Swiss roads and railways.

Investigations of natural hazard impacts on other transport systems than roads and railways are not so numerous. As example, studies about danger of volcanic eruptions to the aviation should be mentioned (Neal et al, 2009; Brenot et al., 2014; Girina et al., 2019). Large explosive eruptions of volcanoes can eject several cubic kilometers of volcanic ash and aerosol into the atmosphere and stratosphere during a few hours or days posing a threat to modern airliners (Gordeev and Girina, 2014).

Only few researches investigate impacts of global processes, such as geomagnetic storms (space weather) and seismic activity. In the early 1990's, Epov (1994) found a correlation (R=0.74) between solar activity and temporal distribution of air crashes. Desiatov et al. (1972) argue that the number of road accidents multiplies by four on the second day after a solar flare in comparison to "inactive" solar days. According to Miagkov (1995), solar activity affects operators, drivers, pilots, etc., causing a "human error" and "human factor" of accidents. Kanonidi et al. (2002) study a relationship between disturbances of the geomagnetic field and the failure of automatic railway machinery. Kishcha et al. (1999), Anan'in and Merzlyi (2002) examine a correlation between seismic activity and air crashes.

The main purpose of this study is to investigate impacts of natural hazards on the transport infrastructure and transport facilities in Russian regions. Using the information collected by the author in the database of technological and natural-technological accidents, contributions of natural factors to road, railway, air, and water transport accident occurrences and traffic disruptions are assessed. All types of natural hazards are considered excluding impacts of global processes (left side in Figure 1) that are not listed in the database. The risk of road and railway accidents and traffic disruptions, as well as the total risk of transport accidents and disruptions caused by adverse and hazardous natural events is estimated for the area of Russia.

2. Materials and methods

2.1. Study region

The Russian Federation is the study region.

Federal regions of the RF were taken as basic territorial units for which all the calculations were performed during the analysis. Federal regions are the main administrative units of the Russian Federation; at this territorial level, all official statistics are published by the Federal State Statistics Service (FSSB) and other federal institutions of Russia.

The main administrative units of the RF comprise of 85 federal regions (Figure 2), including 22 Republics, nine Territories (Kraies), 46 Regions (Oblast's), one Autonomous Region / Autonomous Oblast' (Evreiskaia (Jewish) AO), and four Autonomous Districts (AD) / Autonomous Okrugs. Moscow, Saint Petersburg, and Sevastopol have a special status of Federal Cities. All the federal regions, which are mentioned in the paper, are indicated in Figure 2.

The size and geographical location of the Russian Federation in various climate and geological conditions determine a great variety of dangerous natural processes and phenomena in its area, including endogenous, exogenous and hydro-meteorological hazards. The most characteristic features of the geography of natural hazards in Russia are as follow:

- Natural hazards associated with cold and snow winters are common throughout the country;
- The population and the economy are relatively low exposed to the most destructive types of natural hazards (earthquakes, tsunamis, hurricanes, etc.), and therefore the frequency of occurrence of natural emergencies with severe consequences is low;
- The historically formed strip of the main settlements from the European part of Russia through the south of Siberia to the Far East approximately coincides with the zone of the smallest manifestation of natural hazards (Miagkov, 1995).

In Russia, there are several hundred volcanoes, 78 of which are active. Kamchatka and the Kuril Islands are most at risk of volcanic eruptions; explosive eruptions of two to eight volcanoes are observed annually (Girina et al., 2019). About 20% of the country area with a population of 20 million people is exposed to earthquakes. The most seismically active regions are Kamchatka, Sakhalin, as well as the south of Siberia and the North Caucasus.

Almost the entire territory of Russia is exposed to dangerous exogenous processes; their intensity increases from north to south and from west to east (EMERCOM, 2010). Among exogenous processes, landslides, which are active in 40% of the country area, debris flows (in 20%), snow avalanches (in more than 18% of the area), and other slope processes have the greatest intensity and negative impact on the transport infrastructure. The highest avalanche and debris flow activity is observed in the North Caucasus (Dagestan, North Ossetia-Alania, and Kabardino-Balkaria Republics) and in Sakhalin. The greatest intensity of landslides is in the North Caucasus (Stavropol and Krasnodar Territories, Rostov Region, Dagestan, Karachaevo-Cherkesia, Ingushetia, North Ossetia-Alania, Kabardino-Balkaria, and Chechen Republics), Ural (Chelyabinsk and Sverdlovsk Regions), as well as Irkutsk, Sakhalin, and Amur Regions, Primorsky and Khabarovsk Territories.

Hydro-meteorological hazardous processes and phenomena such as strong winds, squalls, catastrophic showers, floods, snowstorms, thunderstorms, hailstorms, etc. are widespread in the country. The combination of heavy precipitation and strong wind is one of the most dangerous climate situations in the coastal regions of the Far East (Kamchatka, Khabarovsk, and Primorsky Territories, and Sakhalin Region). The highest frequency of strong winds is observed in the south and in the middle part of the European Russia, as well as in the Far East. The most intense rains take place in Kamchatka, Krasnodar and Primorsky Territories; the heaviest snowfalls happen in regions of the North Caucasus, north and south-west of Siberia, as well as Far East (Sakhalin and Magadan Regions, Kamchatka, Khabarovsk and Primorsky Territories, Chukotka). Regions of the Far East, such as Republic of Sakha-Yakutia, Primorsky and Khabarovsk Territories, Amur Region, as well as south of the European Russia (Krasnodar and Stavropol Territories, Republics of the North Caucasus) are mostly exposed to catastrophic floods.

For Russia as a whole, the cumulative degree of natural hazard is increasing from west to east and south, with progress to the mountainous regions. The most dangerous areas in terms of natural hazards manifestation are situated in the Territories and Republics of the North Caucasus, Ural and Altai Mountains, Irkutsk Region and Transbaikalia, the Pacific coast of the Far East (Magadan Region and Khabarovsk Territory), and especially Sakhalin, the Kuril Islands and Kamchatka (Malkhazova and Chalov, 2004).

According to the assessment by EMERCOM (2010), the following federal regions: Republics of Sakha-Yakutia, Komi and Karelia, Khabarovsk and Primorsky Territories, Amur, Arkhangelsk, Irkutsk, Magadan, Murmansk, and Volgograd Regions, as well as Evreiskaia (Yevish) AO, Khanty-Mansiysk and Chukotka Autonomous Okrugs are the most vulnerable to the impacts of natural hazards. The vulnerability is measured as ratio of the total number of realized natural sources of emergencies to the number of emergency situations caused by them. In the listed regions, the vulnerability is higher than an average for Russia.

2.2. Methodology

An assessment was made of the risk of road and railway accidents and traffic disruptions, as well as the total risk of transport accidents and disruptions caused by adverse and hazardous natural impacts on the transport infrastructure in Russian federal regions. Road, rail, air, and water transport were considered in the total risk analysis.

Risk is understood as the possibility of undesirable consequences of any action or course of events (Miagkov, 1995). Risk is measured by the probability of such consequences or the probable magnitude of losses.

There are various methods for assessing risk. In the field of natural hazards, risk is generally defined as by the product of hazard and vulnerability, i.e. a combination of the damageable phenomenon and its consequences (Eckert et al., 2012). The most researchers calculate risk (R) as a function of hazard (H), exposure (E) and vulnerability (V): R=f(H,E,V) (e.g. Arrighi et al., 2013; Falter et al., 2015; IPCC, 2012; Schneiderbauer and Ehrlich, 2004). Various authors propose their own techniques of calculating risk, mainly within the framework of this common approach. In a recent publication, Arosio et al. (2020) propose a holistic approach to analyze risk in complex systems based on the construction and study of a graph modeling connections between elements.

Another one approach to measuring risk suggests using the concept of emergency situation. In Russia, an emergency situation is defined as a disturbance of the current activity of a populated region due to abrupt technological / natural impacts (catastrophes or accidents) resulting in social, economic, and / or ecological damage, which requires special management efforts to eliminate it (Petrova, 2005). An emergency situation caused by the impact of natural hazards on technological systems and infrastructure can be considered as a result of all the factors of risk: hazard, exposure, and vulnerability. It combines hazard defined in its physical parameters, exposure of a population or facilities located in a hazard area and subject to potential losses, and vulnerability that links the intensity of a hazard to undesirable consequences. An emergency resulting from a hazardous impact may be a measure of the losses due to this impact. The total frequency of emergencies of varying severity may serve as a comprehensive indicator of risk assessment (Shnyparkov, 2004).

