



# Understanding the influence of climate elements on traffic: the wind impact approach

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## Abstract

Due to intense highway congestion in Europe, increased percentage of highway accidents, as well as mortality rate, safety is an imperative in highway planning and design. Highway design safety standards have been researched extensively, but not enough attention has been paid to the surrounding environmental impacts, foremost climate elements. Therefore, this research attempts to understand the least researched climate element — the wind, and its impact on highway safety. The highway landscape falls under the category of the wind impacts that can cause significant problems for the drivers throughout the year. The values for wind direction, frequency, and intensity were taken from the CARPATCLIM database and Meteorological Annuals. The evaluation of homogenized and harmonized set of data on a daily basis for a 20-year period documented a variety of high-intensity wind impacts on the researched highway. By using the ArcGIS and the interpolation method, it has been clearly observed at which points the effect of intense winds was present the most. In order to understand the overall problem of the impacts of winds on the researched highway, the fieldwork was conducted in various weather conditions. The checklists photo-documented and qualitatively described the observed extreme wind events (alone or combined with one more climate element). All calculated and collected data were observed and the image of the current situation was provided, and the proposal for control of the impact of wind using an adequate vegetation assembly (windbreaks) and landscape design has been offered.

## 1 Introduction

General Assembly of the United Nations adopted several resolutions regarding traffic safety, but the one adopted in 2010 — *Improving global road safety (A/RES/64/255)*, particularly stands out. This resolution marked the period 2011–2020 as a *Decade of Action for Road Safety* with the aim of stabilizing and halving the estimated number of road traffic deaths. One of the ideas driving the abovementioned resolution is to reach the aim by consistently conducting scientific and professional studies through various activities on a national, regional, and global level. According to “Official Gazette RS” no. 64/2015, Serbia falls into the category of European countries that generally accept the idea of reducing the number of road traffic deaths, but it does not have a strongly built protection system (since there are significant oscillations in the number of road traffic deaths). The increasing trend in the number of road traffic casualties in Serbia can be changed by organized work and implementation of well-designed and coordinated measures. With the adoption of document *Strategy on Road Safety in Republic of Serbia for the Period 2015–2020* (“Official Gazette RS” no. 64/2015),

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Serbia clearly and unequivocally accepted that traffic accidents are not a coincidence, but rather a consequence of a fault in the man-vehicle-road-environment system.

Road construction requires timely and relevant physical-geographical surveys — to avoid exposing the future road to landslides, water retention, high-intensity wind, snowdrifts, floods, etc. (Lovelace 2021; Đorđević 2004). As regards the impact of climate elements, highway landscape must not be regarded as a uniform and single landscape entity. Every highway section is specific and it has to be considered as separate in terms of the impact of climate elements (Sentić et al. 2018). This is necessary if we want to go even further and to obtain rational data about which highway subsections should be considered unsafe and in order to reach adequate landscape design as a measure of traffic safety control (Lorenz 1980; Sentić and Đorđević 2019). In developed European countries, wider approach to the highway landscape design is considered a must in order to increase traffic safety (Löfgren et al. 2018), while in Serbia, this issue is viewed as a craze or a problem that should be resolved by a third party (“Official Gazette RS”, no. 64/2015).

In this research, using various methodologies, the impact of wind on road traffic safety has been examined. The aim was to point out the danger of high-intensity winds occurring during certain periods of the year. The research demonstrates how adequate landscaping can control wind hazards and the road traffic safety as well.

Work structure is organized as follows. Section 2 provides an overview of relevant research on the impact of climate elements on traffic safety with particular reference to the wind. Section 3 describes the researched area, followed by Section 4, which describes the work methodology. The results are presented in Section 5, divided by the methodological steps used in the study. The final stage of the research shows the proposal for the landscape design of a highway exposed to high-intensity winds. Section 6 discusses the results obtained in the study. The main conclusions and considerations for future research are outlined in Section 7.

## 2 Literature review

The improvement of road construction caused an increase in the number of motor vehicles and their speed. The safety of road traffic becomes increasingly important (Forman et al. 2003). Notions about traffic safety have mostly been associated with the knowledge in the field of traffic construction, without delving into the influence of the surrounding landscape (Pérez de la Cruz et al. 1995). Also, there was never a discussion about the not so visible, but very sensitive effects of climate elements on traffic safety, except in case of extreme events (Theofilatos and Yannis 2014).

The importance of the impact of weather conditions on traffic safety (the number of road accidents that they cause) can be found in scientific papers by several European authors (Perry and Symons 1994; Edwards 1996; Hassan and Barker 1999; Musk 2003; Hermans et al. 2006; Bergel-Hayat et al. 2013; Tsapakis et al. 2013). Interest in this topic began to develop in the 1960s, while a considerable rise was noticed in the early twenty-first century. As authors Hassan and Barker (1999) underline, traffic specialists are well aware of the seasonal variation in traffic activity, but it has been noted that the knowledge regarding the impact of all climate elements on traffic flow is far from complete. Climate conditions may not be the most common reason for traffic accidents, but they should not be neglected, as they can create very dangerous driving conditions (Edwards 1996; Hassan and Barker 1999; Chapman 2007; Kim 2018; Wang et al. 2020).

Most of the information in the literature regarding the impact of climate elements on the traffic flow was given at a macro-level (mean values of annual or monthly data), while at a micro-level (surveys based on daily values for specially selected locations), the data are scarce (Edwards 1996; Hermans et al. 2006; Chen et al. 2018). According to the authors (Hassan and Barker 1999; Hermans et al. 2006), traffic activities on a macro-level can be used in the process of passing the laws in transport planning. Evaluation of daily values of traffic activity takes a deeper approach to the issue of influence of climate elements on the traffic safety (Eisenberg 2004). This can be used to improve the future new roads planning and construction process (Musk 2003).

Climate elements that have a major impact on traffic safety include rain, snow, ice, fog, temperature, and wind (Fridstrøm et al. 1995; Hassan and Barker 1999; Chapman 2007; Theofilatos and Yannis 2014). Their effects are even stronger when they occur in combination with one another (Musk 2003). Moreover, the global climate change scenarios indicate the possibility of more frequent occurrences of climate extremes (storms, extreme heat, extreme wind gusts, etc.) and their influence on the environment and human activities (Koetse and Rietveld 2009; IPCC 2014; Lakatos et al. 2016; Deng and Zhu 2021; Oscar Júnior and de Assis Mendonça 2021). All this supports the need for more detailed study of the relation between the climate elements and the traffic safety.

Many authors wrote about the importance of wind from the standpoint of generating electric power (Frandsen et al. 2006), the impact on vegetation (Sellier and Fourcaud 2009; Mitchell 2013), and the impact on people’s lives (Knopper and Christopher 2011), but very few have discussed the impact on traffic safety (Hermans et al. 2006; Theofilatos and Yannis 2014). There is no significant database from which to draw lessons on how to design safe windy highway landscapes. Therefore, any research regarding this issue represents a major contribution to the scientific world. The

attention of researchers (Baker and Reynolds 1992; Perry and Symons 1994; Edwards 1996) was attracted by a severe storm caused by the wind in the British Isles in October 1987 and then again in January 1990, when a large number of fatal traffic accidents was recorded, and these are, at the same time, some of the few studies conducted on the effect of the wind on traffic safety.

According to Perry and Symons (1994) and Forman et al. (2003), wind can significantly upset the drivers directly, by turning or pushing their vehicles off the roadway or indirectly, by drifting and accumulating soil particles, snow, rain, etc. on the road. If trees are planted just near the road, wind can tear them or break branches, which can be a significant obstacle for drivers on the road (Koetse and Rietveld 2009). Baker and Reynolds (1992) and Hermans et al. (2006) underlined that when the wind reaches an intensity of approximately 13–15 m/s, it obstructs the movement of the vehicles. On the other hand, when it reaches intensity of 20 m/s, it can turn over a vehicle on the road which then poses another kind of danger for the drivers. The authors (Baker and Reynolds 1992; Perry and Symons 1994; Hermans et al. 2006) further emphasized that it is sufficient for winds of these intensities to occur only for a few days during the year, or several hours during the day, in order to have devastating effects with fatal outcomes. Other authors (Hassan and Barker 1999; Eisenberg 2004; Dupont and Martensen 2007; Bergel-Hayat et al. 2013) confirmed that large oscillations in meteorological conditions can occur, but extremes on a daily basis are caused by atypical weather in the season, and their impact on traffic safety is not negligible.

