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Natural hazard impacts on transport infrastructure in Russia

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Abstract. Transport infrastructure is considered as a large and complex technological system including railway and bus stations; tunnels, overpasses, and bridges; sea- and river ports; airports; roads, railways, and waterways, as well as other structures, buildings and equipment ensuring the functioning of transport. Almost all of the transport infrastructure facilities are exposed to natural hazard impacts of different genesis. Such impacts pose a threat to transport safety and reliability, trigger accidents and failures, cause traffic disruptions and delays in delivery of passengers and goods. Under conditions of climate changes, these harmful impacts with negative consequences will increase. 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, icing conditions of roads, 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 by adverse and hazardous natural impacts is assessed at the level of Russian federal regions.

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

1. Introduction

Transport infrastructure is considered as a large and complex technological system including railway and bus stations; tunnels, overpasses, and bridges; marine terminals and seaports; ports on inland waterways; airports; sections of roads, railways, and inland waterways, as well as other buildings, structures, devices, and equipment ensuring the functioning of the transport system. The Russian Federation (RF) 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).

Throughout the area of Russia, almost all of the listed facilities of transport infrastructure 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 (Geography…, 2004). These 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.

All natural hazards can be divided into two groups, based on their origin, features of time variability and spatial distribution, as well as the impact pattern 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. They may influence the infrastructure both directly, causing electronics error and automatic machinery failure, as well as indirectly, by reducing reliability of operators, drivers or pilots (Petrova, 2005). Geological, hydro-meteorological, biological, and other natural hazards belonging to the second 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 (Transport…, 2018). Among

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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 adverse weather conditions on the accident rates of motor vehicles were published over the last decades (Brodsky and Hakkert 1988; Edwards 1996; Rakha et al 2007; Andrey 2010; Andersson and Chapman 2011; Petrova 2013; Bergel-Hayat et al 2013; Chakrabarty and Gupta 2013; Jaroszweski and McNamara 2014; Spasova and Dimitrov 2015; Shiryaeva 2016). All the authors agree that the weather is a major factor affecting road situation. 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). However, no integrated review of all kinds of natural hazards exists.

As for railway transport, most of 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). 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, rockfall, flood, snow avalanche, and others. None of the studies provides a comprehensive analysis of the harmful influence of natural events.

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 (Brenot et al., 2014; Girina et al., 2019).

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. Shcha et al. (1999), Anan'in and Merzlyi (2002) examine a correlation between seismic activity and a ashes.

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 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 study. 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, 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.

2.2. Methodology

The information collected by the author in an electronic database of technological and natural-technological accidents is analyzed in this study. The database is constantly updated with new information (Petrova, 2011). Currently, it contains about 20 thousand events from 1992 to 2018. Official

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daily emergency reports of the EMERCOM[1] of Russia and media reports serve as data sources. Only open data is used. The time and place of occurrence, type of accident, the number of deaths and injuries, economic and environmental losses, if any, the probable cause of the accident, if available, a brief description and source of information are recorded there (Figure 2). The transport accidents and traffic interruptions caused by natural events 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. The minimum quantitative criterion for entering an event into the database is as follows: at least five dead, ten injured or large economic damage. Only such severe accidents are reported by the EMERCOM of Russia. Nevertheless, the database provides a unique opportunity to monitor and analyze the events that are not always included into the statistics (e.g., impacts of natural hazards, etc.).

Statistical and geographical analysis of the information accumulated in the database was carried out. Based on the results of the analysis, the role of natural factors among all the causes of various types of transport accidents and traffic disruptions was evaluated. Road, railway, air, and water transport were taken into consideration.

An assessment was made of the risk of road and railway accidents and traffic disruptions, as well as the total risk of all the considered transport accidents and disruptions caused by adverse and hazardous natural impacts on the transport infrastructure in Russian federal regions. Occurrence frequencies of transport accidents and traffic disruptions for the six-year period from 2013 to 2018 were used as risk indicators. For this purpose, the average annual number of accidents was calculated for each federal region and each type of transport. All the federal regions were divided into groups by their levels of risk. For the analysis, the period from 2013 to 2018 was chosen, since it covered the most representative information. Using the method of cartogram, maps were created showing the results of the assessment.