In this study, the above approach using frequency of emergency situations as a measure of risk was applied. As an indicator of risk, the average frequency of occurrence of transport accidents and traffic disruptions triggered by natural hazard impacts, which led to emergency situations of different scale and severity, was used. Risk indicators were calculated for each federal region as average annual numbers of emergency situations in each type of transport, as well as a resulting average annual number of

emergencies due to all transport accidents and disruptions. Thus, the calculated indicators included the probability of undesirable consequences (emergencies) due to impacts of natural hazards on transport infrastructure exposed and vulnerable to these influences. Quantitative and qualitative criteria for classifying transport accidents and disruptions as emergency situations are listed below. For the analysis, the period from 1992 to 2018 was chosen, since it covered data accumulated in the author's database.

The information collected by the author in an electronic database of technological and natural-technological accidents (Petrova, 2011) is analyzed in this study. Figure 3 shows the relational structure of the database and the procedure for conducting data analysis.

The database is constantly updated with new information. Currently, it contains about 20 thousand events from 1992 to 2018. Official daily emergency reports of the EMERCOM[1] of Russia and media reports serve as data sources. Only open data is used. Emergency reports are publicly available on the EMERCOM website (https://www.mchs.gov.ru), but only in Russian.

The format of the database makes it possible to structure the collected information and classify it according to the author's assessment. The main database table, into which all the information is entered, has the following structure (the listed sections correspond to the column names of the table in Figure 3):

1) event number - the number changes automatically as information is entered;
2) date of the incident;
3) country;
4) region;
5) location - the distance to the nearest settlement is additionally indicated;
6) type of accident – according to the EMERCOM classification and assessment by the author;
7) a brief description of the event, including the time of occurrence, probable cause of the accident if available, its consequences, and measures taken to eliminate them;
8) geographical coordinates if applicable;
9) the scale of the emergency situation caused by the accident – local, inter-municipal, regional, inter-regional, cross-border;
10) the number of deaths;
11) the number of injuries;
12) economic and environmental losses if any;
13) source of information.

All types of technological accidents occurring in Russia are recorded in the database, including those triggered by impacts of natural events of various genesis. Such accidents in technological systems and infrastructure due to natural impacts are classified as natural-technological. The transport accidents and traffic interruptions caused by natural hazards are also listed.

It should be noted that it is not possible to fully cover all the accidents in the database, because they are too numerous, especially road accidents. According to the State traffic inspectorate of the Ministry of Internal Affairs of Russia, 168 thousand road accidents are registered in Russia in 2019.

The criteria for statistical accounting and reporting information about transport accidents by the EMERCOM of Russia are as follows:

1) for road accidents:
   - Any fact of an accident during the transportation of dangerous goods;
   - Damage to 10 or more motor units;
   - Traffic interruptions for 12 hours due to an accident;
   - Severe accidents with the death of five or more people or injured 10 or more people.
2) for railway accidents:
   - Any fact of the train crash;
   - Damage to wagons carrying dangerous goods, causing people to be injured;
   - Traffic interruptions: on the main railway tracks – for 6 hours or more; in the subway – for 30 minutes and more;
3) for air transport accidents – any fact of the aircraft fall or destruction;
4) for water transport accidents:
   - Emergency release of oil and oil products into water bodies in the amount of 1 ton or more;

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[1] The Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters

- Accidental ingress of liquid and loose toxic substances into water bodies exceeding the maximum permissible concentration by 5 or more times;
- Any fact of flooding or throwing of ships ashore as a result of a storm (hurricane, tsunami), landing of ships aground;
- Accidents on small vessels with the death of five or more people or injured 10 or more people;
- Accidents on small vessels carrying dangerous goods.

The same selection criteria are used for events to be included into the author's database. Events that meet these criteria are characterized as emergency situations.

The accumulation of all the information in the form of an electronic database allows conducting various thematic search queries and analyzing their results depending on the goals and objectives of the research.

For the purposes of this study, a search of information about transport accidents and traffic disruptions caused by the impacts of natural hazards was made. Road, rail, air, and water transport were included in separate search queries. Statistical and geographical analysis of data obtained as a result of these search queries was carried out.

The proportion of accidents and disruptions triggered by natural factors was evaluated. All types of natural hazards and adverse weather conditions were taken into account. The main natural causes of accidents and failures were identified for each mode of transport.

Additionally, all the federal regions were divided into groups according to their risk level. The risk level was estimated for each federal region and each type of transport by the average annual number of emergency situations in comparison with the average value of the indicator in Russia. The number of groups was determined in each case depending on the dispersion of the calculated value.

Using the cartogram method, maps were created, on which the results of the assessment were presented (Figures 4-6).

3. Results
3.1. Contributions of natural hazards

The transport infrastructure of Russia is exposed to multiple impacts of various natural hazards and weather phenomena such as heavy rains and snowfalls, strong winds, floods, earthquakes, volcanic eruptions, landslides, debris flows, snow avalanches; rock falls, icing conditions of roads, and others. In many cases, these impacts occur simultaneously or successively, one after another, and reinforce each other. Some natural hazards trigger hazards of other types, e.g. earthquake or volcanic eruption can provoke such slope processes as rock falls, ice collapses, landslides, debris flows / lahars, snow avalanches, and others; heavy rain can cause debris flows, landslides or floods, etc. Gill and Malamud (2016) examine hazard interrelationships in more detail. These triggering impacts are also recorded in the database and taken into account in the analysis.

Contributions of various natural factors to occurrences of different types of transport accidents and traffic disruptions including road, railway, air, and water transport were found as results of relevant searches in the database.

Table 1 shows these results. The "+" sign marks impacts of natural hazards listed in the first column on the corresponding type of transport. Only accidents and disruptions occurred in Russia and recorded in the database are taken into consideration.

As the analysis of the database revealed, transport infrastructure of Russia is most often affected by adverse impacts of meteorological and hydrological origin, especially by hazards associated with cold and snow winters, as well as exogenous slope processes including those provoked by the hydro-meteorological hazards. The majority of emergency situations due to natural hazards are registered from November to March (more than 67%); among the warmer months, the largest number of transport accidents occurs in July.

The frequencies of occurrence of accidents and disruptions caused by the impacts of natural hazards, as well as their proportion among other factors of accidents are discussed in the following sections.

3.1.1. Road transport

Road transport is one of the main means of moving passengers and goods over short and medium distances in Russia. In terms of transport security, it is the most dangerous means of transportation with the highest number of fatalities and injuries in accidents (Petrova, 2013) and one of the most common

sources of technological hazard, as the number of cars on roads increases significantly faster than the quality of road infrastructure (EMERCOM, 2010).

335 More than 20% of road accidents and traffic disruptions registered in the database were caused by the impacts of various natural hazards. This refers to those incidents where the natural impact was indicated as the cause of the accident. Their real contribution can be even greater.

Road transport facilities and road infrastructure are exposed to adverse and hazardous natural processes and phenomena of hydro-meteorological character practically all around Russia. Many sections of roads, bridges and other road infrastructure are subject to impacts of snowfalls and snowstorms, heavy rainfalls,
340 flooding, and icing roads; from among exogenous hazards, landslides, debris flows, snow avalanches, rock falls, and other natural hazards affect road infrastructure. These negative impacts trigger road accidents and traffic disruptions leading to emergency situations and causing many social problems. Under unfavorable meteorological conditions, the risks of car crashes as well as the delay of transportation are increasing, whereas the speed of traffic flow is decreasing (Petrova and Shiryaeva
345 2019).