The greatest danger for drivers on the road is crosswind (Perry and Symons 1994). In order to increase the traffic safety, more recent researches focus on identifying strong crosswinds by using mobile mapping technologies (Chen et al. 2010; Pu et al. 2018). These modern technologies are used for collecting data on crosswind speed in specific locations for moving vehicles (Chen et al. 2010). Considering that its distribution varies in both spatial and time domains, it is necessary to identify specific locations in which there is a high possibility of strong crosswind and where safety measures should be implemented. In the last few years there have been some studies focusing on this issue (Chen et al. 2018; Pu et al. 2018). Researchers Shin and Lee (2014) also showed that traffic safety is a worldwide issue that affects human life by taking it one step further and doing a reliability-based analysis of road vehicle accidents and the optimization of roadway radius and speed limit design based on vehicle dynamics, mainly focusing on windy environments. Windy traffic environments were studied by Maruyama and Yamazaki (2006) as well. The authors have investigated the moving stability of a vehicle under seismic motion based on both numerical simulation and virtual experiments using a driving simulator.

All of this shows that traffic safety is broad and multi-disciplinary issue and that it arouses attention of scientists working in various disciplines. The mentioned issue needs to be seen from different aspects of view so that future highway projects and traffic safety assessments can be improved.

Therefore, afforestation of the windy roadside is more than necessary. In this way, protection from strong steady winds is provided, as well as protection from individual crosswinds (Alemu 2016). Depending on the density, the vegetation belt (windbreak) can be used to protect the road from excessive snowdrifts, dust, etc. (Lorenz 1980). A properly formed windbreak provides protection in the area at a distance of 20 times the height of the largest tree in the assembly, in the area on the leeward side, as well as 5–10 times the height of the largest tree on the windward side (Alemu 2016). The role of windbreaks in traffic planning has been addressed by other authors as well (Wight and Straight 2015).

### 3 The study area

This paper presents the study of wind impact on traffic safety at a specific highway route in Serbia. This route connects two largest cities in the country, Belgrade and Novi Sad. Therefore, the traffic is very heavy. The researched highway route is located in the northern part of the Republic of Serbia, in the Autonomous Province of Vojvodina (Fig. 1), and geographically, it belongs to the Pannonian Plain. It is an integral part of several important European transport-infrastructure corridors, such as European Road E75, Pan-European Corridor X (Section Xb) and it is a part of the TEM Road Network (Trans European Motorways). As such, it represents an important connection of roads in Europe, and it can be a model by which highway landscapes of this type can be designed.

During the highway construction, the terrain was raised by several meters from its original level, so the entire route was constructed on a significant embankment (Sentić and Dorđević 2019). This makes the traffic route itself additionally exposed to wind, snowdrifts, earth, and other loose material deposits on the highway pavement.

The total length of the researched highway route is 65,460 m (“Official Gazette RS” no. 69/03, 143/14). It can be split into several landscape subsections (Fig. 2). The subsection from Belgrade to Indija is constructed on a shallow embankment on flat terrain, so the high speeds can be achieved easily. Furthermore, wavy terrain exposed to landslides is present on the subsection from Indija to the crossing across the Danube River (the bridge near Beška). The following subsection from Kovilj to the exit to Novi Sad has the characteristics of a plain route (“Official Gazette RS” no. 69/03, 143/14).

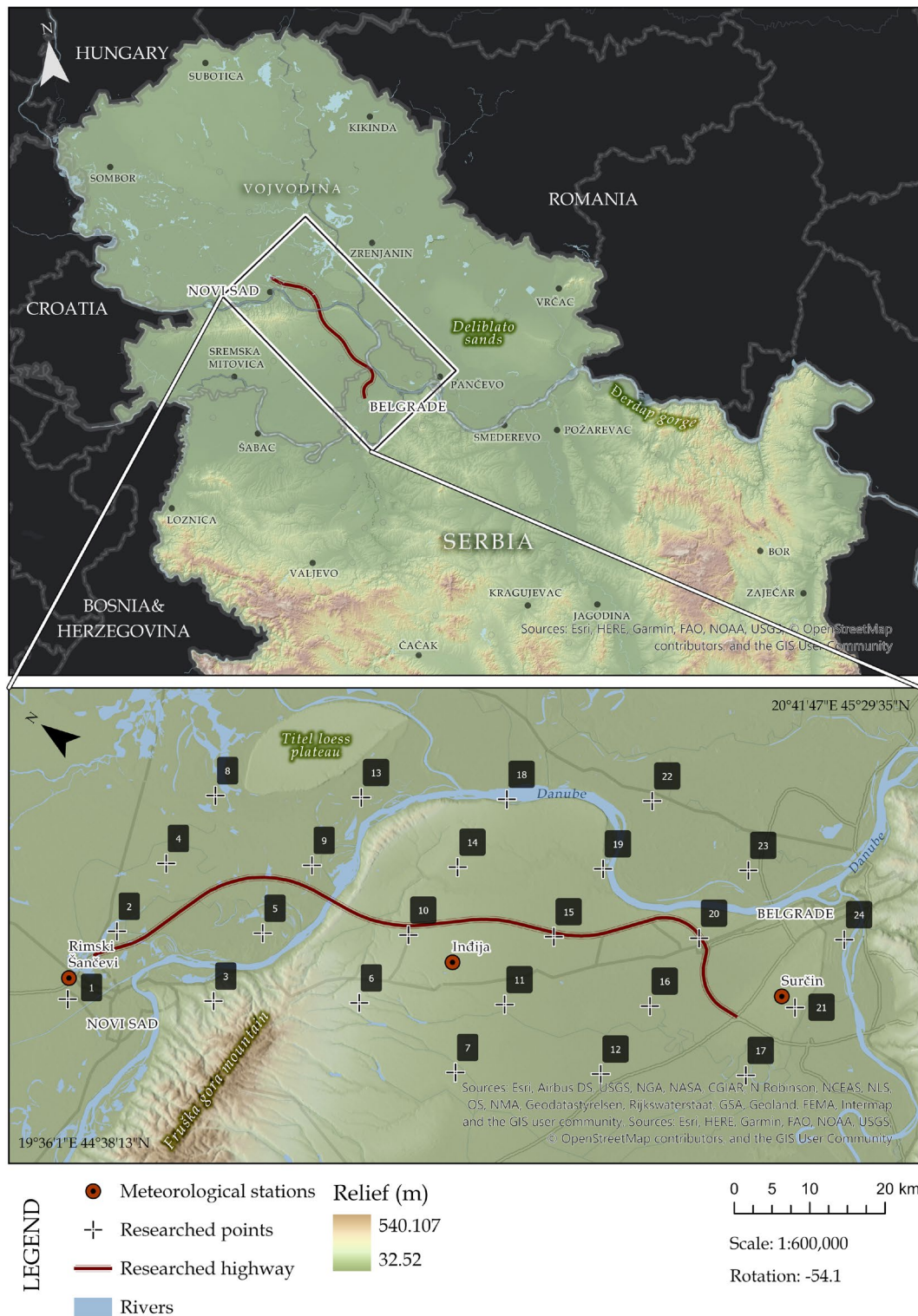


Fig. 1 The position of researched area

According to the authors (Plaznić 1985; Dukić 2006), four types of wind mainly occur in Vojvodina: the south-east wind — *Košava*, the north wind (very cold and intense), the south warm wind, and the west wind (which

brings rain or snow). By researching the frequencies of medium seasonal winds in northern Serbia, Tošić et al. (2017) found that in the territory of Vojvodina, the prevailing winds come from the northwest and southeast. It was



**Fig. 2** The landscape subsections of the highway route Belgrade–Novi Sad. **A** subsection from Belgrade to India, June 2015. **B** subsection from India to danube River, March 2016. **C** subsection from Kovilj to the exit Novi Sad, March 2016

also determined that maximum wind speeds (over 15 m/s) are associated with prevailing winds, while wind speeds between 2 and 5 m/s are the most dominant throughout the year (Tošić et al. 2017). A high-pressure field in Eastern Europe and a low-pressure field in the western Mediterranean establish a strong pressure gradient force over the Balkan Peninsula, producing wind from the high- to the low-pressure area. On its path over Eastern Europe, the air flow encounters the Carpathian Mountains. Passing over the mountain ridge, it significantly increases in speed (above 11 m s<sup>-1</sup>); when it reaches Serbia as a southeastern wind, it is known as *Košava* (Lalić et al. 2018). *Košava* is a strong and cold southeast wind. It occurs from autumn to spring with a speed of about 7 m/s, but also it can reach a wind intensity of about 30 m/s (Plaznić 1985). Later, the northwest wind, much less intense, took over. This shows that the conditions for the occurrence of extreme values of wind speed are present and that they can have a very significant impact on traffic safety, especially if they are observed on a daily basis (Mihailović 2017). *Košava* rarely blows for just one day. It usually lasts 2 to 3 days, also much longer (Zarić 2014).