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, 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.

Contributions of various natural factors to occurrences of different types of transport accidents and traffic disruptions including road, railway, air, and water transport are revealed. Table 1 shows these results. The "+" sign marks impacts of the listed natural hazards that caused accidents and disruptions on the corresponding type of transport recorded in the database over 1992 to 2018. The most adverse impacts were caused by natural hazards of meteorological and hydrological origin.

3.1.1. Automobile transport

Automobile transport facilities and road infrastructure are exposed to adverse and hazardous natural processes and phenomena practically all around Russia. Many sections of roads, bridges and other road infrastructure are subject to impacts of snowfalls and snowstorms, heavy rainfalls, flooding, landslides, icy conditions, debris flows, snow avalanches, rock falls, and other natural hazards. These negative impacts trigger road accidents and traffic disruptions 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 2019).

During the study period from 1992 to 2018, the following natural hazard impacts that caused accidents and traffic disruptions are identified. The brackets indicate the regions where these accidents and failures occurred:

- ***heavy snowfall*** (Altai Republic; Altai, Kamchatka, Krasnodar, Krasnoyarsk, Primorsky, Stavropol, and Khabarovsk Territories; Jewish AO; Yamalo-Nenets AD; Amur, Volgograd, Magadan, Murmansk, Orenburg, Rostov, Sakhalin, and Chelyabinsk Regions);
- ***bottom snowstorm*** (Republics of Bashkortostan and Komi; Altai, Kamchatka, and Krasnoyarsk Territories; Volgograd, Magadan, Murmansk, Orenburg, Sakhalin, Ulyanovsk, and Chelyabinsk Regions);

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

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- ***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, 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);
- ***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);
- ***rock fall*** (Republic of Dagestan, North Ossetia-Alania);
- ***volcanic eruption*** (Kamchatka Territory).

3.1.2. Railway transport

More than 7% of all railway accidents and failures registered in the database were triggered by natural factors. Over 1992 to 2018, impacts of natural hazards 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-Nenezkii 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).

3.1.3. Air transport

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. Over 1992 to 2018, these events were registered in Moscow, Sakhalin, Irkutsk, Magadan, Murmansk, and Rostov Regions, Kamchatka, Khabarovsk, Krasnodar, and Krasnoyarsk Territories, and the Republic of Khakassia. The following impacts of natural hazards were revealed: strong winds, thunderstorms, heavy rains, snowfalls, snowstorms, sleets, runway icing, fog, and snow avalanches.

3.1.4. Water transport

The greatest contribution of natural factors to the accident rate was recorded for water transport. Almost 16% of all the water transport accidents registered in the database were caused by various natural hazards. The following impacts were revealed from 1992 to 2018: strong winds, storms, snowstorms, icing, thunderstorms, fog, and mist.

3.2. Risk of transport accidents and traffic disruptions

Occurrence frequencies of road, railway, air, and water accidents and failures due to natural hazard impacts at the level of Russian federal regions were estimated. 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. 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 assessment.

3.2.1. Automobile transport

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Risk of road accidents and traffic disruptions due to natural hazard impacts within the Russian federal regions is assessed. Occurrence frequencies (annual average numbers) of road accidents and traffic disruptions over 2013 to 2018 are used as risk indicators. 484 serious road accidents and traffic disruptions caused by impacts of natural hazards were taken into consideration. All the federal regions are divided into five groups by their risk levels. The resulting map is shown in the Figure 3. Regions of the Far East of Russia (Magadan and Sakhalin Regions, Khabarovsk Territory) and Krasnoyarsk Territory in the southern part of Central Siberia have the highest risk level. The road infrastructure in these regions is mostly affected by the above listed natural hazard impacts especially those of heavy snowfalls and snowstorms, ice phenomena, abnormally low air temperature, heavy rains, and debris flows.

3.2.2. Railway transport

Risk of railway accidents and traffic disruptions due to natural hazard impacts at the level of Russian federal regions is assessed. 63 serious events were taken into consideration. Occurrence frequencies (annual average numbers) of railway accidents and disruptions are used as risk indicators. All the federal regions are divided into three groups by their risk levels. The resulting map is shown in the Figure 4. Regions of the Far East (Sakhalin Region; Khabarovsk Territory) and Krasnodar Territory in the southern part of European Russia have 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

The number of air transport accidents and traffic disruptions was included in the calculation of the total risk of transport accidents and disruptions. 70 serious incidents were taken into consideration.

