Road accidents in Moscow: weather impact

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Abstract. We investigate the impact of weather conditions on the number and severity of road accidents in Moscow, Russia. Both seasonal and weekly variations in the number and severity of road accidents are considered. Two seasons of the year - the warm season (from May to September) and the cold season (from October to April) - are considered separately. Weather phenomena and meteorological parameters that trigger road accidents during both warm and cold seasons are identified. More meteorological events influencing an increase in the number and severity of road accidents are revealed for cold season rather than for warm months. The number and severity of road accidents are correlated with the weather conditions on a daily basis. In cold months, weather factors contribute to about 90% and in warm months – to about 80% of all the "emergency" and "super-emergency" days when the number of accidents or severity indicator is exceeding a seasonal average for this day of the week. Additionally, the weather conditions on days with serious road accidents are examined over a 23-year period. Total 82% of all the serious road accidents during the cold season and 61% during the warm one occur in difficult weather conditions. The most significant weather factors are found to be precipitation (especially heavy snowfall) in winter, as well as heavy rain and heat in summer. The bright sun, which serves as a factor reducing the driver's vision, leads to increasing in the total number of road accidents, but does not influence on their severity.
Key Words: road accident, weather condition, severity indicator, seasonal variation, weekly variation.

Introduction. Road transport is the most dangerous means of modern transportation in comparison to railway and air transport. Road safety is of primary concern around the world, especially in low-income-, upper-middle- and lower-middle-income countries, which record 28.5, 19.5 and 19.1 road deaths per 100 000 population, respectively (the global rate is 18.3) (WHO 2017). According to the World Health Organization (WHO), road injuries are among the world's top 10 causes of death, having killed 1.3 million people in 2015, about three-quarters (76%) of whom were men and boys (WHO 2017). According to Eurostat statistics, transport accidents remain the largest single cause of death among people aged 15 to 29. More than a quarter (27%) of world's deaths due to injuries is caused by road accidents.

In Russian Federation, upper middle-income economy country (based on World Bank classification), road crashes are responsible for the biggest part of deaths and injuries among all the 'technological' accidents; they rank second by the number of accidents after fires (Petrova 2005). In this regard, 125.7 road accidents with 15.8 deaths per 100 000 population are registered in Russia in 2015 (FSSS 2016a). Most critical fact is that 35% of all road traffic deaths occur among pedestrians and cyclists (Petrova 2013).

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. 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. According to the Federal Highway Administration (FHWA), U.S. Department of transportation, weather-related delay costs the truck industry of the USA $8 billion to $9 billion annually. Ice, snow, fog, heavy rain, wind, and extreme temperature events are the most correlated with reduced traffic speeds, with the largest decreases occurring during the first hour of storms (FHWA 2016).

A large number of studies devoted to the influence of weather conditions on the accident rates of motor vehicles were published over the last decades (Brodsky & Hakkert 1988; Edwards 1996; Rakha et al 2007; Andrey 2010; Andersson & Chapman 2011; Petrova 2011; Govorushko 2012; Bergel-Hayat et al 2013; Chakrabarty & Gupta 2013; Jaroszweski & McNamara 2014; Spasova & Dimitrov 2015; Shiryaeva 2016). All the authors agree that the weather is a major factor affecting road situation. However, none of the studies provides a comprehensive analysis of this influence.

Different studies estimate the contribution of the weather factor to accident rates differently. Vasil'ev (2004) concludes that adverse weather conditions are among of the active or indirect causes of traffic accidents in 50-80% and the main cause in 15-20% of cases. According to U.S. Department of transportation, about 28% of all highway crashes and 19% of all fatalities involve weather-related adverse road conditions as a factor (FHWA 2009).

Some studies are based on datasets, which take into account accident location and event information, but not consider characteristics and behavior of drivers (Petrova 2011). Andersson & Chapman (2011) investigate the relationship between temperature and severe road accidents in the West Midlands, UK. Yang et al (2013) evaluate road transport system vulnerability against meteorological disasters from the view of risk analysis theory. Bergel-Hayat et al (2013) focus on three climatic situations: rainfall, fair weather and frost for France, the Netherlands and the Athens region finding significant correlations between average weather variables and aggregate numbers of injury accidents. Other studies based on datasets with driver characteristics may lack some of the location information (Chakrabarty & Gupta 2013).