In meteorology and climatology, geographical data plays a key role. They are used in analyses for various kinds of spatial interpolation and modeling in which the data are a factor that determinates the spatial distribution of analyzed meteorological phenomena or climate elements (Dobesch et al. 2007).

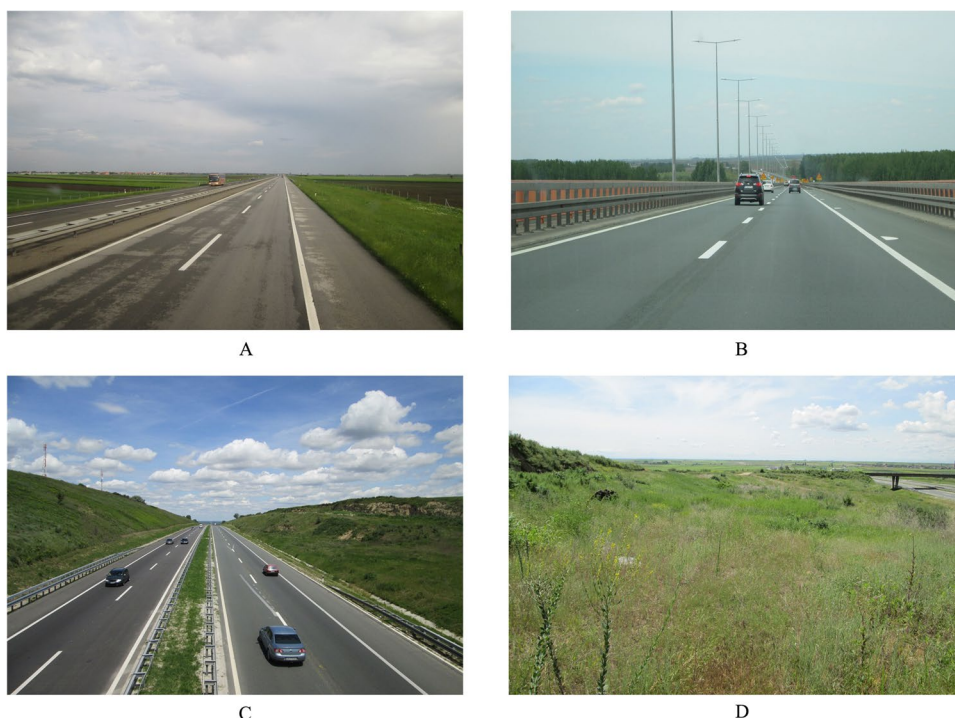
The landscape of the researched highway section is very diverse and approaches different landscape units (Fig. 3) such as steppes, loess plateaus, alluvial plains, agricultural fields, and the foot of mountain slopes (Sentić and Đorđević 2019). According to Vlatković (1981), in terms of vegetation, the landscape of Vojvodina has changed considerably from the middle of the twentieth century until today. From 15.5% of the total area that consisted of linear green corridors and massifs along the reclamation canals and roads, there is not much left today. The role of vegetation was multiple: to protect the road

from snow in the winter months, to protect road users from high temperatures in the summer months, and to protect the land from eolian erosion. As Vlatković (1981) states, the roads passed through windbreaks, avoiding the wind turbulence. At the same time, they had a protective role against the snow.

Forests as a special category in the territory of Vojvodina today cover 6.70% of its total area, which according to the authors Orlović and Tomović (2011) are alarming and very worrying. According to data given from the Institute of Lowland Forestry and Environment in Novi Sad, there are several forest complexes along the researched route of the Belgrade–Novi Sad. The first forest unit along the highway (observed from the direction of the Kovilj–Petrovaradin marsh towards Novi Sad) is the forest around the Arkanj channel. It is taken care of by the Serbian Orthodox Church and the Kovilj Monastery. The next forest unit from the Danube River is at the gas station “Minut levo” (west of the gas station), managed by the company “Vode Vojvodine.” It is a very small area with middle-aged and young cultures of Euro-American poplar which are in a good condition in terms of preservation. The next forest complex is currently a forest with an area of 200 ha whose user is the Institute of Lowland Forestry and Environment Novi Sad. The entire forest area is a set of departments/sections that each represents an experiment with the predominant species Euro-American poplar. Other species are white willow, acacia, and white poplar. After this area is a forest complex of about 22.8 ha with Euro-American poplar in the form of preserved forests and the user is the agricultural company “AD Sloga Kać.”

This is all that can be seen speaking about the forest along the Belgrade–Novi Sad highway route. The rest of the vegetation is very diverse. These forests fragments were not planted because of the wind protection, but for the purpose of dendro-species cultivation and for the needs of the companies that manage them. All this reflects the significant wind exposure of the highway, which will be further discussed in the results and conducted checklists.

**Fig. 3** The landscape character of the researched highway route. **A** agriculture fields, May 2014. **B** alluvial plains, April 2017. **C** loess plateaus, May 2014. **D** steppes, May 2014

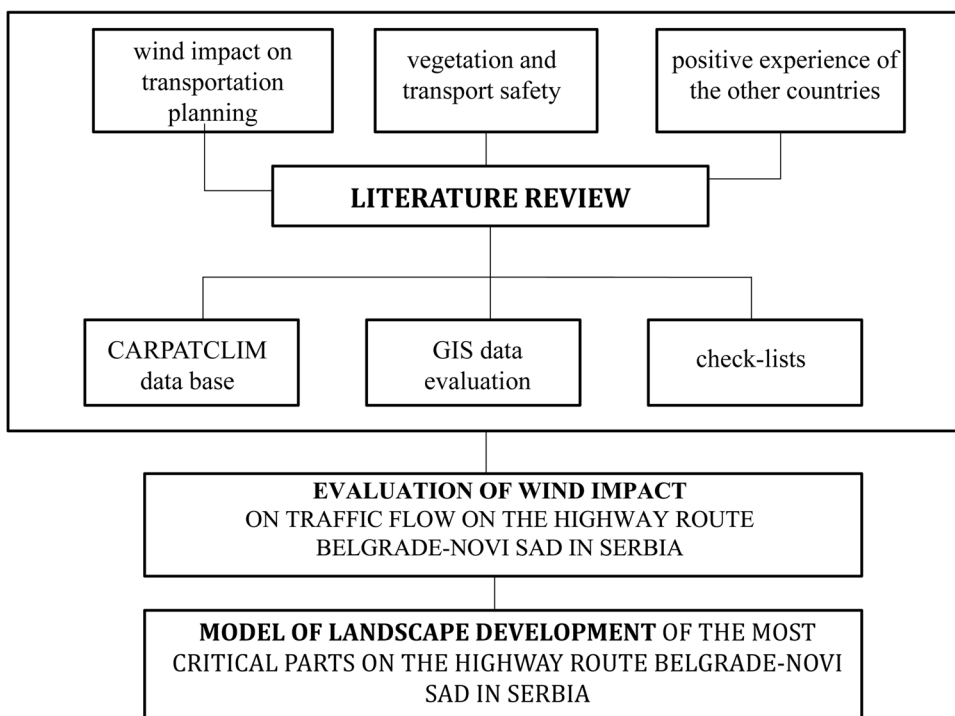


### 4 Methodology

The total conceptual research framework is shown in Fig 4. Considering that the goal of this paper was to reduce the impact of winds on highway traffic flow with adequate

landscape design, it was necessary to study the climatological profile of the Belgrade–Novi Sad highway route. There were two approaches to getting the climatological data. The first one was to obtain data from official meteorological stations. Of all meteorological stations (main and supplementary) that cover the territory of Vojvodina,