During the study period from 1992 to 2018, the following natural hazard impacts that caused accidents and traffic disruptions are identified. They were recorded in 70 from 85 federal regions of Russia. The brackets indicate the regions where these accidents and failures occurred:

- ***heavy snowfall and snowdrift*** (Altai Republic; Altai, Kamchatka, Krasnodar, Krasnoyarsk,
350 Primorsky, Stavropol, and Khabarovsk Territories; Jewish AO; Yamalo-Nenets AD; Amur, Arkhangelsk, Astrakhan, Volgograd, Magadan, Murmansk, Novosibirsk, Omsk, Orenburg, Rostov, Sakhalin, Saratov, Sverdlovsk, and Chelyabinsk Regions);
- ***bottom snowstorm*** (Republics of Bashkortostan and Komi; Altai, Kamchatka, and Krasnoyarsk Territories; Volgograd, Magadan, Murmansk, Orenburg, Sakhalin, Ulyanovsk, and Chelyabinsk
355 Regions);
- ***ice phenomena*** (Republics of Bashkortostan, Kalmykia, and Khakassia; Primorsky, and Khabarovsk Territories; Jewish AO; Leningrad, Magadan, Rostov, Sakhalin, and Chelyabinsk Regions);
- ***abnormally low air temperature*** (Yamalo-Nenets AD; Krasnoyarsk Territory; Kemerovo,
360 Novosibirsk, Omsk, and Tomsk Regions);
- ***flooding of road due to heavy rain*** (Moscow; Altai Republic, Bashkortostan, Buryatia, Sakha-Yakutia, Khakassia, and Tyva; Chukotka AD; Altai, Krasnodar, Primorsky, and Stavropol Territories; Amur, Arkhangelsk, Leningrad, Magadan, Moscow, Nizhny Novgorod, Novgorod, Sakhalin, and Saratov Regions);
365 - ***washout of road*** (Republic of Sakha-Yakutia; Kamchatka Territory; Sverdlovsk and Tyumen Regions);
- ***debris flow*** (Chechen Republic, Kabardino-Balkaria, Karachay-Cherkessia, and Republic of North Ossetia-Alania; Krasnodar Territory; Sakhalin Region);
- ***snow avalanche*** (Republic of Dagestan, North Ossetia-Alania);
370 - ***rock fall*** (Republic of Dagestan, North Ossetia-Alania);
- ***volcanic eruption*** (Kamchatka Territory).

The majority of all the emergencies revealed (almost 73%) happened during the cold season from November to March. A significant increasing in their number occurred during abrupt changes in weather conditions, such as heavy precipitation, temperature drops, icing. Emergency situations caused by snow
375 related natural hazards were most often and most common. Snow drifts on the roads became a real disaster leading to long-term traffic disruptions in many regions of Russia, especially in Arkhangelsk, Novosibirsk, Omsk, Orenburg, Rostov, Sakhalin, Sverdlovsk, and Chelyabinsk Regions, Altai, Krasnodar, and Khabarovsk Territories.

The frequencies of occurrence of road accidents and disruptions due to natural hazards are discussed in
380 section 3.2.1.

3.1.2. Railway transport

In the Russian Federation, due to its vast and extended territory and natural features, a large distance of the raw material base from processing enterprises, railway transportation is the basis of the transport
385 system. It accounts for more than 80% of the freight turnover of all types of transport (without pipelines) and over 40% of the passenger traffic of public transport in long-distance and suburban communications. Railway transport is considered the safest form of modern transportation, although railway catastrophes

with a large number of victims and injuries occur in many countries. The main causes of railway accidents in Russia are technical problems, a high degree of depreciation (of tracks, rolling stocks, signaling means, and other equipment), and a "human factor" such as errors of dispatchers and drivers, etc. (Petrova, 2015).

More than 7% of all railway accidents and failures registered in the database were triggered by natural factors. This refers to those incidents where natural impacts were indicated as causes of accidents. Over 1992 to 2018, impacts of natural hazards of various genesis caused railway accidents and traffic disruptions in 29 from 85 federal regions of Russia.

The identified natural hazards that caused these harmful events are listed below. The brackets indicate the regions where these accidents and failures occurred:

- **_heavy snow_** (Yamalo-Nenets AD; Orenburg and Sakhalin Regions);
- **_washout of railway as a result of heavy rain and flash flood_** (Dagestan, Karelia, Udmurtia, and Chuvashia Republics; Amur and Sakhalin Regions; Khabarovsk and Krasnodar Territories);
- **_snow avalanche_** (Sakhalin Region; Khabarovsk Territory);
- **_rails deformation due to heat wave_** (Kalmykia Republic; Rostov Region);
- **_landslide_** (Krasnodar Territory; Orel Region);
- **_debris flow_** (Sakhalin Region; Krasnodar Territory);
- **_rock fall_** (Khabarovsk and Krasnodar Territories; Bashkartostan Republic);
- **_flooding due to melting snow_** (Murmansk and Vologda Regions).

Regarding seasonality of accidents, they had two peaks: in summer (in June and July) and in November. The most part of emergency situations were caused by snow drifts, washout or flooding of railway tracks due to heavy rains or floods, as well as by the slope processes such as landslides, snow avalanches, debris flows, and rock falls.

The frequencies of occurrence of railway accidents due to natural hazards are discussed in section 3.2.2.

3.1.3. Air transport

Air transport is the fastest and most expensive mode of transportation. That is why it is primarily used to transport passengers over distances of more than 1,000 km. In many distant areas of Russia (in the mountains, in the Far North), it is the only means of transport. The main causes of accidents are technical failures or "human errors", as well as various natural factors including adverse weather or collision with a flock of birds (EMERCOM, 2010).

The adverse weather conditions and other natural hazard impacts caused more than 8% of all the air transport accidents and traffic disruptions recorded in the database. This refers to those incidents where natural impacts were indicated as causes of accidents. Over 1992 to 2018, these events were registered in 27 from 85 federal regions of Russia.

The following impacts of natural hazards were revealed:

- **_strong winds_** (Moscow, Irkutsk, Murmansk, Omsk, Rostov, Sakhalin, Saratov, and Ulyanovsk Regions, Kamchatka, Krasnodar, and Krasnoyarsk Territories, Bashkortostan, Chuvashia, and Tatarstan Republics);
- **_thunderstorms_** (Irkutsk Region, Republic of Sakha-Yakutia);
- **_heavy rains_** (Moscow, Irkutsk Region, Krasnodar and Khabarovsk Territories);
- **_snowfalls and snowstorms_** (Moscow, Leningrad, Magadan, Rostov, and Sakhalin Regions, Kamchatka, Krasnodar, and Krasnoyarsk Territories, Republic of Khakassia);
- **_sleets_** (Moscow, St. Petersburg, Rostov Region, Kamchatka and Krasnodar Territories, Bashkortostan, Chuvashia, and Tatarstan Republics);
- **_runway icing_** (Moscow, Kaluga and Murmansk Regions, Kamchatka and Primorsky Territories);
- **_fog_** (Moscow, Sverdlovsk Region, Chechen and Ingushetia Republics);
- **_snow avalanche_** (Kamchatka);
- **_volcanic eruption_**.

In many cases, these adverse impacts occurred simultaneously. Thus, the majority of emergency situations were caused by the combination of heavy snow and strong winds. Almost 66% of events occurred during the cold season from November to March; another one peak of accidents was in July.

A unique incident, when a helicopter was damaged as a result of an avalanche, was recorded in the database on April 10, 2010 in Kamchatka.

For the study period, there was not a single accident caused by volcanic eruption in Russia. Due to the eruption of the Icelandic volcano Eyyafyatlayokudl, airlines canceled and delayed more than 500 flights at ten Russian airports in April 2010; 32 thousand passengers could not fly.

445 The frequencies of occurrence of air transport accidents caused by natural hazards are discussed in section 3.2.3 and included in the total risk analysis (section 3.2.5).

3.1.4. Water transport

Water transport includes both sea and river transport. Despite the relatively low speed and seasonal
450 limitations on traffic, this type of transport is widely used for transporting large volumes of goods and passengers at different distances. The main causes of accidents in water transport are violations of the rules of navigation and transportation, of fire safety, and technical operation of vessels; depreciation of ships, ports' equipment, and other objects of infrastructure, as well as impacts of natural hazards and adverse weather conditions (EMERCOM, 2010).

455 The greatest contribution of natural factors to the accident rate after road transport was recorded for water transport. Almost 16% of all the water transport accidents registered in the database were caused by various natural hazards. These events were registered in 21 from 85 federal regions of Russia.