The weather parameters and types of meteorological events considered also vary depending on country and region. In France for instance, during the period 1990–2000, 14% of all injury accidents took place during rainy weather and 1% during fog, frost or snow/hail (Aron et al 2007). Many authors connect the maximum number of road accidents with precipitations. 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. Results by Brodsky & Hakkert (1988) with data from Israel and the United States did indicate that the added risk of an injury accident in rainy conditions can be two to three times greater than in dry weather. And when a rain follows a dry spell – the hazard could be even greater.

There are very few studies estimating the contribution of the weather factor to accident statistics for the territory of Russia. Some researchers suggest overall evaluations without explaining the methods for obtaining their results (Vasil'ev 2004). The only study dedicated to the Moscow region is by Durnev et al (2003), which assesses road accident risks in various weather conditions over 2000-2003. However, these authors use qualitative analysis only and their results are highly overestimated.

The main goal of this study is to reveal the contribution of weather conditions to road accidents in the case of Moscow that is the most populous city of Russia (with 12.4 million residents on 01.01.2017) and the northernmost and coldest megacity in the world. Unlike previous investigations cited above, all unfavorable weather conditions are taken into account. The daily number and severity of road accidents, their temporal – both seasonal and weekly – variations and their correlation with weather phenomena in Moscow region in 2013-2014 are analyzed. In addition, a variation of serious road accidents in Moscow over a 23-year period (1993-2015) is considered in connection with adverse weather conditions and meteorological parameters to find out the most significant weather factors.

Material and Method. At the end of 2015, Russia has 1480.8 thousand km of public roads, 70.6% of them, or 1045.3 thousand km, are hard-surface roads (FSSS 2016c). With a large area of the country, the road density is the lowest of all the G8 countries, equal to 86.5 km per 1,000 km^2 (FSSS 2016b). However, it is much higher in the densely populated regions of the European part of Russia. Moscow, which is the capital federal region situated in central Russia, has the highest density of hard-surface roads (including

streets) among all the federal regions (the highest level units of the administrative division of the Russian Federation), equal to 2453 km per 1,000 km^2 (FSSS 2016a).

By its territorial expansion on July 1, 2012 southwest into the Moscow Oblast (Moscow region), the total area of Moscow more than doubled, going now to 2561.5 км². The share of urban built-up area accounts to 19%, suburban built-up – to 16%, rural built-up – to 1%, and urbanized open space – to 38%. The share of built-up area in Moscow occupied by roads is 19% that is similar to their share in Europe, but slightly less than the world's average (21%). Almost all roads of Moscow are hard-surface roads (99.8%).

To compare the car transport accessibility of federal regions of Russia, we have created a map (Figure 1) using the Engel - Yuzuru Kato index (Ushakov & Vasilevsky 1971). The index is calculated according to the equation: $D = L / \sqrt{S \times H}$, where L is the total length of hard-surface roads in each federal region (km), S – area of a region (hundreds km^2), H – population (tens of thousands people).

The European part of Russia, except its northeast part, is relatively well equipped with hard-surface roads. In the Asian part of Russia, only some areas in the south-western and south-eastern regions have a satisfactory network of hard-surface roads (with D > 20). The Engel - Yuzuru-Kato index for the whole area of the country is rather low, equal to only 24.5; for Moscow it is more than twenty times higher and accounts to 560.5 because of the highest street density in the city.

There are more than 53.3 million motor vehicles registered in Russia, including 41.2 million cars (77.3%), 2.5 million motorized 2- and 3-wheelers and 4-wheeled light vehicles, more than 6.0 million heavy trucks, and 886.9 thousand buses (RSD 2014). The highest numbers of registered cars per 1,000 inhabitants have the Far-Eastern regions of Russia such as Kamchatskii and Primorskii Territories with 486.9 and 388.8 cars per 1,000 inhabitants in 2015, respectively. Moscow, with 291 cars per 1,000 inhabitants, is just slightly above the national average of 288.8 (FSSS 2016a). There are over 5.5 million cars registered in the city. As for the number of road accidents and road deaths, Moscow is the 77th and 85th among all the 85 federal regions, respectively, with 84.8 accidents and 5.5 deaths per 100 000 population (FSSS 2016a).