**Fig. 4** The conceptual framework of the research process



only two main can be useful for this research (the one is near Novi Sad and the other one is near Belgrade–Surčin). Other stations are too far from the researched highway route and their measuring results were not of interest for this research study. The distance between these two mentioned stations is about 80 km. This is a significant distance for a landscape to be considered homogeneous, to expect that there are no major oscillations of the wind impact on traffic and that landscape design should be uniform from the starting to the endpoint. In this regard, it was necessary to use more detailed climatological data for the wind (daily values for at least 20 years) to highlight the dangerous zones along the highway route and to create an adequate model of highway landscape design.

There was a possibility of events with a consequent outcome on highways due to increase the impact of wind, so it was important to study their effects at the micro-level. In order to highlight the microlocalities, i.e., the points exposed to high-intensity winds, it was necessary to obtain daily data for wind intensity and direction. So the data from the two abovementioned meteorological stations were not nearly enough to obtain relevant microdata on the impact of wind on traffic safety. Thus, the second approach for obtaining the climatological data was providing the daily wind values from microlocalities along the highway route. As in Serbia, there is not developed any kind of monitoring of the impacts of climate elements on highway traffic, the wind data for the points that define the researched highway route were obtained from the CARPATCLIM database (“CARPATCLIM: Climate of the Carpathian region”). According to authors Szalai et al. (2013) and Spinoni et al. (2015), this database contains detailed homogenized and harmonized climate data for the Carpathian region acquired using MASH v3.03 and MISH v1.03 software programs. The database is a product of meteorological observations for the period from 1961 to 2010 from the official meteorological stations of chosen countries from the Carpathian region. The following climate elements were measured: mean temperature, maximum and minimum temperature, precipitation, duration of solar insolation, cloudiness, global radiation, relative humidity, steam pressure, air pressure, snow cover height, snow and water uniformity, wind speed at a height of 2 m and 10 m, and wind direction at a height of 10 m. In order to provide microdata, in the CARPATCLIM database, interpolation method was applied. This opens the opportunity to use interpolated data to obtain microdata for any selected location geographically covered by the CARPATCLIM. Thus for this research, points between latitudes 45.3° N and 44.8° N, and longitudes 19.8° E and 20.4° E (Fig. 1) were considered. Data were taken on a daily basis. Wind characteristics were evaluated through two parameters: wind direction and wind speed. Both parameters were measured at a height of 10 m relative to the height of the Earth’s

surface. In order to get a view of the high-intensity winds (extremes) on the researched highway route, the period between 1990 and 2010 was researched. Also, in an effort to facilitate the understanding of the data, the data were further categorized according to the Beaufort scale, the officially adopted nomenclature for evaluation of wind intensity. For this research and monitoring of high-intensity winds, the daily average wind speeds  $\geq 8$  m/s were considered (5 on the Beaufort scale). In this way, it was possible to present a clearer view of the existing situation and the segments of the researched route exposed to high-intensity winds were underlined.

Since the CARPATCLIM database has consisted of average daily values from the official meteorological stations, the data was further enriched by measured data of high-intensity winds of more than 6 (10.8 m/s) and 8 (17.2 m/s) levels of Beaufort scale (further 6B and 8B).

The data were further analyzed and mapped using ArcGIS software. This kind of data mapping was also used in other studies of similar issues (Wang and Cheng 2001; Corcoran et al. 2014; Loidl et al. 2016; Ulak et al. 2017). In the CARPATCLIM database, the data are given at the field level of  $10 \times 10$  km. To make data on the maps easier to read and interpret, daily wind data were interpolated using Digital Elevation Model (DEM). When interpolating wind-related data, DEM plays an important role in obtaining the most accurate values as possible, and in order to obtain accurate data with the help of DEM, the cokriging method of interpolation, which proved to be the most favorable, was used (Palomino and Martín 1995; Apaydin et al. 2004). The data of interpolation ( $100 \times 100$  m resolution) were displayed on maps. As a result, the obtained maps showed the points with the strongest wind influence on the highway route Belgrade–Novi Sad.

Since the groundwork of the CARPATCLIM database was an interpolation method, it was necessary to do fieldwork and obtained results compared with the current situation. The checklists were chosen as a suitable methodology. The conduction of checklists is a qualitative methodology, based on the knowledge and experience of a researcher. The aim is not to quantify specific elements, but to evaluate elements in the field that satisfy the function for which they are predetermined. The results of checklists are guidance for a further step in the research process (Scriven 2000; Martz 2010).

For the purpose of this research, the checklists were used to confirm the results of the CARPATCLIM database and to give some further perspective on highway landscape design. Their content was based on methodologies previously applied by several authors (Gehl 2006; García-Montero et al. 2008; Blagojević and Đorđević 2013). Examined criteria were adapted to the subject and objectives of this research. It was difficult, and very dangerous, to “hunt” the extremes.

So, in order to get a realistic image of the current situation of the impact of wind on the researched highway route, the checklists were made under different weather conditions (without precipitation, strong winds with rain, and light snow with the moderate wind).

In the previous methodological step, there were emphasized the exact highway sections, exposed to the high-intensity winds. Since those sections were several kilometers long it was very difficult to determine at which point in such a long section to stop and do checklist analyzes. Due to that, the parameters in the field trip, within the created checklists, were evaluated at almost 2–5 km. There was total of 48 stopping points in both directions of the highway Belgrade–Novi Sad. Two checklists were made for each direction of the highway route (Belgrade–Novi Sad and the opposite).

The first checklist examined the impact of the wind on highway safety and the presence of natural (windbreaks or grouped vegetation) or artificially constructed elements (some barriers or windbreak netting systems) that could be potential in the process of controlling the influences of high-intensity winds on the highway. The second checklist examined the existence of different forms of vegetation on the highway. Criteria selection for the evaluation of checklists was based on the researchers' general knowledge, intuition, and experience, as well as terrain attributes and the defined research objective. The criteria were evaluated qualitatively, based on the following parameters: negative, light, mild, intensive, and very intensive (for the first checklist) and absent/present in aesthetical, ecological, and technical terms (for the second checklist), meaning according to researchers' opinion what is the primary function of the vegetation. The photo documentation was made for each stopping point.

The model of landscape design of the researched highway area was based on the proposal of an adequate vegetation assembly in the form of the windbreak belts.

## 5 Results

Due to the inability to present all of the obtained data in detail, the focus will be on highlighting the high-intensity winds, as they are closely linked to traffic safety and directly condition the highway landscape design.

### 5.1 The review of wind intensity for the period 1990–2010

The climate data for wind are mostly available in the form of average values. It has already been pointed out that high-intensity winds and extremes could be fatal for drivers and that recording and monitoring them is of great importance for traffic safety. However, average values only diminish the importance of this issue. By analyzing the results of

the average monthly or annual values for the wind for the Vojvodina region and compare with the researched area, no alarming data were found. For the best representation of all wind parameters from CARPATCLIM database, wind roses were used (Fig. 5a, b). All wind speed values, and wind directions are represented on them for the researched period (1990–2010). It can clearly be seen that the wind speeds of less than 4 m/s are most common in the researched period. Daily average wind speed from 4 to 8 m/s is much less frequent and wind direction is in compliance with previous research of winds in Vojvodina. Although there are some differences when comparing the researched points through wind roses, generally this data is too generalized for any conclusions. For this reason, the high-intensity wind speed is shown separately in Table 1.