The following impacts were revealed from 1992 to 2018:

- ***strong winds*** (Leningrad, Sakhalin, and Sverdlovsk Regions, Kamchatka, Krasnodar, and
460 Primorsky Territories);
- ***storms*** (Astrakhan, Irkutsk, Magadan, Murmansk, Rostov, Ryasan, Sakhalin, and Yaroslavl Regions, Kamchatka, Khabarovsk, Krasnodar, and Primorsky Territories, Dagestan, Karelia, and Tatarstan Republics, Yamalo-Nenets AD);
- ***snowstorms*** (Irkutsk and Sakhalin Regions);
465 - ***icing*** (Sakhalin Region, Primorsky Territory, Republic of Sakha-Yakutia);
- ***thunderstorms*** (Leningrad Region, Komi Republic);
- ***fog and mist*** (Leningrad and Sakhalin Regions).

The most part of accidents (more than 70%) occurred during the cold season from September to January.

The frequencies of occurrence of water transport accidents due to natural hazards are discussed in section
470 3.2.4 and included in the total risk analysis (section 3.2.5).

3.2. Risk of transport accidents and traffic disruptions

Occurrence frequencies of road, railway, air, and water accidents and traffic disruptions due to natural hazard impacts at the level of Russian federal regions were estimated for the risk analysis. As mentioned
475 in section 2.2, only accidents and disruptions, which reached the scale of an emergency situation, were taken into account. Annual average numbers of such events over 1992 to 2018 were used as risk indicators.

All the federal regions were divided into groups by their risk levels of road and railway accidents, as well as the total risk of transport accidents and traffic disruptions. In each case, the risk level was determined
480 in comparison with the average value of the corresponding indicator for Russia.

The resulting maps were created and analyzed. Regional differences in the risk of transport accidents were found. Below are the main results of the risk analysis.

3.2.1. Road transport

485 Risk of emergencies in road transport depends on the density of the road network, traffic intensity, human factors (violation of traffic rules by drivers and pedestrians, etc.), as well as climatic conditions, seasonality, and other circumstances. With a large area of the country, the paved public road density in Russia is the lowest of all the G8 countries, equal to 63 km per 1,000 km^2 (FSSS, 2020). However, it is much higher in the densely populated regions of the European part of Russia. In the Asian part, only some
490 south-western and south-eastern regions have a satisfactory network of hard-surface roads (Petrova and Shiryaeva, 2019). Federal Cities Moscow and St. Petersburg have the highest density of paved public roads, which comprises to about 2,500 km / 1,000 km^2; it is also high in federal regions of the central Russia (Moscow and Belgorod Regions) and the North Caucasus (Ingushetia and North Ossetia-Alania Republics), equal to 700-850 km / 1,000 km^2 (FSSS, 2020).

495 Risk of road accidents and traffic disruptions due to natural hazard impacts within the Russian federal regions was assessed.

635 emergency situations of various scale and severity caused by the impacts of natural hazards on road infrastructure were taken into consideration. The main triggers of these emergencies and the regions of their occurrence were identified in section 3.1.1. The risk indicator was calculated as an average annual number of emergency situations of this type in each federal region as well as the average for Russia.

All the federal regions are divided into five groups in accordance with risk level by comparing their risk indicators with the average for Russia. The resulting map is shown in Figure 4.

Regions of the Far East of Russia (Magadan and Sakhalin Regions, Kamchatka and Khabarovsk Territory), Krasnoyarsk Territory in the southern part of Central Siberia, and Republic of North Ossetia-Alania in the North Caucasus have the highest risk level. The road infrastructure in these regions is mostly affected by the above listed natural hazards especially by heavy snowfalls and snowstorms, ice phenomena, abnormally low air temperature, and heavy rains. In North Ossetia-Alania impacts of snow avalanches and debris flows are most significant.

3.2.2. Railway transport

Risk of emergencies in railway transport depends on the density of the railway network, traffic intensity, human factors, climatic conditions, and seasonality. The highest density of the public railway network is in Federal Cities Moscow (1,921 km / 10,000 km^2) and St. Petersburg (3,082 km / 10,000 km^2), as well as federal regions of the central and north-western parts of the European Russia such as Moscow, Kaliningrad, Tula, Kursk, Vladimir, and Leningrad Regions (300-500 km / 10,000 km^2). With a lack of railways in a large part of the country area, especially in its Asian part, the average density of railways in Russia is 51 km / 10,000 km^2; in the central part of the European Russia it is 263 km / 10,000 km^2 (FSSS, 2020).

Risk of railway accidents and traffic disruptions due to natural hazard impacts at the level of Russian federal regions was assessed.

63 emergency situations of various scale and severity caused by the impacts of natural hazards on railway infrastructure were taken into consideration. The main triggers of these emergencies and the regions of their occurrence were identified in section 3.1.2. Occurrence frequencies (annual average numbers) of these events were calculated for each federal region as well as the average for Russia.

All the federal regions are divided into three groups by their risk levels. In this case, only three groups are chosen, since the number of accidents and dispersion of risk indicators are not as great as in the case of road accidents. The resulting map is shown in Figure 5.

Krasnodar Territory in the southern part of European Russia and regions of the Far East (Sakhalin Region; Khabarovsk Territory) are characterized by the highest level of risk. Railways in these regions are mostly affected by the impacts of heavy snowfalls, heavy rains, snow avalanches, landslides, debris flows, and rock falls.

3.2.3. Air transport

Risk of emergencies in air transport depends on the aircraft technical condition, air traffic intensity, human factors, meteorological conditions, and seasonality.

The number of air transport accidents and traffic disruptions due to impacts of natural hazards was included in the calculation of the total risk indicator. 70 emergency situations were taken into consideration. The main triggers of these emergencies and the regions of their occurrence were identified in section 3.1.3.

3.2.4. Water transport

Risk of emergencies in water transport depends on technical conditions of vessels, traffic intensity, human factors, climatic conditions, and seasonality.

Water transport accidents due to natural impacts were also included in the calculation of the total risk of transport accidents and disruptions. 70 emergency situations were taken into consideration. The main triggers of these emergencies and the regions of their occurrence were identified in section 3.1.4.

3.2.5. The total risk

Additionally, the total risk of transport accidents and traffic disruptions was assessed for the area of Russia. Occurrence frequencies of accidents and disruptions in all the above examined types of transport over 1992 to 2018 were used as risk indicators.

838 emergency situations of various scale and severity caused by the impacts of natural hazards on transport infrastructure were taken into consideration. The main triggers of these accidents were identified

555 in section 3.1 and shown in Table 1; annual average numbers of these events were calculated for each federal region as well as the average for Russia.

All the federal regions were divided into five groups by their risk levels. The procedure for selecting groups was described in section 2.2.

The resulting map is shown in Figure 6. Regions of the Far East (Magadan and Sakhalin Regions; Kamchatka, Khabarovsk, and Primorsky Territories), Krasnoyarsk Territory in the south part of Central
560 Siberia, Murmansk Region in the north and Krasnodar Territory in the south part of European Russia and North Ossetia-Alania Republic in the North Caucasus have the highest level of risk. The transport infrastructure in these regions is mostly affected by the adverse impacts of natural hazards listed in Table 1, primarily those of hydro-meteorological genesis. Kamchatka, Khabarovsk, and Primorsky Territories, as well as Sakhalin Region are characterized by the most dangerous meteorological combinations of
565 heavy precipitations and strong winds. In Kamchatka, Krasnodar and Primorsky Territories, the most intense rains are recorded. In winter, the heaviest snowfalls happen in all the above regions. In spring and early autumn, Khabarovsk, Krasnodar and Primorsky Territories are subject to catastrophic floods. Kamchatka is most at risk of volcanic eruptions. North Ossetia-Alania and Sakhalin are characterized by the highest avalanche and debris flow activity. All of the mentioned natural hazards trigger accidents and
570 lead to delay in the transportation of passengers and goods by road, railway, air, and water transport. In addition, Kamchatka, Sakhalin, south part of Siberia, and the North Caucasus are among the most seismically active regions of Russia; during the study period, no traffic accidents due to the earthquake were recorded, but their possibility should be taken into account.

575 **4. Concluding remarks and discussion**

Contributions of various natural hazards to occurrences of different types of transport accidents and traffic disruptions including road, railway, air, and water transport are revealed. Among all the identified types of natural hazards, the largest contributions to transport accidents and disruptions have hydro-meteorological hazards such as heavy snowfalls and rains, floods, and ice phenomena, as well as
580 dangerous exogenous slope processes including snow avalanches, debris flows, landslides, and rock falls. The most dangerous is the combination of heavy precipitations and strong winds.