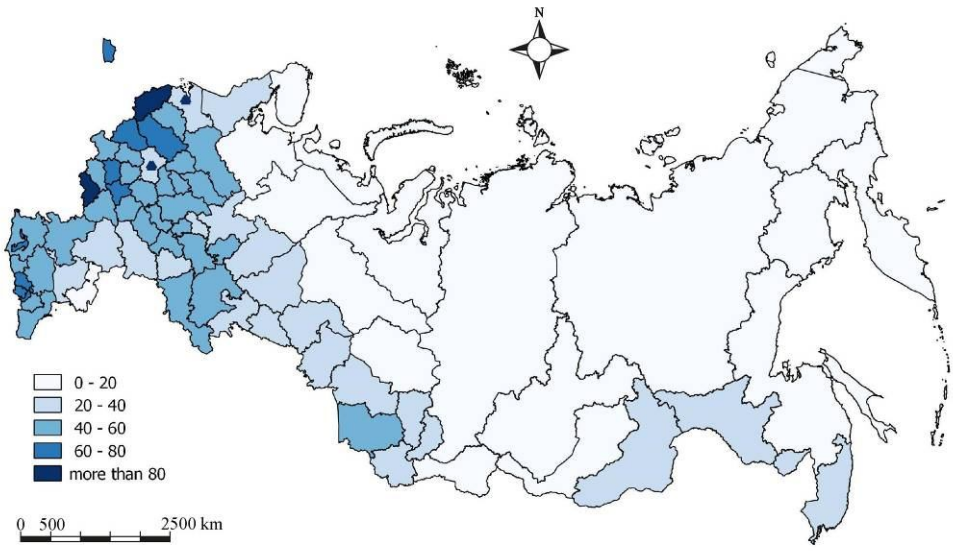


Figure 1. Car transport accessibility of federal regions of Russia according to the Engel-Yuzuru Kato index for hard-surface roads.

Official statistics of the Road Safety Department (RSD), the Ministry of Internal Affairs of the Russian Federation as well as information of the Federal State Statistics Service (FSSS) were mainly used for this study. Meteorological data of the Moscow weather station "VDNKh" (located in the northern part of Moscow) were taken from the All-Russian Research Institute of Hydrometeorological Information - World Data Centre

(RIHMI-WDC). Various meteorological archives from 600 Russian weather stations are freely available on the website of the RIHMI-WDC (http: www.meteo.ru).

Additionally, an electronic database of technological and natural-technological accidents including road accidents that occurred in the Russian Federation since 1992 was used.

The database is created by Petrova (2008). Official daily reports of the Russian Ministry of Emergency and mass media news reports serve as initial source of the information. These reports are publicly available. Occurrence time and location, type of accident, number of deaths and injuries, economic and ecological losses as well as a probable cause of any accident, if available, are registered in the database; a short description of each event is also recorded. Of course, the database cannot claim complete coverage of all road accidents that are too numerous to be listed. Only serious road traffic crashes causing five or more fatalities or over ten injuries, which are reported by the Ministry of Emergency and draw attention of mass media, will be recorded there. However, the database allows us to analyze some information that is not usually included into the official statistics, for example, about the impact of adverse weather condition and some other factors.

Firstly, the road police data of daily road accidents in Moscow from January 2013 to October 2014 (i.e. all 12 months of 2013 and 10 months of 2014) were analyzed. In this analysis, the timeframe was limited to only 22 months due to data availability. These data included the daily number of road accidents as well as the number of deaths and injuries caused by the reported accidents.

The severity indicator (SI) calculated as the number of deaths per 100 casualties (the total number of deaths and injuries) was used to estimate the severity of accident consequences.

Seasonal and weekly variations of road accidents were examined to take account of differences in traffic volumes between months of the year and days of week. Two seasons of the year – the warm season (from May to September) and the cold season (from October to April) were considered separately to exclude an intra-annual variation in the population mobility. A daily average number of accidents recorded by the road police of Moscow during the warm and cold seasons accounted to 34 and 29, respectively. These are only injury accidents or accidents with insured damages. The total number of road accidents is higher because drivers are not required to report accidents to the police if no one was injured and an agreement about compensation is achieved, but the variation is approximately the same.