3.2.4. Water transport

Water transport accidents were also included in the calculation of the total risk of transport accidents and disruptions. 70 serious incidents were taken into consideration.

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 all the above listed types of accidents and disruptions over 2013 to 2018 were used as risk indicators; annual average numbers of these events were calculated for each federal region. All the federal regions were divided into five groups by their risk levels. The resulting map is shown in the Figure 5. Regions of the Far East (Magadan and Sakhalin Regions; Kamchatka, Khabarovsk, and Primorsky Territories), Krasnoyarsk Territory in the southern part of Central Siberia, and Krasnodar Territory in the southern part of European Russia have the highest level of risk. The transport infrastructure in these regions is mostly affected by the impacts of the above listed natural hazards.

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.

An annual average frequency of occurrences of severe events was chosen in this study among all possible methods for assessing risk. The index used combines both the probability and severity of the adverse 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 the total risk of transport accidents and traffic disruptions. The resulting maps were created and analyzed. The Magadan and Sakhalin Regions; Kamchatka, Khabarovsk, Krasnodar, Krasnoyarsk, and Primorsky Territories are characterized by the highest risk of transport accidents and traffic disruptions. More than five severe events per year during 2013-2018 were recorded in these regions (Figure 5). Murmansk, Orenburg, and Rostov Regions, Altai Territory, the Republic of North Ossetia (Alania) and Moscow also have a high risk level with an average probability of 3.0-4.5 events per year. It is in these regions that the

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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 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 (Geography…, 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 in the identified regions most at risk. In this regard, continuous monitoring and assessment of natural hazard impacts is especially relevant and important.

Only severe accidents 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.

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 confidential and property of Lomonosov Moscow State University and cannot be made available publicly.

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

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

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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	+	+	+	

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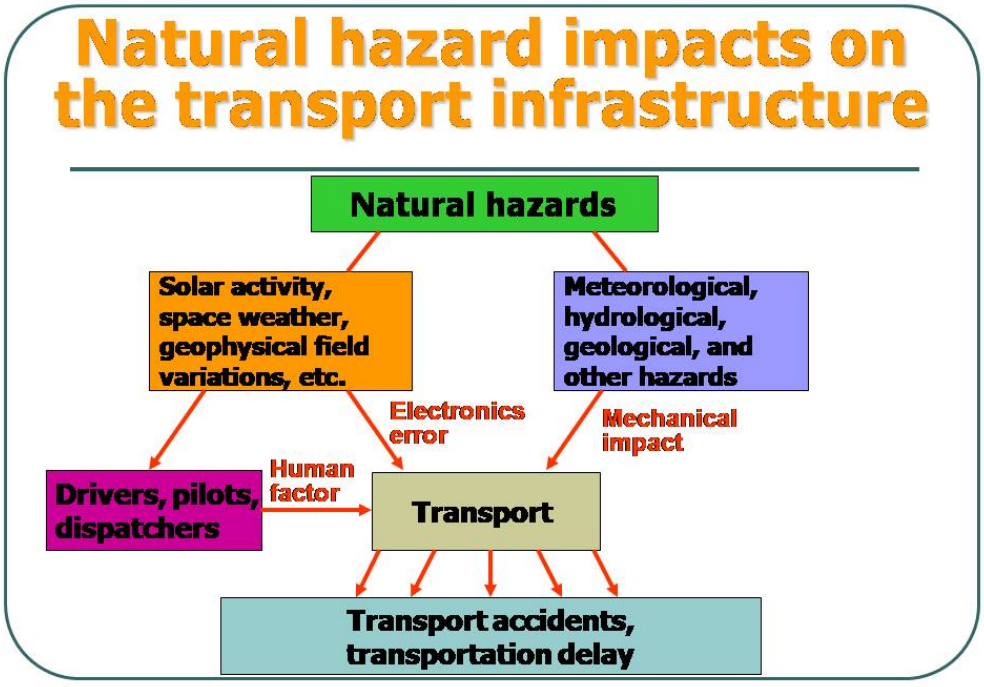