An annual average frequency of occurrences of emergency situations of various scale and severity is applied in this study among all possible methods for assessing risk. Unlike methods that assess risk by measuring its components such as hazard, exposure and vulnerability, this approach takes into account the
585 resulting consequences of the above factors and the probability of these consequences. Transport accidents and disruptions are considered in this case as consequences of natural hazard impacts on transport infrastructure that is exposed and vulnerable to these impacts. The risk index is calculated as an annual average number of emergency situations caused by natural hazard impacts in each federal region and each type of transport. Thus, the index used combines both the probability and severity of the adverse
590 impacts of natural hazards on transport infrastructure, as well as vulnerability of infrastructure to these adverse impacts resulting in accidents and malfunctions. Using this method, it is possible to compare between different regions and identify deficiencies that need to be addressed.

Regional differences in the risk of transport accidents between Russian federal regions were found. All the federal regions were divided into groups by their risk levels of road and railway accidents, as well as
595 the total risk of transport accidents and traffic disruptions due to natural hazard impacts. The resulting maps were created and analyzed.

Magadan, Murmansk, and Sakhalin Regions; Kamchatka, Khabarovsk, Krasnodar, Krasnoyarsk, Primorsky Territories, and North Ossetia-Alania Republic are characterized by the highest risk of transport accidents and traffic disruptions caused by natural events. Emergencies of various scales occur
600 in these regions on average more often than once a year (Figure 6). Chelyabinsk, Orenburg, and Rostov Regions, Altai Territory, Dagestan and Bashkortostan Republics, and Moscow have a high risk level with an average probability of one event in 1-2 years (0.6-1.0 events per year).

For the study period of 1992 to 2018, the database mainly recorded events caused by hydro-meteorological and exogenous natural hazards. With high value of the risk index, Kamchatka, Sakhalin,
605 the North Caucasus, and south of Siberia are also among the most seismically active regions of Russia, which further increases the likelihood of emergencies in these regions in case of an earthquake. It is in these regions that the necessary measures should first be taken to reduce the vulnerability of transport infrastructure to undesirable natural impacts and increase level of protection and preparedness.

Under conditions of observed and forecasted global and regional climate changes, adverse and hazardous
610 natural impacts on various facilities of transport infrastructure, primarily from natural hazards of

meteorological and hydrological origin, as well as other natural events triggered by them such as landslides, snow avalanches, and debris flows are expected to increase (Malkhazova and Chalov, 2004; Yakubovich et al., 2018). Other factors, such as growing transportation network, increased traffic, and the lack of funding will also lead to increasing of adverse impacts, especially with further development of transport infrastructure to areas with high level of natural risk. In this regard, continuous monitoring and assessment of natural hazard impacts is especially relevant and important.

Only severe accidents leading to an emergency situation were considered in this study due to a lack of data on small events. This gap should be filled in a future research because small events can also cause a great damage to the infrastructure and trigger accidents and traffic interruptions (Voumard et al., 2018).

Effects of global processes such as space weather on the transport infrastructure facilities, especially on electronics and automatic machinery were not taken into consideration because these events were not recorded in the database. In the future, these impacts should be also investigated; risk of these events should be considered in the risk assessment.

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Data availability:
The data used in this study are collected by the author in an electronic database, which is not available publicly.

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Author's contribution: The work presented in this study was conducted by E. Petrova.

References
Anan'in, I. V. and Merzlyi, A. M.: Tectonically active zone of Russian northern areas and their impact on air crashes, Ecology of Russian Northern Areas, Problems, situation forecast, ways of development, decisions, Proceedings, Arkhangelsk, 2, 4-8, 2002. (In Russian).

Andersson, A. K. and Chapman L.: The impact of climate change on winter road maintenance and traffic accidents in West Midlands, UK, Accident Analysis and Prevention, 43, 284-289, 2011.

Andrey, J.: Long-term trends in weather-related crash risks, J. of Transport Geography, 18 (2), 247–258, 2010.

Aron, M., Bergel-Hayat, R., Saint Pierre, G., Violette, E.: Added risk by rainy weather on the roads of Normandy-centre region in France, Proceedings of 11th WCTR, World Conference on Transport Research Society, 2007.

Arosio, M., Martina, M. L. V., and Figueiredo, R.: The whole is greater than the sum of its parts: a holistic graph-based assessment approach for natural hazard risk of complex systems, Nat. Hazards Earth Syst. Sci., 20, 521–547, https://doi.org/10.5194/nhess-20-521-2020, 2020.

Arrighi, C., Brugioni, M., Castelli, F., Franceschini, S., and Mazzanti, B.: Urban micro-scale flood risk estimation with parsimonious hydraulic modelling and census data, Nat. Hazards Earth Syst. Sci., 13, 1375–1391, https://doi.org/10.5194/nhess-13-1375-2013, 2013.

Bergel-Hayat, R., Debbarh, M., Antoniou C., and Yannis, G.: Explaining the road accident risk: Weather effects, Accident Analysis and Prevention, 60, 456-465, 2013.

Bil, M., Andrasik, R., Nezval V., and Bilova M.: Identifying locations along railway networks with the highest tree fall hazard, Applied Geography, 87, 45-53, doi:10.1016/j.apgeog.2017.07.012, 2017.

Bíl, M., Kubeček, J., and Andrášik, R.: An epidemiological approach to determining the risk of road damage due to landslides, Nat. Hazards, 73, 1323–1335, 2014.

Brenot, H., Theys, N., Clarisse, L., van Geffen, J., van Gent, J., Van Roozendael, M., van der A, R., Hurtmans, D., Coheur, P.-F., Clerbaux, C., Valks, P., Hedelt, P., Prata, F., Rasson, O., Sievers, K., and Zehner, C.: Support to Aviation Control Service (SACS): an online service for near-real-time satellite monitoring of volcanic plumes, Nat. Hazards Earth Syst. Sci., 14, 1099–1123, https://doi.org/10.5194/nhess-14-1099-2014, 2014.

Brodsky, H. and Hakkert, A. Sh.: Risk of a road accident in rainy weather, Accident Analysis and Prevention, 20(3), 161-176, 1988.

Budetta, P. and Nappi, M.: Comparison between qualitative rockfall risk rating systems for a road affected by high traffic intensity, Nat. Hazards Earth Syst. Sci., 13, 1643–1653, https://doi.org/10.5194/nhess-13-1643-2013, 2013.

670 Bunce, C. M., Cruden, D. M., and Morgenstern, N. R.: Assessment of the hazard from rock fall on a highway, Can. Geotech. J., 34, 344–356, 1997.

Chakrabarty, N. and Gupta, K.: Analysis of Driver Behaviour and Crash Characteristics during Adverse Weather Conditions, Procedia - Social and Behavioral Sciences, 104, 1048-1057, 2013.

Desiatov, V. P., Osipov, A. I., and Suzdal'skaya, O. V.: Solar Activity and Death-Rate Statistics, The Sun,
675 Electricity, Life, Proceedings of Memorial Readings devoted to A. L. Chijevskii, Moscow, 90-92, 1972. (In Russian).

Eckert, N., Keylock, C. J., Bertrand, D., Parent, E., Faug, T., Favier, T., Naaim, M.: Quantitative risk and optimal design approaches in the snow avalanche field: Review and extensions, Cold Regions Science and Technology, Vol. 79–80, 1-19, 2012.

680 Edwards, J. B.: Weather-related road accidents in England and Wales: a spatial analysis, J. of Transport Geography, 4(3), 201-212, 1996.

Eidsvig et al.: Assessing the risk posed by natural hazards to infrastructures, Nat. Hazards Earth Syst. Sci., 17, 481–504, 2017.

EMERCOM: Atlas of natural and technological hazards and risks. The Russian Federation, Publishing
685 House: Design. Information. Cartography, Moscow, 2010.

Epov, A. B.: Regularities in Occurrence of Technological Emergencies and their Relationship with Natural Processes, Problems of Safety under Emergencies, 12, 14-20, 1994. (In Russian).

Falter, D., Schröter, K., Dung, N. V., Vorogushyn, S., Kreibich, H., Hundecha, Y., Apel, H., and Merz, B.: Spatially coherent flood risk assessment based on long-term continuous simulation with
690 a coupled model chain, J. Hydrol., 524, 182–193, https://doi.org/10.1016/j.jhydrol.2015.02.021, 2015.