The further calculation procedure is as follows: for each week (from Monday to Sunday) and separately holidays, a weekly average number of accidents and SI is calculated; for each day, a deviation from the weekly average for this week – a daily variation – is considered. A daily variation can be both positive, when the number of accidents or SI on this day is higher than a weekly average, and negative – in the opposite case. A seasonal average variation for each day of the week for the warm (May to September) and cold (October to April) seasons is calculated separately. If the number of accidents or SI on a particular day exceeds the seasonal average for this day of the week, then this day is considered as an "emergency" day; if it is higher than the seasonal average plus σ (standard deviation) – as a "super-emergency" day. Further, the proportion of "emergency" and "super-emergency" days for different weather conditions is calculated. The method allows identifying the contribution of each weather factor among other causes of accidents. If the number of accidents or SI on a particular day exceeds a critical value for this day of the week, this situation can be attributed to weather factors.

The database of technological accidents is also analyzed using similar methodology. The database includes information about 148 serious road accidents in Moscow over 1993-2015. For each day with accident, the following weather conditions are considered: fog, the air temperature transition through 0° C, daily precipitation less than 5 mm, daily precipitation more than 5 mm, snowfall with intensity of 0-2 cm, 2-5 cm and over 5 cm snow per day, the air temperature exceeding +30° C, as well as such phenomena as glassy ice on the ground, freezing rain, rain, and sleet. The applied

categories for rainfall and snowfall are based on previous findings (Shiryaeva 2016). The proportion of accidents on days with at least one of above weather parameters and phenomena are calculated for cold and warm seasons separately. Then, the proportion of days with accidents under different weather conditions are compared to the total percentage of days with these weather conditions during warm and cold seasons over a 23-year period (1993-2015).

Results and Discussion. As analysis of the database of technological and natural-technological accidents revealed, about 3% of all the serious road accidents with registered cause of accident were triggered by various natural factors. The most important among these natural factors were meteorological hazards and adverse weather conditions such as snowfall and snowstorm, icy condition of road, rain, fog, mist, and drizzle. However for the most part of accidents the weather conditions were not recorded by the road police. Thus, we had to analyze additionally the weather reports on days with accidents using the information of the Moscow weather station mentioned above.

Seasonal variation. About 200,000 road traffic crashes with 27,000 deaths and 250,000 injuries are registered in Russia annually (RSD 2014). All three road (un-)safety indicators are subject to seasonal variations, having the highest numbers of road accidents, road deaths and injuries in summer, especially in August, and the lowest ones during the cold "off-season", especially in February (Figure 2). This fact can be explained by the increasing mobility of the population during the "peak season" throughout summer holidays that is characterized by increasing driving, cycling, and walking in warmer summer months. Adverse weather conditions such as heavy rain, snowfall, blizzard, foggy or icing roads, etc., additionally trigger road crashes, especially during the "shoulder season" in the late autumn, in winter and early spring.

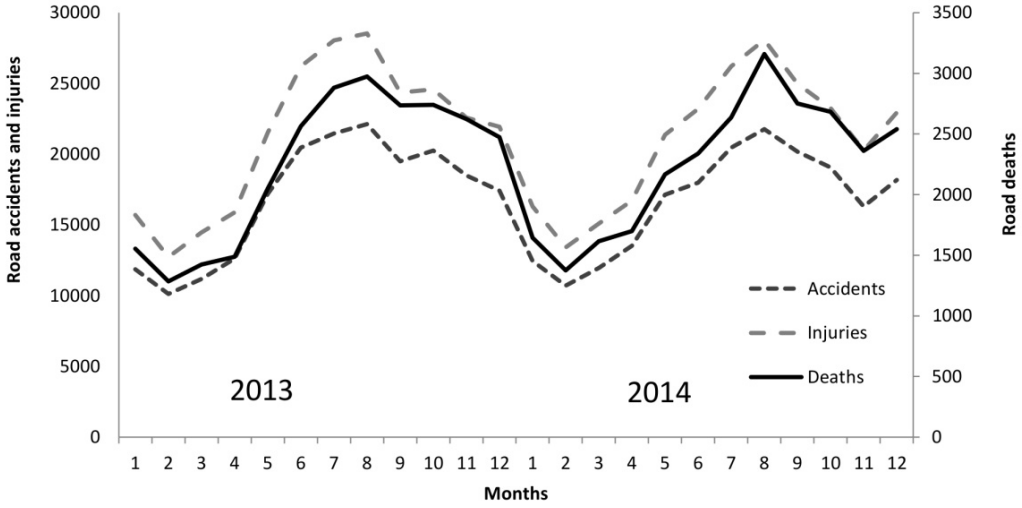
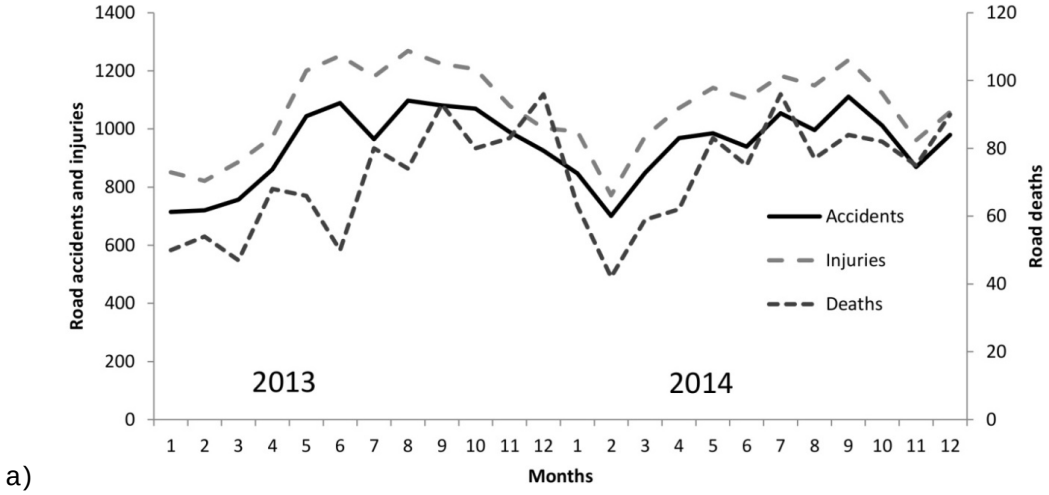