420 **Figure 1: Grouping of natural hazards based on their genesis and impacts on transport infrastructure**

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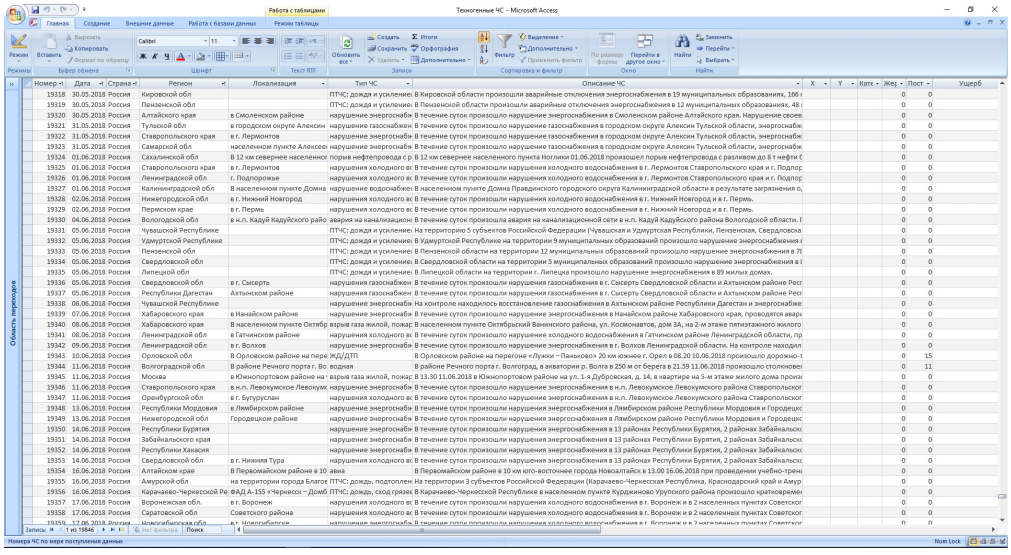

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Figure 2: Fragment of the database

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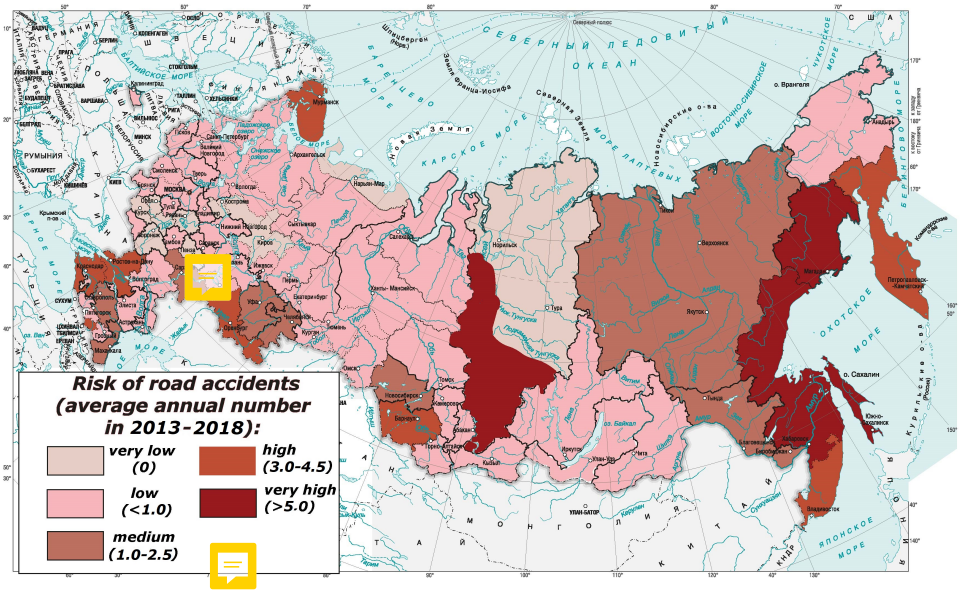

Figure 3: Risk of road accidents and traffic disruptions triggered by natural hazards in the RF (base map: © DIK - Publishing House Design. Information. Cartography)