Federal Law of the Russian Federation N 16-FZ "On Transport Security" (as amended on 12/02/2019).

FSSS: Regions of Russia. Socio-economic indicators 2019, Rosstat, Moscow, 2020.

FSSS: Russian Statistical Yearbook 2018: Stat .book, Rosstat, Moscow, 2018.

695 Gill, J. C. and Malamud, B. D.: Hazard interactions and interaction networks (cascades) within multi-hazard methodologies, Earth Syst. Dynam., 7, 659–679, https://doi.org/10.5194/esd-7-659-2016, 2016.

Girina, O. A., Manevich, A. G., Melnikov, D. V., Nuzhdaev, A. A., and Petrova, E. G.: 2016 volcano eruptions in Kamchatka and the Northern Kuriles and their danger to aviation, J. of Volcanology
700 and Seismology, 3, 34-48, 2019.

Gordeev, E. I. and Girina, O. A., Volcanoes and the threat they pose for aircraft, Vestnik Rossiiskoi Akademii Nauk, 84, 2, 134--142, 2014. Doi:10.7868/S0869587314020121.

Govorushko, S. M.: Natural processes and Human impacts: Interaction between Humanity and the Environment, Springer, Dordrecht, 2012.

705 Hong, L., Ouyang, M., Peeta, S., He, X., and Yan, Y.: Vulnerability assessment and mitigation for the Chinese railway system under floods, Reliability Engineering and System Safety, 137, 58-68, 2015.

IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea,
710 M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012.

Jaiswal, P. and van Westen, C. J.: Use of quantitative landslide hazard and risk information for local disaster risk reduction along a transportation corridor: a case study from Nilgiri district, India, Nat. Hazards, 65, 887-913, https://doi.org/10.1007/s11069-012-0404-1, 2013.

715 Jaroszweski, D., and McNamara, T.: The influence of rainfall on road accidents in urban areas: A weather radar approach, Travel Behaviour and Society, 1(1), 15-21, doi:10.1016/j.tbs.2013.10.005, 2014

Kanonidi, H. K., Oraevskii, V. N., Belov, A. V., Gaidash, S. P., and Lobkov, V. L.: Railway Automatic System Failures under Geomagnetic Storms, Problems of Emergency Forecasting, Proceedings, Moscow: Russian Ministry of Emergencies, 41-42, 2002. (In Russian).

720 Kaundinya, I., Nisancioglu, S., Kammerer, H., and Oliva, R.: All-hazard guide for transport infrastructure, Transportation Research Procedia, 14, 1325-1334, 2016.

Kellermann, P., Schoenberger, C., and Thieken, A. H.: Large-scale application of the flood damage model Railway Infrastructure Loss (RAIL), Nat. Hazards Earth Syst. Sci., 16, 2357-2371, 2016.

Kishcha, P. V., Ivanov-Cholodny, G. S., and Shelkovnikov, M. S.: Zoning of air crashes, Physical Problems of Ecology, Proceedings, Moscow, 18-19, 1999.

Liu, B., Siu, Y. L., and Mitchell, G.: Hazard interaction analysis for multi-hazard risk assessment:a systematic classification based on hazard-forming environment, Nat. Hazards Earth Syst. Sci., 16, 629–642, 2016. https://doi:10.5194/nhess-16-629-2016

Ludvigsen, J. and Klæboe, R.: Extreme weather impacts on freight railways in Europe, Nat. Hazards, 70, 767-787, https://doi.org/10.1007/s11069-013-0851-3, 2014.

Malkhazova, S. M. and Chalov, R. S. (Eds.): Geography, Society and Environment. Vol. IV: Natural-Anthropogenic Processes and Environmental Risk, Gorodets Publishing House, Moscow, Russia, 2004.

Mattsson, L. G., and Jenelius, E.: Vulnerability and resilience of transport systems - a discussion of recent research, Transportation Research A: Policy and Practice, 81, 16-34, 2015.

Miagkov, S. M.: Geography of Natural Risk, Moscow: Moscow Univ. Press, 1995. (In Russian).

Ministry of Transport of the Russian Federation: Transport Strategy of the Russian Federation for the period until 2030, as amended on 12/05/2018, available at: https://www.mintrans.ru/documents/3/1009

Neal, Ch., Girina, O., Senyukov, S., et al., Russian eruption warning systems for aviation, Natural Hazards, Springer Netherlands, 51, 2, 245–262, 2009.

Nogal, M., O'Connor, A., Caulfield, B., and Brazil, W.: A multidisciplinary approach for risk analysis of infrastructure networks in response to extreme weather, Transportation Research Procedia, 14, 78–85, 2016.

Nyberg, R. and Johansson, M.: Indicators of road network vulnerability to storm-felled trees, Nat. Hazards, 69, 185. https://doi.org/10.1007/s11069-013-0693-z, 2013.

Petrova, E.: Critical infrastructure in Russia, Geographical analysis of accidents triggered by natural hazards, Env. Eng. and Management J., 10(1), 53–58, 2011.

Petrova, E.: Natural hazards and technological risk in Russia: the relation assessment. Nat. Hazards Earth Syst. Sci., 5, 459–464, doi: 10.5194/nhess-5-459-2005, 2005.

Petrova, E.: Road accidents in Russia: statistical and geographical analysis, Scientific Annals of "Alexandru Ioan Cuza" University of Iasi, Geography series, 2013, 59(2), 111-123.

Petrova, E.: Road and railway transport in Russia: safety and risks, AES Bioflux, 7(2), 259-271, 2015.

Petrova, E. G., Shiryaeva, A. V.: Road accidents in Moscow: weather impact, AES Bioflux, 11(1), 19-30, 2019.

Rakha, H., Farzaneh, M., Arafeh, M., Hranac, R., Sterzin, E. and Krechmer, D.: Empirical Studies on Traffic Flow in Inclement Weather, Final Report – Phase I, 2007.

Redelmeier, D. A., and Raza, Sh.: Life-threatening motor vehicle crashes in bright sunlight, Medicine, 96(1), e5710, 2017. doi: 10.1097/MD.0000000000005710

Schlögl, M., Richter, G., Avian, M., Thaler, T., Heiss, G., Lenz, G., and Fuchs, S.: On the nexus between landslide susceptibility and transport infrastructure – an agent-based approach, Nat. Hazards Earth Syst. Sci., 19, 201–219, https://doi.org/10.5194/nhess-19-201-2019, 2019.

Satterthwaite, S. P.: An assessment of seasonal and weather effects on the frequency of road accidents in California. Accident Analysis & Prevention 8(2), 87-96, 1976.

Schneiderbauer, S. and Ehrlich, D.: Risk, hazard and people's vulnerability to natural hazards: A review of definitions, concepts and data, Eur. Comm. Jt. Res. Centre. EUR, 21410, 40, https://doi.org/10.1007/978-3-540-75162-5_7, 2004.

Shabou, S., Ruin, I., Lutoff, C., Debionne, S., Anquetin, S., Creutin, J.-D., and Beaufils, X.: MobRISK: a model for assessing the exposure of road users to flash flood events, Nat. Hazards Earth Syst. Sci., 17, 1631–1651, https://doi.org/10.5194/nhess-17-1631-2017, 2017.

Shiryaeva, A. V.: Meteorological Conditions for Functioning of Automobile Transport in Moscow and Moscow Oblast, Izvestia Russia Academy of Sci., 6, 94-101, 2016. (In Russian).

Shnyparkov, A. L.: Methods of natural risk evaluation. Malkhazova, S. M. and Chalov, R. S. (Eds.): Geography, Society and Environment. Vol. IV: Natural-Anthropogenic Processes and Environmental Risk, Gorodets Publishing House, Moscow, Russia, 349-356, 2004.

Spasova, Z. and Dimitrov, T.: The effects of precipitation on traffic accidents in Sofia, Bulgaria, Asklepios, International Annual for History and Philosophy of Medicine, X (XXIX), 1, 76–81, 2015.

Tanner, J. C.: Effect of Weather on Traffic Flow, Nature, 4290, 1952.