Figure 2. Seasonal variation in the number of road accidents, deaths and injuries in Russia (aggregated data from RSD 2013-2014).

Seasonal variation in the number of road accidents, road deaths and injuries in Moscow is similar to that reported above for Russia as a whole, with a maximum in summer and a minimum in the winter months (Figure 3a). First of all, this situation may be explained by increasing in the number of motor vehicles on Moscow roads during the warm season: many people use cars primarily to visit their country houses (seasonal or year-round second home, also called "dacha"), which are typical for the most Russian large cities, especially for Moscow. On the other hand, many people avoid travelling by car in winter due to difficult weather conditions.

However, there are almost no seasonal differences in SI variation (Figure 3b), because this indicator is calculated as the number of road deaths normalized to the total number of casualties, which, in its turn, is related to the number of accidents. Thus, the seasonal SI variation is leveled. Important to note, the value of SI for Moscow is less

than for the country as a whole. This may be due to a better level of medical services in the capital.



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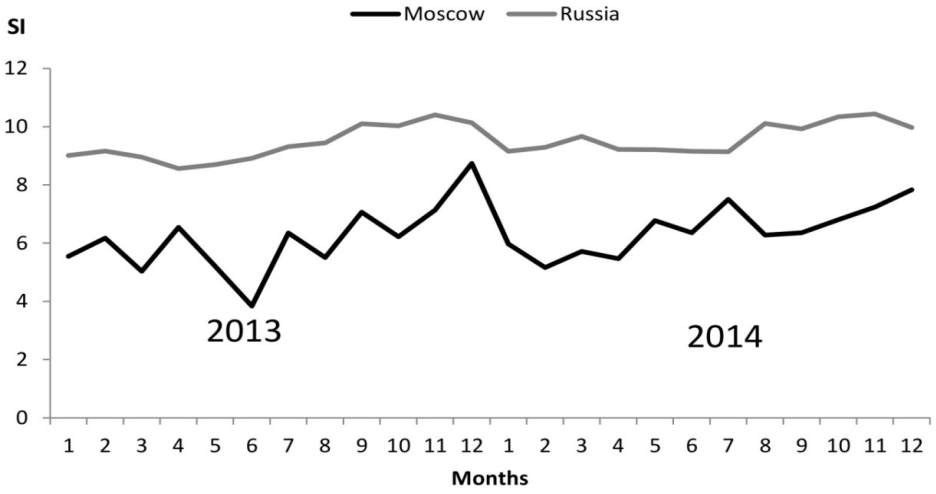


b)

Figure 3. Monthly average numbers of road accidents, deaths and injuries (a) and severity indicator (b) in Moscow and Russian Federation (calculated from RSD 2013-2014).