Looking further at the average values both on the twentieth and on the annual and monthly levels, we concluded that there are almost no significant differences between the points (Table 1). If we take into account the average annual values, the windiest city in Serbia, Vršac, in 2010 had an average wind speed of 3.5 m/s and Novi Sad 2.3 m/s. But if we add the fact that Novi Sad (the meteorological station Rimski Šančevi) had 10 days with the wind over 8B in 2010 year and Vršac had as many as 85 days with the wind over 8B (Meteorological Yearbook 2010), it can be understood that these values cannot show the real danger of wind in these areas.

Given that the high-intensity winds are the ones that pose danger and reduce traffic safety, considering all points of the researched area, it is important to look at the frequency of average daily winds with speeds of 8 m/s and more (Table 1). The table shows the number of days with an average daily wind speed over 8 m/s for the period from 1990 to 2010. For easier interpretation, the values in Table 1 are shown in Fig. 6.

The highest number of days with an average daily wind speed over 8 m/s is present at points 1, 2, and 3 near Novi Sad. The minimum number of days with average daily wind speed is present at point 5 (5 days). The studied points 1 and 21 are located next to the existing meteorological stations (1-Rimski Šančevi, 21-Surčin) and these values are equal to those from the meteorological yearbooks and represent the true measured values. Points 6, 7, 10, and 11 that surround the supplementary meteorological station Indija which, despite the fact that started to work in 2002 (it is not possible to verify data before this year and this station was not used for the CARPATCLIM database), show compliance with the values measured at the station and we consider that data to be valid. Apart from Novi Sad, where high values were recorded, and Belgrade, where lower values of the number of days with average daily wind speed over 8 m/s were recorded, we notice that the area on the east side of the highway is exposed to stronger winds than the western part (Fig. 6).