780   Voumard, J., Derron, M.-H., and Jaboyedoff, M.: Natural hazard events affecting transportation networks in Switzerland from 2012 to 2016, Nat. Hazards Earth Syst. Sci., 18, 2093–2109, https://doi.org/10.5194/nhess-18-2093-2018, 2018.

WHO: The top 10 causes of death. Available from: http://www.who.int/mediacentre/factsheets/fs310/en/, 2017.

785   Yakubovich, A., Trofimenko, Y., Pospelov P.: Principles of developing a procedure to assess consequences of natural and climatic changes for transport infrastructure facilities in permafrost regions, Transportation Research Procedia 36, 810–816, 2018.

Yang, J., Sun, H., Wang, L., Li, L., and Wu, B.: Vulnerability Evaluation of the Highway Transportation System against Meteorological Disasters, Procedia - Social and Behavioral Sciences, 96, 280 – 293,

790   2013.

Table 1: Transport accidents and traffic disruptions caused by natural hazards in Russia (1992-2018)

Type of transport — Natural hazard	Road transport	Railway transport	Air transport	Water transport
Strong wind, storm			+	+
Snowfall, snowstorm, snowdrift, sleet	+	+	+	+
Rainfall, hailstone	+	+	+	
Hard frost, icing, ice-crusted ground	+		+	+
Thunderstorm, lightning			+	+
Fog, mist	+		+	+
Flood	+	+		
Heat wave		+		
Earthquake, volcanic eruption	+		+	
Landslide, slump, debris flow	+	+		
Rock fall	+	+		
Snow avalanche	+	+	+	

795

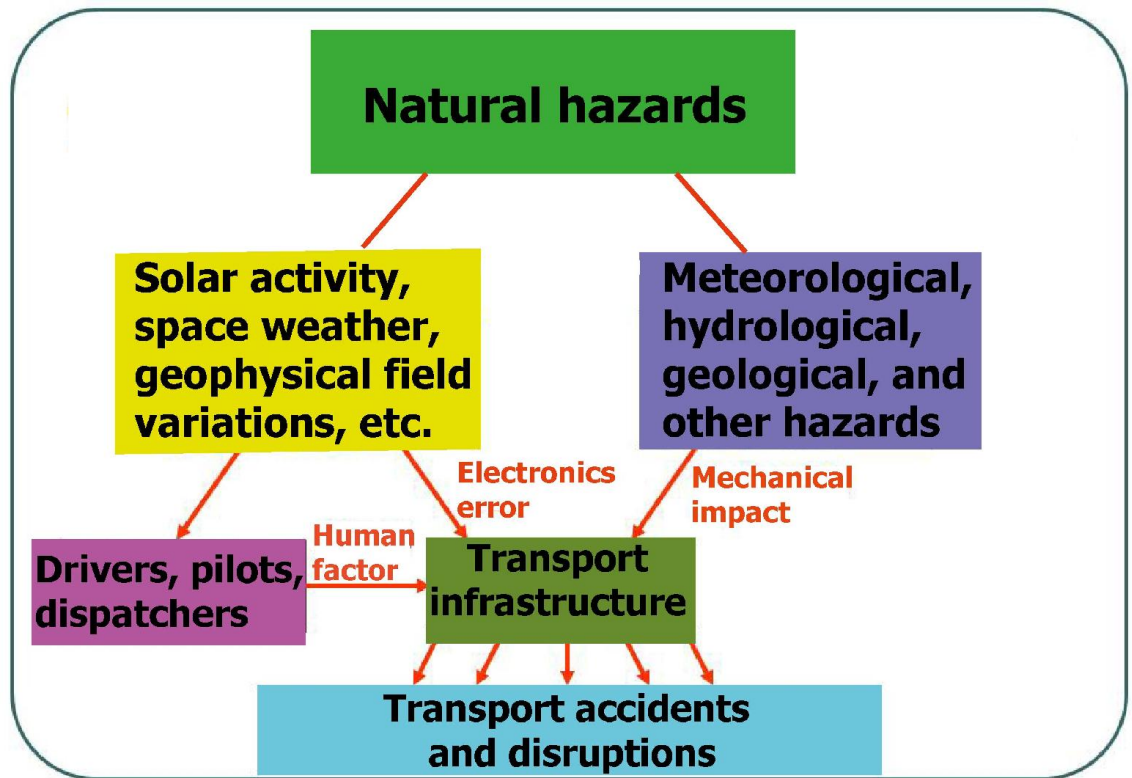



Figure 1: Grouping of natural hazards based on their genesis and impacts on transport infrastructure

800

Figure 2: Federal regions of the Russian Federation
(Base map: © DIK - Publishing House: Design. Information. Cartography)