Table 1 presents the daily average numbers of road accidents, road deaths and injuries as well as the severity indicator of accident consequences during both the warm and cold seasons of the study period (January 2013 to October 2014) in Moscow. The severity indicator for both seasons is the same, although we can see seasonal differences in the number of road accidents, road deaths and injuries. The timeframe of two years is too short to talk about seasonality in the accident parameters, but other authors (Zhulev & Gir'ko 1997) as well as reports of the Road Safety Department of Moscow also confirm an increase in the accident number during the warm months.

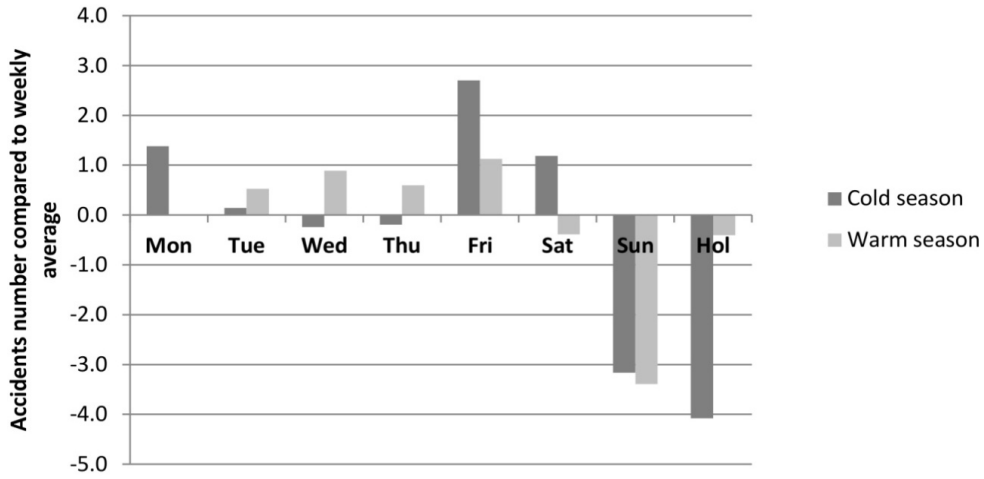
Table 1

Seasonal variation in the daily number of road accidents, deaths and injuries in Moscow (calculated from RSD 2013-2014)

	Number of	*Monthly average*	*Standard deviation*	*Max*	*Min*
Cold months	Accidents	29	8	51	7
	Road deaths	2	2	9	0
	Road injuries	32	9	63	10
	SI	6	5	23	0
Warm months	Accidents	34	7	54	13
	Road deaths	3	2	20	0
	Road injuries	39	9	87	16
	SI	6	4	21	0

Important to note, the seasonality in road accidents can differ in other cities and regions. For example, according to Spasova (2012), the highest number of road accidents in Sofia (Bulgaria) occurs in December, followed by November and October; and the lowest one occurs in August, followed by July and April.

Weekly variation. The weekly variation in the number of road accidents is less evident during the warm season than during the cold one – with a small maximum on Friday and a strong minimum on Sunday (Figure 4a). The minimum on public holidays in the late spring and early summer is insignificant in comparison to that during the cold season (January 1 to 7, May 1, May 9, and June 12 are National holidays in Russia. If an annual public holiday falls on a Tuesday, the Monday will be declared a bridge holiday and a Saturday will be declared a working day as compensation); apparently, this situation is explained by a larger number of visits to country houses on weekends and public holidays in May and June. As for winter weekends as well as Christmas and New Year's holidays, the most people traditionally spend them at home or use public transport for long distance trips. The maximum of accidents on Monday and Friday can be explained by pendulum migrations of working people who come to Moscow on Monday from the Moscow region and return home on Friday for weekend.