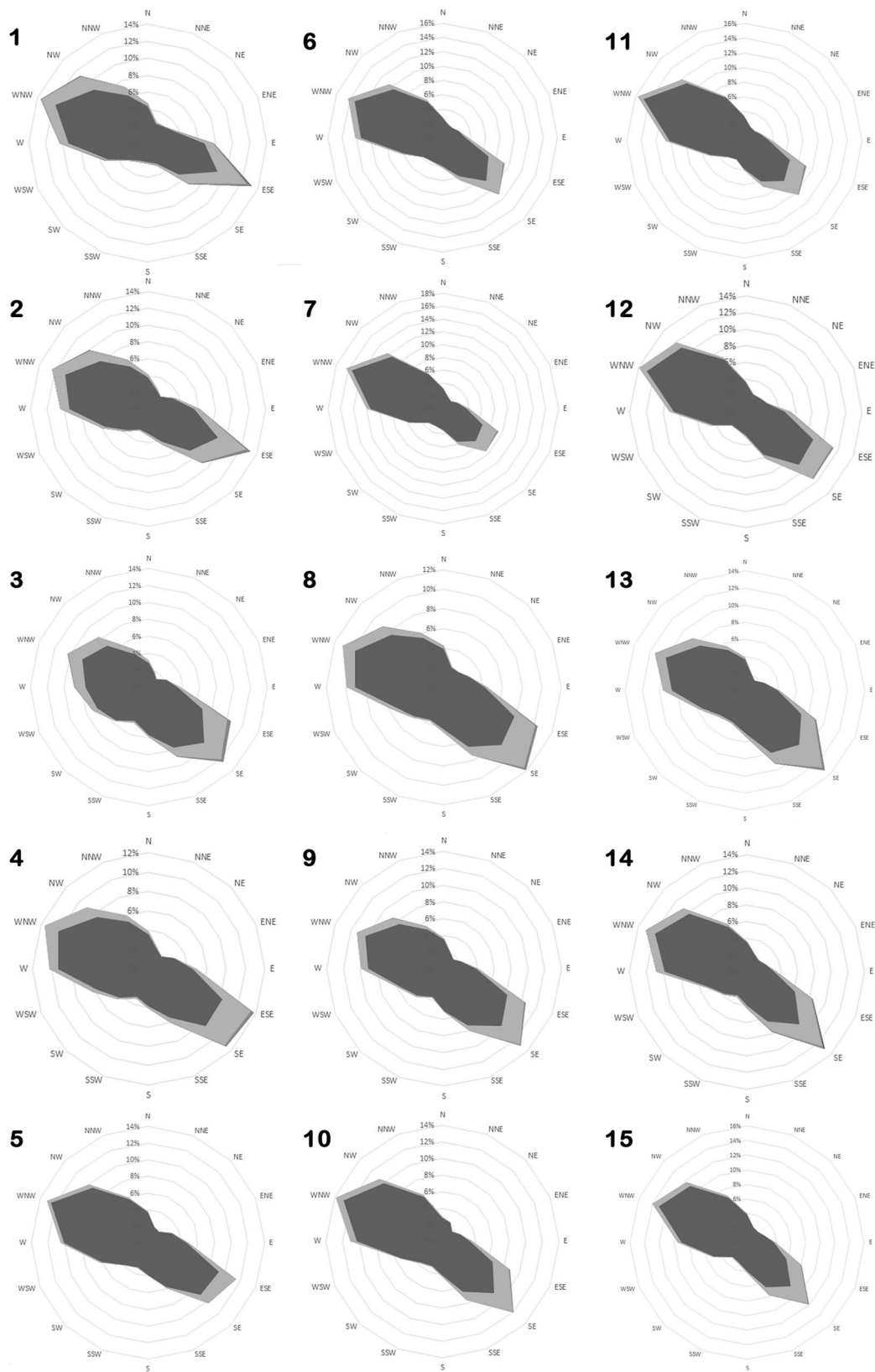


Fig. 5 Wind roses for researched points for period from 1990 to 2010

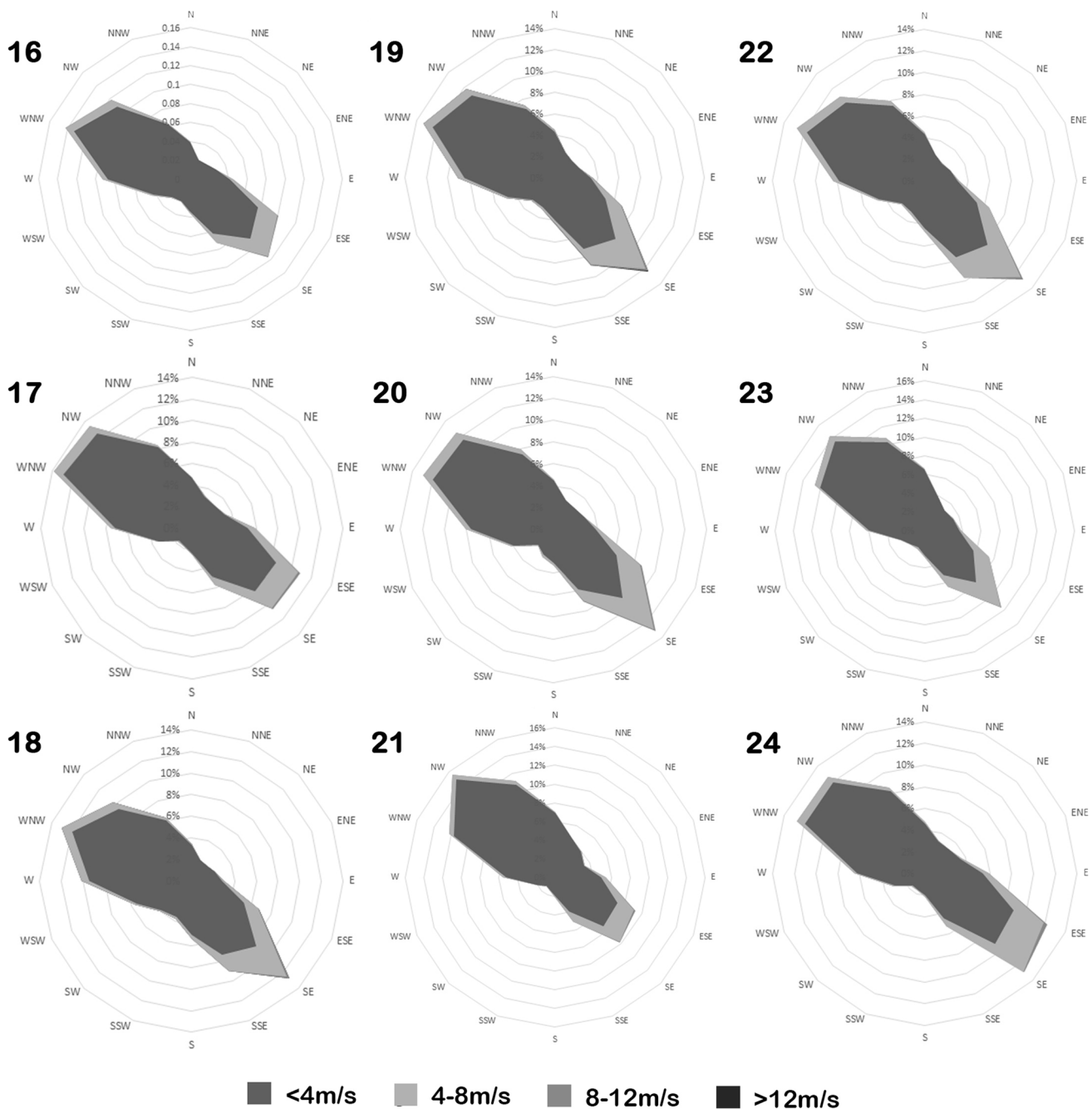


Fig. 5 (continued)

The dominant wind directions for the researched period and all wind speeds vary from point to point (Table 1). These directions coincide with the general descriptions of winds in Vojvodina given by authors (Plaznić 1985; Dukić 2006). Although they are an indicator of the climate conditions prevailing in the area of the highway, these winds mostly do not pose a danger to traffic, so the dominant directions were studied only for days with an average daily wind speed over 8 m/s. In this case, all points showed the same, the prevailing

wind blows from the direction of ESE/SE, which is the main characteristic of the *Košava* wind (Table 1). In addition to being a dominant wind, by comparing the number of days with average daily wind speed over 8 m/s and the number of days with average daily wind speed over 8 m/s from the ESE/SE/SSE (*Košava*) wind direction, we clearly see that for further research it is necessary to follow the appearance of *Košava* in this area. If we take into account that *Košava* is a gustly wind and that the average daily values are far

**Table 1** Wind parameters for researched points

Points No.	Longitude and latitude	Average daily wind speed	Number of days with average daily wind speed over 8m/s	Prevailing wind direction	Prevailing wind direction for higher wind speeds (avg. daily wind speed over 8m/s)	Number of days with average daily wind speed over 8 m/s from ESE-SE-SSE (Košava) wind direction	Highest average daily wind speed
1	45.3° N 19.8° E	2.67	79	WNW	ESE	61	12.69
2	45.3° N 19.9° E	2.66	63	ESE	ESE	54	12.39
3	45.2° N 19.9° E	2.76	75	SE	ESE	66	11.92
4	45.3° N 20.0° E	2.63	52	ESE	ESE	48	11.79
5	45.2° N 20.0° E	2.07	5	WNW	ESE	5	9.34
6	45.1° N 20.0° E	2.35	24	WNW	ESE	23	10.82
7	45.0° N 20.0° E	2.31	19	WNW	ESE	17	10.71
8	45.3° N 20.1° E	2.58	48	SE	SE	44	11.79
9	45.2° N 20.1° E	2.44	33	SE	ESE	31	11.34
10	45.1° N 20.1° E	2.38	32	WNW	ESE	31	11.4
11	45.0° N 20.1° E	2.32	21	WNW	ESE	20	11.01
12	44.9° N 20.1° E	2.36	22	WNW	ESE	18	11.6
13	45.2° N 20.2° E	2.57	48	SE	SE	46	12.44
14	45.1° N 20.2° E	2.53	42	WNW/SE	SE	41	12.7
15	45.0° N 20.2° E	2.40	26	WNW	ESE/SE	26	11.54
16	44.9° N 20.2° E	2.36	21	WNW	ESE	18	11.24
17	44.8° N 20.2° E	2.30	23	WNW	ESE	18	11.84
18	45.1° N 20.3° E	2.47	36	WNW	SE	35	12.54
19	45.0° N 20.3° E	2.45	37	WNW	SE	36	12.11
20	44.9° N 20.3° E	2.49	37	SE	ESE/SE	34	11.66
21	44.8° N 20.3° E	2.16	19	NW	ESE	18	11.71
22	45.0° N 20.4° E	2.46	32	SE	SE	31	11.66
23	44.9° N 20.4° E	2.31	18	NW	SE	17	11.35
24	44.8° N 20.4° E	2.39	35	SE	ESE	34	11.21

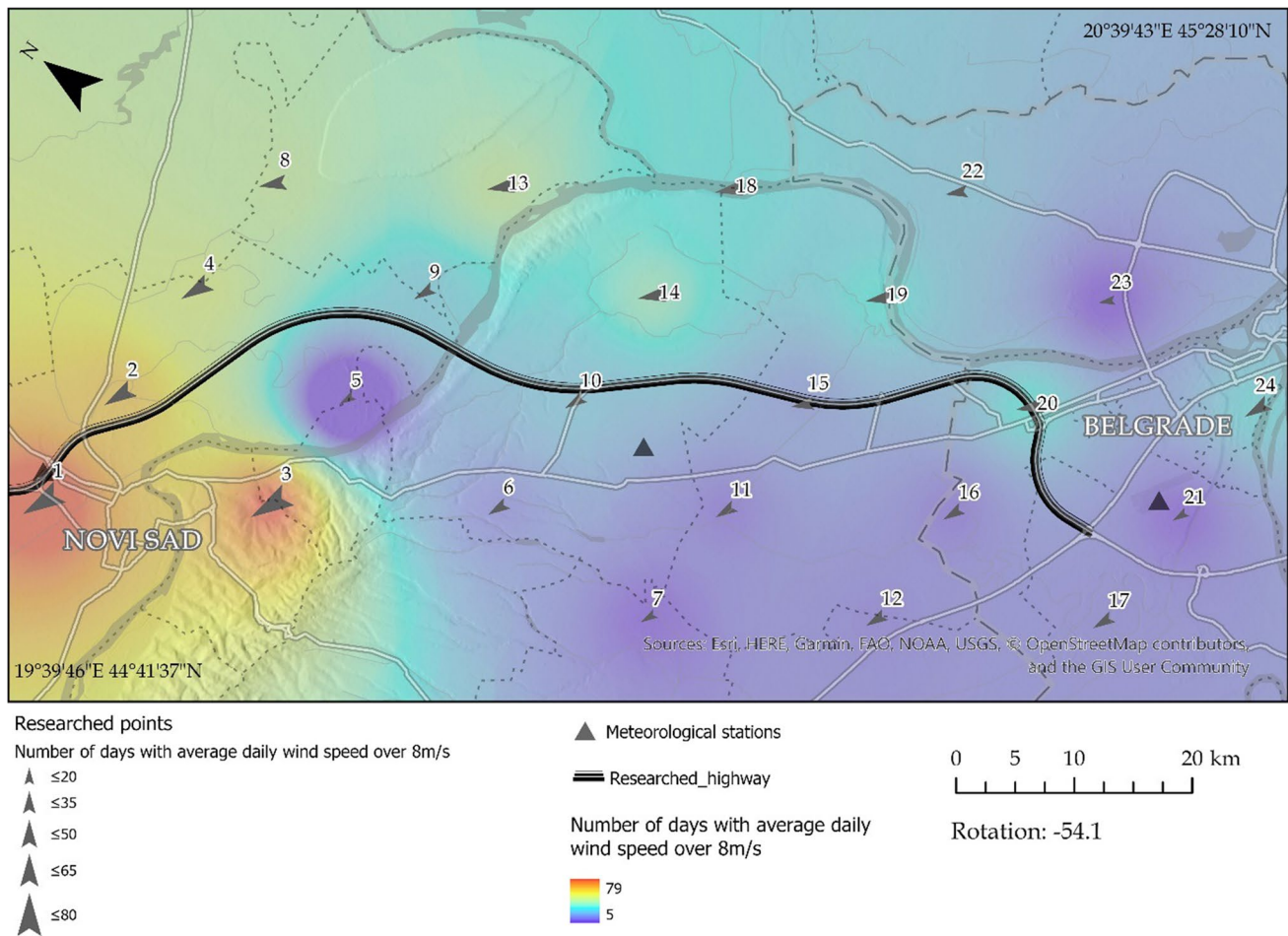
Source: Table based on the data obtained from the CARPATCLIM database

from those felt in the affected area on the days of *Košava*, the number of days with winds above 6 and 8B for meteorological stations (Table 2) was added to the average daily values of wind speed to achieve a better understanding of the *Košava* wind.