805

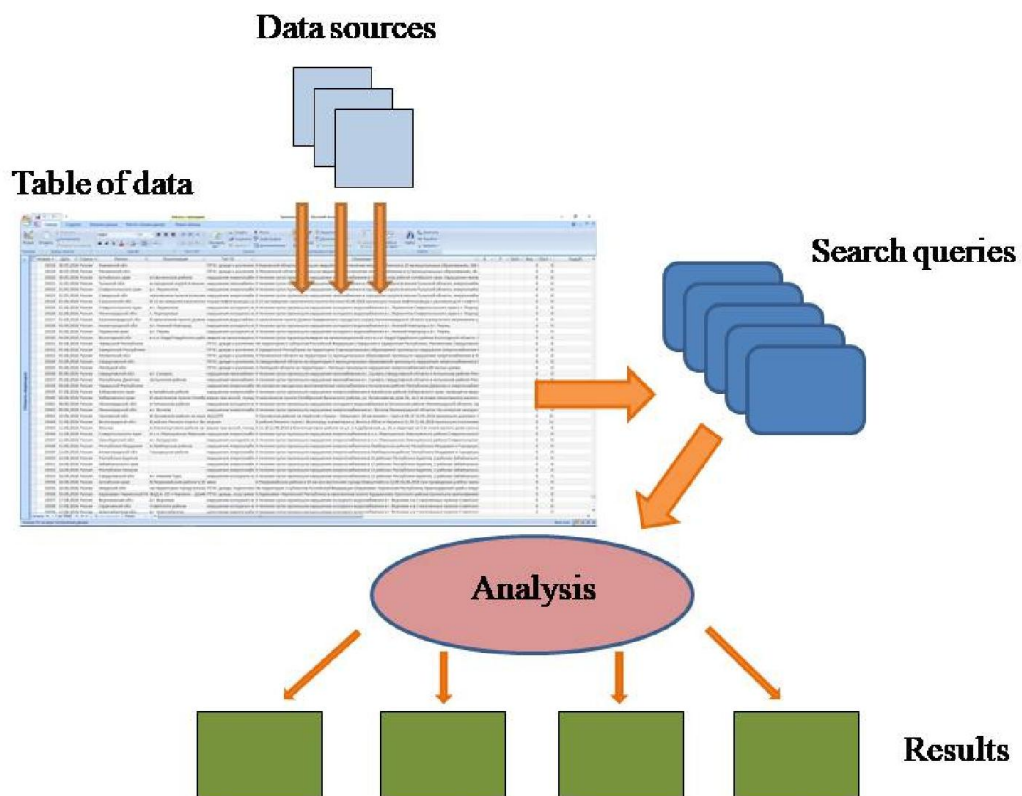



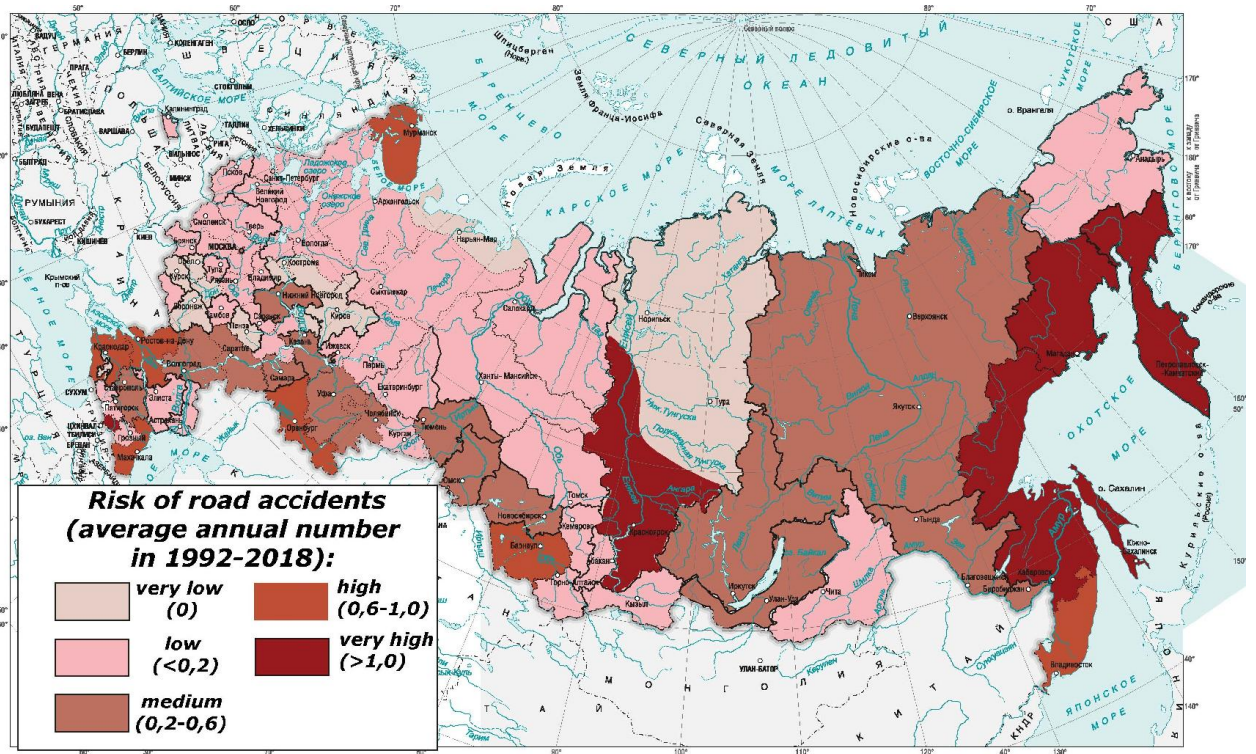
Figure 3: Relational structure of the database

810

Figure 4: Risk of road accidents and traffic disruptions triggered by natural hazards in the RF (base map: © DIK - Publishing House: Design. Information. Cartography)

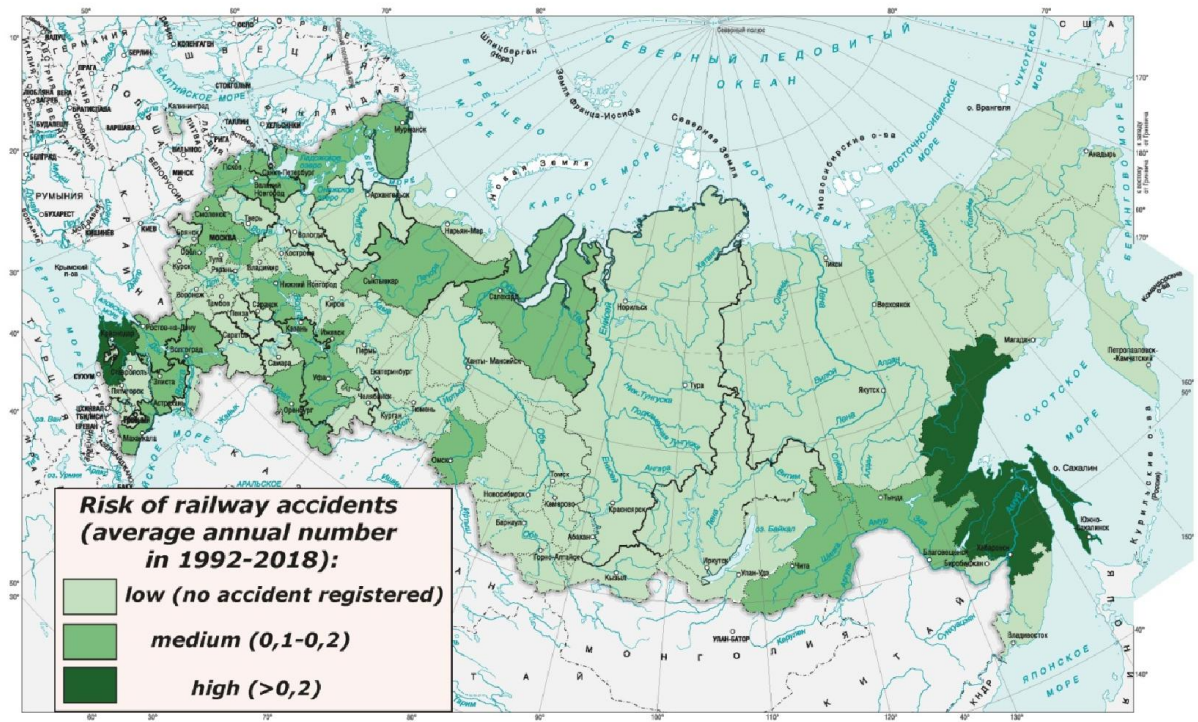



Figure 5: Risk of railway accidents and traffic disruptions triggered by natural hazards in the RF (base map: © DIK - Publishing House: Design. Information. Cartography)

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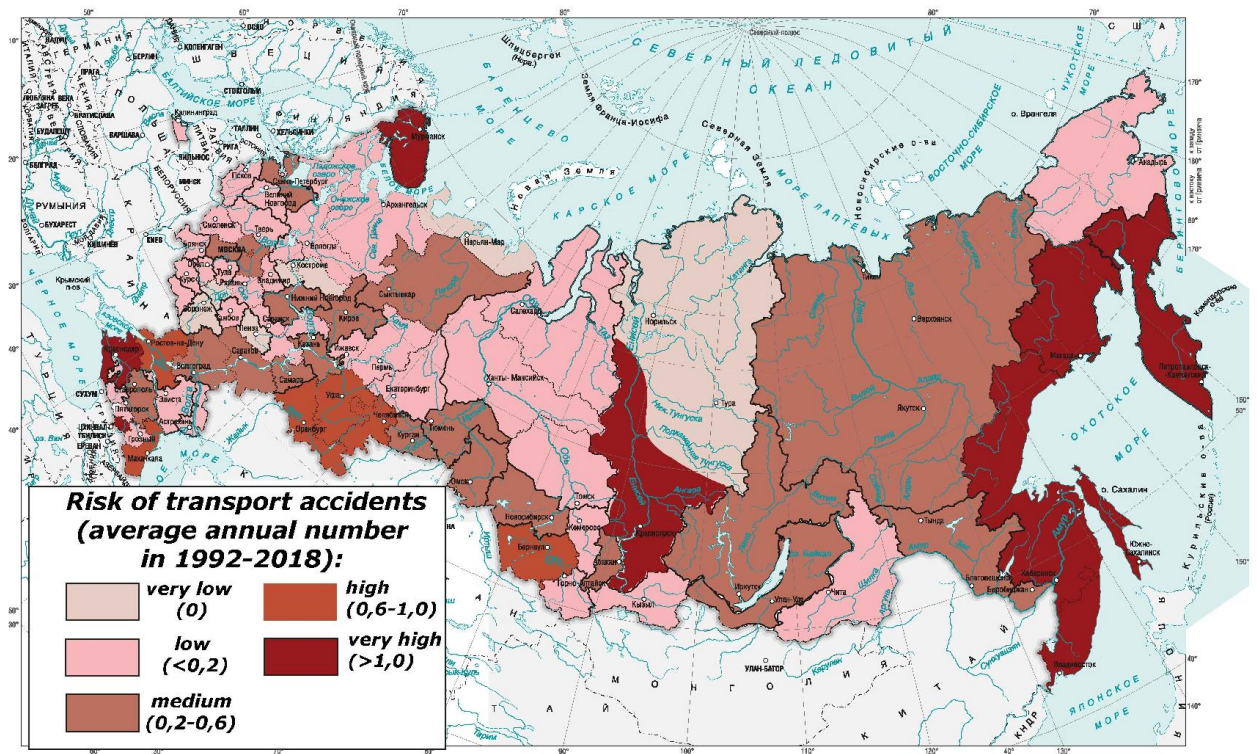
Figure 6: Risk of transport accidents and disruptions triggered by natural hazards in the RF
820   **(Base map: © DIK - Publishing House: Design. Information. Cartography)**