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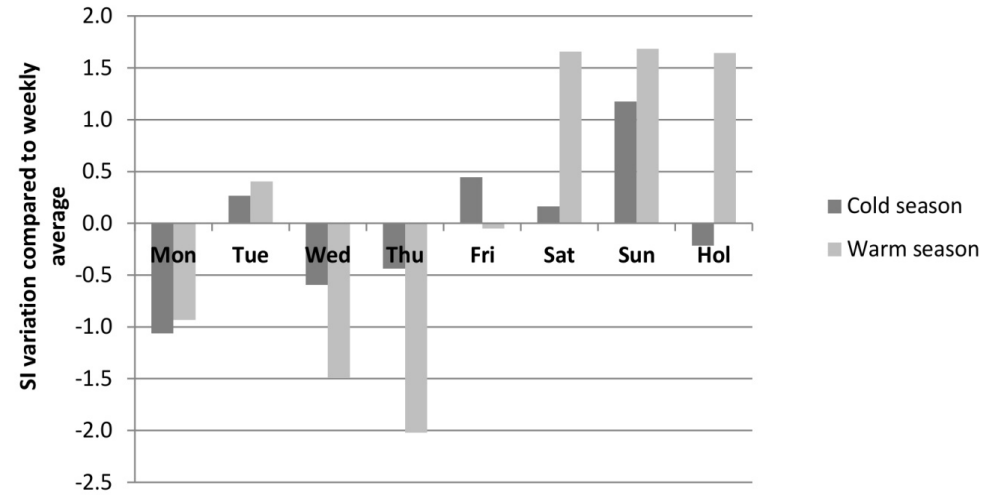

b)

Figure 4. Weekly variation in the number of road accidents (a) and severity indicator (b) during the cold and warm seasons in Moscow (calculated from RSD 2013-2014).

In opposite, the weekly SI variation is more evident during the warm season than during the cold one (Figure 4b). Although, in general, it is similar for both seasons: with SI increasing on weekends and decreasing on all weekdays, except Tuesday. The summer maximum of the SI growth on weekends and holidays is due to seasonal increase in the population mobility (by driving, cycling, and walking) along with higher speeds and drunk driving.

Weather influence. Table 2 shows meteorological phenomena that affect an increase and decrease in the number of road accidents as found by Shiryaeva (2016) and in the severity of their consequences. Table 2 includes all weather events (and only those weather events) that may influence on road accident parameters. There are much more weather events influencing the frequency of occurrence of traffic accidents during the cold season than during the warm months.

Table 2

Seasonal variation of "emergency" and "super-emergency" days in different weather conditions

Weather event	*An increase of*		*A decrease of*	
	"Emergency" days, %	*"Super-emergency" days, %*	*"Emergency" days, %*	*"Super-emergency" days, %*
	by the road accident number		*by the severity indicator*	
		Cold season		
Snowfall < 2 cm	-21	-17	-4	-6
Snowfall 2-5 cm	16	6	-9	-8
Snowfall > 5 cm	6	7	14	18
Fog	6	1	-5	0
Sleet	-10	-3	-5	-17
Drizzle	12	4	-2	-10
Blizzard	3	-1	1	1
Temperature transition through 0°C	2	-2	1	-1
Cloudless sky	11	8	2	-1
		Warm season		
Daily precipitation > 5 mm	-18	-4	+1	+8
Daily precipitation < 5 mm	+2	0	-4	-6
Fog	-4	-4	-2	0
Maximum air temperature > +30°C	+10	+8	+19	+7
Thunderstorm	-16	-5	+3	-2
Cloudless sky	+16	+6	+4	0

In the cold season, the number of accidents increases mostly in drizzle, fog, moderate snowfall (2-5 cm snow per day), but also by a cloudless sky, when the bright sun serves as a factor reducing the driver's vision and attention. In opposite, by light snowfalls (up to 2 cm snow per day) as well as by rain with snow there is a significant decrease in the accident rate. This finding can be explained by the fact that in such difficult weather conditions many people avoid driving or drive more carefully. The accident severity increases significantly in heavy snowfalls, while the number of accidents does not grow much. Some other adverse weather phenomena often lead to SI reduction, which is, apparently, linked to decreasing speed of driving. In total, the weather factors cause 89% of all the "emergency" days (by both the number and severity of accidents), 92% of all the "super-emergency" days by the number and 88% – by the severity of accidents.

In the warm season, the number of "emergency" and "super-emergency" days increases under the hot weather (when the maximum air temperature exceeds +30°C) by 10% and 8%, respectively. The accident severity also increases significantly with high temperatures. This finding can be explained by a decreasing concentration of attention and declining drivers' health in these conditions.

The bright sun in a cloudless sky leads to an increase in the number of "emergency" days by 16% in terms of the number of accidents and by 4% in their severity. Weak precipitation and fog do not lead to a significant change in the accident rate. In total, the weather factor is involved in 79% of the "emergency" days by the accident number and in 82% of days by the severity of accident consequences; on "super-emergency" days the contribution of the weather factor accounts to 81% and 80%, respectively.