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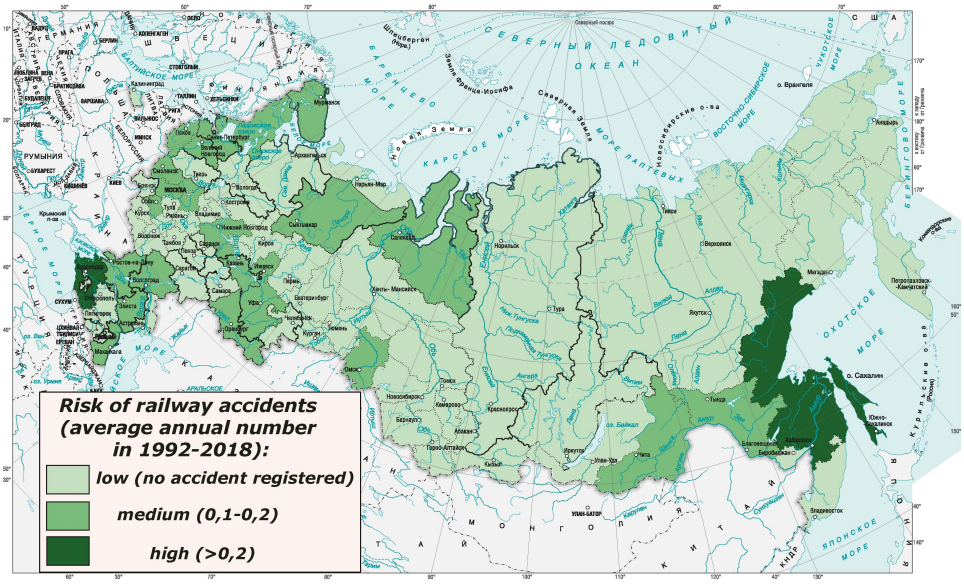

435 **Figure 4: Risk of railway accidents and traffic disruptions triggered by natural hazards in the RF (base map: © DIK - Publishing House Design. Information. Cartography)**

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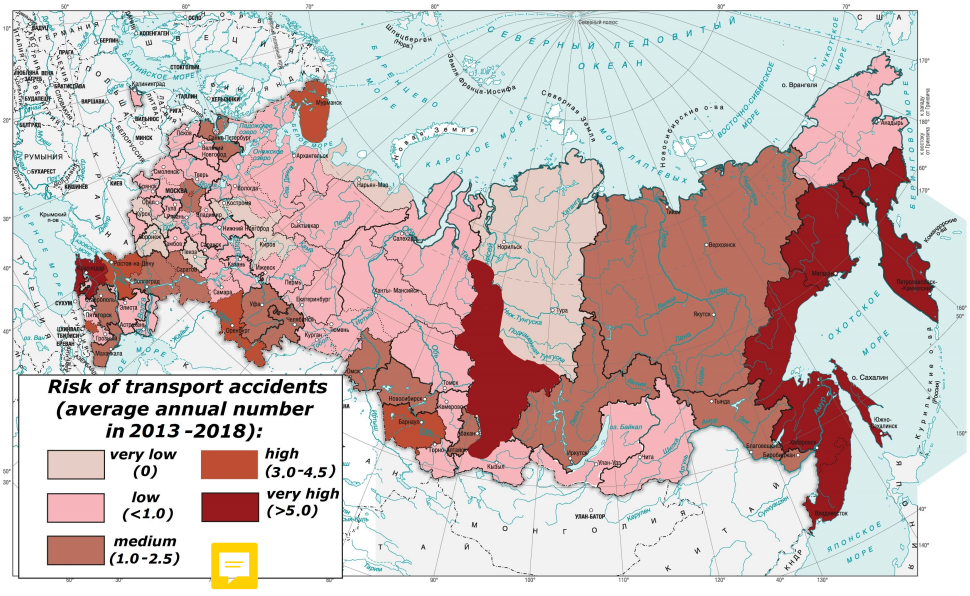

Figure 5: Risk of transport accidents and disruptions triggered by natural hazards in the RF (base map: © DIK - Publishing House Design. Information. Cartography)