Table 2 shows that from 1990 to 2010, the meteorological station in Surčin has the highest values of the average annual number of days with the wind over 6B (97.33 days), followed by Novi Sad (Rimski Šančevi — 74.2 days) and Inđija (45.75 days). As expected, the average yearly number of days with the wind over 8B for a period of 1990 to 2010 has the same distribution of values. What is best shown here is the difference between the average values of wind speed and wind gusts (Table 2), which are not measured at meteorological stations regularly, but only with the help of these indicators (number of days with the wind over 6 and 8B). What is particularly interesting is the comparison of these values with the total number of days with an average wind speed of over 8 m/s (5B). At point 1, the meteorological

station Rimski Šančevi has 79 days with an average wind speed over 5B for the period from 1990 to 2010, while the number of 1484 days with the wind over 6B and 194 days with the wind over 8B was recorded. This difference testifies to the claim that *Košava*, as the dominant strong wind, is gusty and can pose a great danger to traffic. From Table 2, an extremely high monthly number of days with winds over 6 and 8B can be seen, which indicates that in the months when *Košava* blows, traffic can be difficult for days. The meteorological station in Surčin has the biggest blows of *Košava* with 2044 days with the wind over 6B and 299 days with the wind over 8B. The total number of days for the supplementary meteorological station Inđija is not comparable with those from the remaining two meteorological stations due to the period of available measurements (2002–2010).

Figure 7 shows the oscillations of the most intense average daily values of wind speeds at each point of the researched area. Analysis confirmed that there is no even uniformity in the occurrence of winds with extreme intensity



**Fig. 6** Number of days with wind speed over 8 m/s for researched points from 1990 to 2010

**Table 2** Number of days with wind over 6B and 8B measured in meteorological stations

Meteorological station	Coordinates	Average yearly number of days with wind over 6B from 1990 to 2010	Average yearly number of days with wind over 8B from 1990 to 2010	Number of days with wind over 6B from 1990 to 2010	Number of days with wind over 8B from 1990 to 2010	Highest monthly number of days with wind over 6B	Highest monthly number of days with wind over 8B
Novi Sad (RimskiŠančevi)	45° 20' 19" 51'	74.2	9.7	1484	194	18	6
Indija*	45° 03' 20" 05'	45.75	3.87	366	31	17	3
Surčin (Belgrade)	44° 49' 20" 17'	97.33	14.23	2044	299	18	7

\*Data collection started in 2002

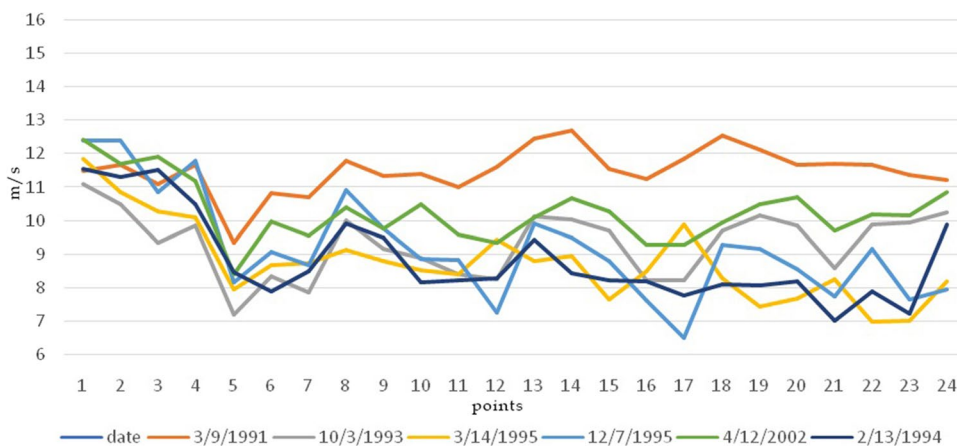
Source: RHMZ-Republic Hydrometeorological Service of Serbia, Meteorological Annuals from 1990 to 2010

at researched points during the studied 20-year period, not a certain pattern. All this confirms the fact that nature is complex and fundamentally very unpredictable, so we have to study it more deeply in order to understand it better — we have to study it on the micro-level.

The results also showed that the winds with speeds of over 8 m/s mostly occur in the period from October to January

(November the most), as well as in March and April (March, the most). The other months during the year are periods of quieter winds at all points of the researched area (average daily values of wind speeds are around 4 m/s). According to the Beaufort scale, at the points of the researched area, during the observed 20-year period, both winds such as lahore and breeze and storm-intensity winds were noticed.

**Fig. 7** Oscillations of average daily wind speed in wind speed — selected dates with average daily wind speed over 11 m/s in at least one researched point



It is worth mentioning that the total area of all plots along the researched highway route is mostly agricultural land. This raises another problem, which is the crosswind that causes the soil particles from the surrounding plots to drift onto the road. This is particularly emphasized in the period from September/October, all the way until March/April. The reason for this is the establishment of the crop rotation in the plots. Where and when the deposits of soil particles could be expected depends on the wind intensity and the period when high-intensity winds are occurring. The points where this problem is to be expected are 2, 9, 10, 15, and 20.

Also, wind, due to its combined effect with other climate elements, such as snow and precipitation, can cause distress to drivers on the road. This kind of problem is also expected in the points where high-intensity winds are noticed.

### 5.2 Checklists for traffic safety approach

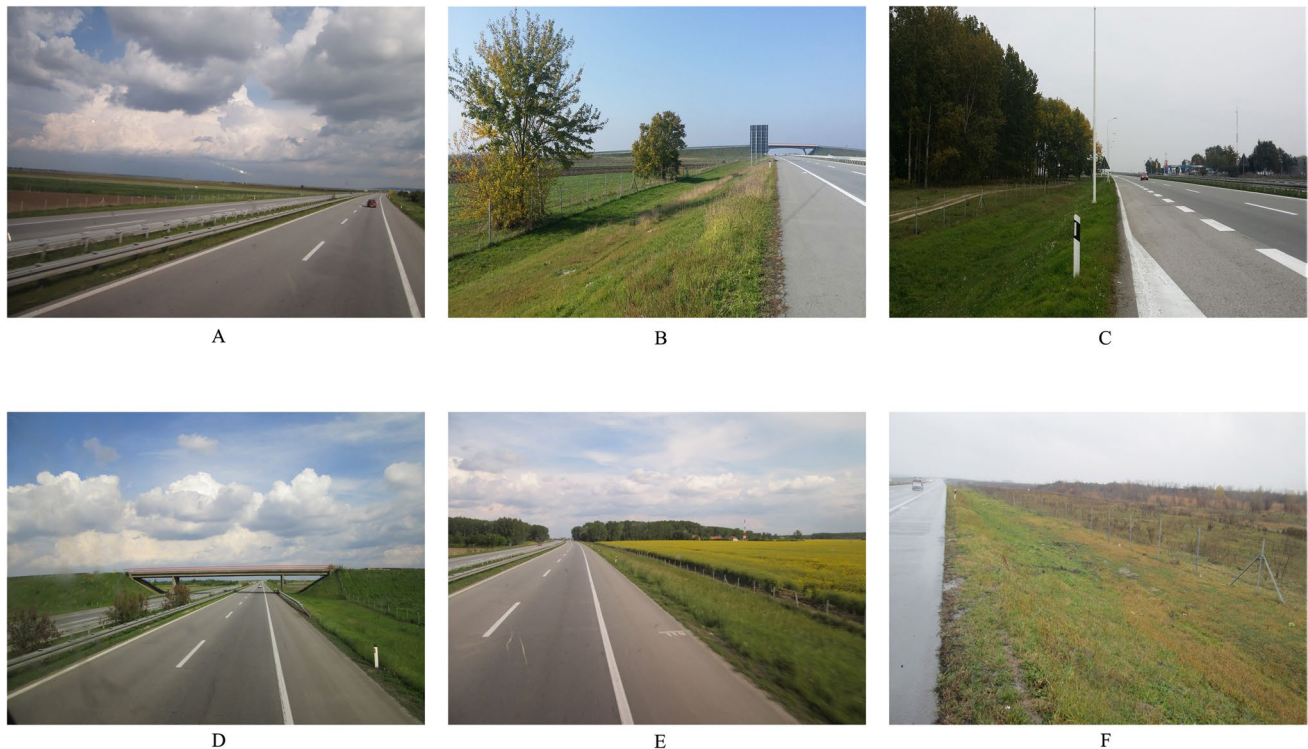
Checklists confirmed, explained, and photo-documented critical points and subsections of the researched highway route that have already been singled out (based on the evaluated data from the CARPATCLIM database). Those points are located near settlements named Batajnica (point 20), Stara Pazova (point 15), Beška (point 10), Gardinovci