Some other results are obtained from the analysis of the database for serious accidents (Table 3). During the cold season, the accident rate increases under the cloudless sky and, most strongly, with precipitation: the proportion of days with serious road accidents in these weather conditions exceeds the total proportion of days with these conditions by more than 4%. However, the type of precipitation does not play a significant role; a slightly more important is snow, especially heavy snowfalls, and freezing rain. The number of serious road accidents decreases slightly in icy conditions, apparently, due to more careful driving. During the warm season, the number of serious road accidents increases in hot weather, under the cloudless sky and heavy rainfall. In opposite, it decreases with weak rainfall.

Total 82% of serious road accidents occurred in complicated weather conditions in the cold season and 62% – in warm months during the study period of 1993-2015.

Table 3

The proportion of serious road accidents in adverse weather conditions

Weather event	*Proportion of accidents*	*Proportion of days with this weather event*	*Difference*
	Cold season		
Precipitation	65%	54%	11%
Snow	38%	34%	4%
Rain	19%	17%	2%
Sleet	20%	18%	2%
Various precipitation on the same day	16%	13%	3%
Snowfall 0.1-2 cm	20%	18%	2%
Snowfall 2-5 cm	9%	11%	-2%
Snowfall > 5 cm	9%	4%	5%
Freezing rain	5%	1%	4%
Fog	2%	3%	-1%
Cloudless sky	25%	21%	4%
Temperature transition through 0°C	30%	31%	-1%
Glassy ice on the ground	28%	31%	-3%
	Warm season		
Rain	50%	50%	0%
Daily precipitation 0.1-5 mm	27%	34%	-7%
Daily precipitation > 5 mm	23%	15%	8%
Maximum air temperature > +30°C	8%	3%	5%
Fog	5%	4%	1%
Cloudless sky	34%	31%	3%

Conclusions. The authors have analyzed the daily number of road accidents, road deaths and injuries reported by the road police of Moscow in 2013-2014 as well as the information collected in the database of serious road accidents over a 23-year period (1993-2015). The accident parameters have been considered in connection with adverse weather conditions and meteorological parameters by analyzing the weather reports on days with accidents. The results obtained from the analysis of both data sets are difficult to compare quantitatively due to different approaches and types of data. However our principal findings from both analyses are similar. They show that weather conditions influence on both the number and severity of road accidents, although the weather is not the main factor that contribute to the accident rate in such a large metropolis as Moscow.

The contribution of weather conditions is leveled by the more careful driving in difficult weather, so it is very difficult to evaluate the resulting impact.

Unfortunately, data on traffic volumes and other traffic characteristics as well as car insurance claim data are not available to cross validate our data sets.

Nevertheless, the authors can state that the number and severity of accidents increases significantly with precipitation during the cold season, while the type of precipitation does not play a big role, but the intensity of precipitation matters. More important is snow (especially heavy snowfalls) and freezing rain. The number of accidents also increases under the cloudless sky due to decreasing concentration of drivers' attention. The other weather events are not very important. In total, there are much more weather events influencing the accident parameters during the cold season than during the warm one. The weather factors cause about 90% of all the "emergency" and "super-emergency" days by both the number and severity of accidents in the cold season and about 80% in the warm months.

The timeframe of only 22 months (all 12 months of 2013 and 10 months of 2014) in the first data set is too short to talk about seasonality in the accident parameters. However other authors as well as reports of the Road Safety Department of Moscow also confirm our findings that show an increase in the accident number during the warm months.

The second data set of serious road accidents includes information over a 23-year period, which allows revealing seasonality. During the warm season, the number of serious road accidents and their severity are increasing in heavy rainfall, while the total number of accidents is decreasing. With weak precipitation, the number of serious road accidents and SI are decreasing due to the more careful driving. The number of accidents also increases by the hot weather and cloudless sky. The bright sun, which serves as a factor reducing the driver's vision, leads to increasing in the total number of road accidents, but does not influence on their severity. Total 82% of serious road accidents occur in complicated weather conditions in the cold season and 62% – in warm months.

The most significant weather factors during both cold and warm seasons were revealed. These findings may apply to other large urban areas in similar climate conditions. The methodology proposed in this study can be also used for the weather factor investigations in other regions. These methods allow revealing the contribution of the weather factor among other road accident factors using "emergency' and "super-emergency" days' calculation procedure as described in the methods' section.

In the future research, the influence of weather factors on road accident parameters should be tested on longer data series.

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