(point 9), and Kać (point 2). The fieldwork showed occurrence of individual wind impacts, but also its synergy with some of the other climate elements (mostly rain and snow). Along the almost entire highway route, there were very noticeable deposits of soil particles, waste (the most critical were landfill near Batajnica — direction from Belgrade to Novi Sad, and landfill near Indija — direction from Novi Sad to Belgrade), and snowdrifts and its retention in the stop lanes (Fig. 8).

Evaluation of the criteria in the first checklist showed that there are no visible natural or artificially constructed elements for wind protection. Therefore, this kind of landscape design enables the occurrence of crosswind on both sides of the road (which was very noticeable on the field in different weather conditions) and strikingly reduces traffic safety (Fig. 9A). Analyzing the landscape of the researched highway route in both road directions and through the realized stopping points within the second checklist, it can be concluded that considering the current state of the highway greenery, very modest and non-compact vegetation has been noticed. It cannot have a stronger effect on mitigating high-intensity winds. The most noticeable forms of vegetation are arable land, shrubs (in small groups), and woody adult individuals (solitaires, small groups of trees or smaller forest massifs) (Fig. 9B–F).

**Fig. 8** Photo documentation of wind-rain and wind-snow synergy. **A** snow deposits on the stopping line, location Batajnica, December 2017. **B** the exist of soil deposits in the rainy day, near Belgrade, October 2017





**Fig. 9** Photo documentation of the checklist criteria. **A** agricultural landscape with no visible natural or artificially constructed elements for wind protection, May 2014. **B** woody adult individuals, Novem-

ber 2017. **C** smaller forest massifs - fragmented forest, October 2017. **D** greenery of the overpass, May 2014. **E** wetland forest, May 2014. **F** green channel along the highway, October 2017

Considering the amount of data that the checklists provided, it is not possible to present everything in detail in this paper. Therefore, the method for checking the researched criteria and the parameters at chosen stops is presented only as of the example of checklist 1 (Table 3) and checklist 2 (Table 4) in order to understand the whole method process. For the presentation of the checklist methodology, the most critical site on the researched highway route, subsection near Batajnica, direction Belgrade–Novi Sad, was chosen. On this site, several elements reduce traffic safety (wind, precipitation, damaged pavement, undefined shoulder with the canal along the roadway, landfill, and traffic overpass). Using the same principle, other stopping points were also analyzed and checked.

### 5.3 Windbreak efficiency in highway landscape

Windbreaks are the most common tool for controlling the wind intensity in the highway landscape. The role that different vegetation assemblies play in the landscape also determines their design, i.e., the selection of species, the number of rows, the distance between the trees in a row, as well as the distance between rows (Ferber 1974). The front part of the windbreak is the one that is hit the

most. Therefore, it is reasonable to assume that it has the most influence on decreasing the wind speed (Read 1964). In order to achieve the maximum wind protection, low-branch shrubs need to be planted in the first rows of the windbreak. The space between the rows should provide sufficient space for the passage of machinery (Ferber 1974). It is also suggested that the edges of the windbreaks should consist of low-branch shrubs or conifers; furthermore, the central part should consist of adult woody individuals of broadleaf and conifers, with an average height of about 15 m. In this way, the wind is allowed to pass through the canopy at different heights, by which its speed decreases. The optimal width of the vegetation belt should not be below 8 rows (Fig. 10).

In order to develop high productivity and adaptability to environmental conditions, authors Wight and Straight (2015) recommend that windbreaks should be raised using native species, resistant to high-intensity winds, which have a dense and well-developed canopy. In case of the researched highway route, choice of type and character of the vegetation should be directed towards the selection of different types of broad leaves, conifers, and evergreen plant species (to contain the snow in winter months). Monoculture plantings should be avoided and non-invasive native species headlined. The following

**Table 3** An example of the first checklist conduction. Source: Table based on the data obtained from the entire fieldwork observation using the checklists method

**Date:** 11/26/2017  
**DIRECTION:** Belgrade—Novi Sad  
**Review of meteorological parameters on the day of the fieldwork:** Cloudy, in the morning partly rainy with a decrease in temperature. The wind is light and mild, in the *Košava's* windy region it will blow strong, south and southeastern wind, during the day turning northwestward and with higher intensity. Maximum daily temperature 6 °C [1].

criteria	Distance from the starting point (Dobanovci tintersection)	Location	Wind intensity	Are there any visible wind deposits on the road?	Presence of artificial elements for wind control	Vegetation planted for the purpose of wind control	Notes
parameter with notes	10.7 km	Batajnica	4	3	0	0	A very dangerous spot. Damaged pavement. Intense wind deposits in the form of gravel and garbage from a nearby landfill. No edge fence, undefined shoulder.



**Legend:**

0 - negative      1 - light      2 - mild      3 - intensive      4 - very intensive

types are proposed: *Celtis australis* L., *Chamaecyparis lawsoniana* (A. Murray) Parl., *Corylus colurna* L., *Picea pungens* Engelm., *Pinus nigra* Arn., *Pinus sylvestris* L., *Populus alba* L., *Populus nigra 'Italica'* L., *Prunus avium* L., *Prunus spinosa* L., *Juniperus communis* L., *Berberis vulgaris* L., *Caragana arborescens* Lam.

Establishing the windbreaks is certainly welcome along the entire Belgrade–Novi Sad highway route, especially at the points where the high-intensity winds occur throughout the year. The results of the underlined methodology (considering this research) have emphasized the points (as the points are exposed to the high-intensity winds) that should be especially designed in the landscape by raising the windbreaks with an adequate selection of vegetation and at a certain distance from the highway. This is extremely important in the process of “calming”

the impact of wind and increasing traffic safety. Based on the results obtained in this research, the points suitable for raising the windbreaks are Batajnica (21), the subsection around Stara Pazova (16), and in the vicinity of Beška (11), Gardinovci (10), and Kać (3). Although the results of the research showed that high-intensity winds were more felt in the Belgrade–Novi Sad direction of the highway than the opposite, due to different directions of dominant winds throughout the year, windbreaks should still be planted alongside both directions of the researched highway route.

As the results showed, on the bridge near Beška, there is a strong impact of winds throughout the year since the winds are coming from different directions. Unfortunately, it is not possible to raise any kind of windbreak there, but speed control of vehicles on should be imperative to raise traffic safety to a higher level.

**Table 4** An example of the second checklist conduction

criteria	location	arable land	shrub species	individual woody plant	forests	presence of weeds	green channel	vegetation at the exit points	highway overpass
parameter with notes	Batajnica	0	2, 3, 4	2, 3, 4	0	1	low grass and weed	-	Surrounded by landfill Strong wind gusts under traffic overpass. No greenery.

Legend:

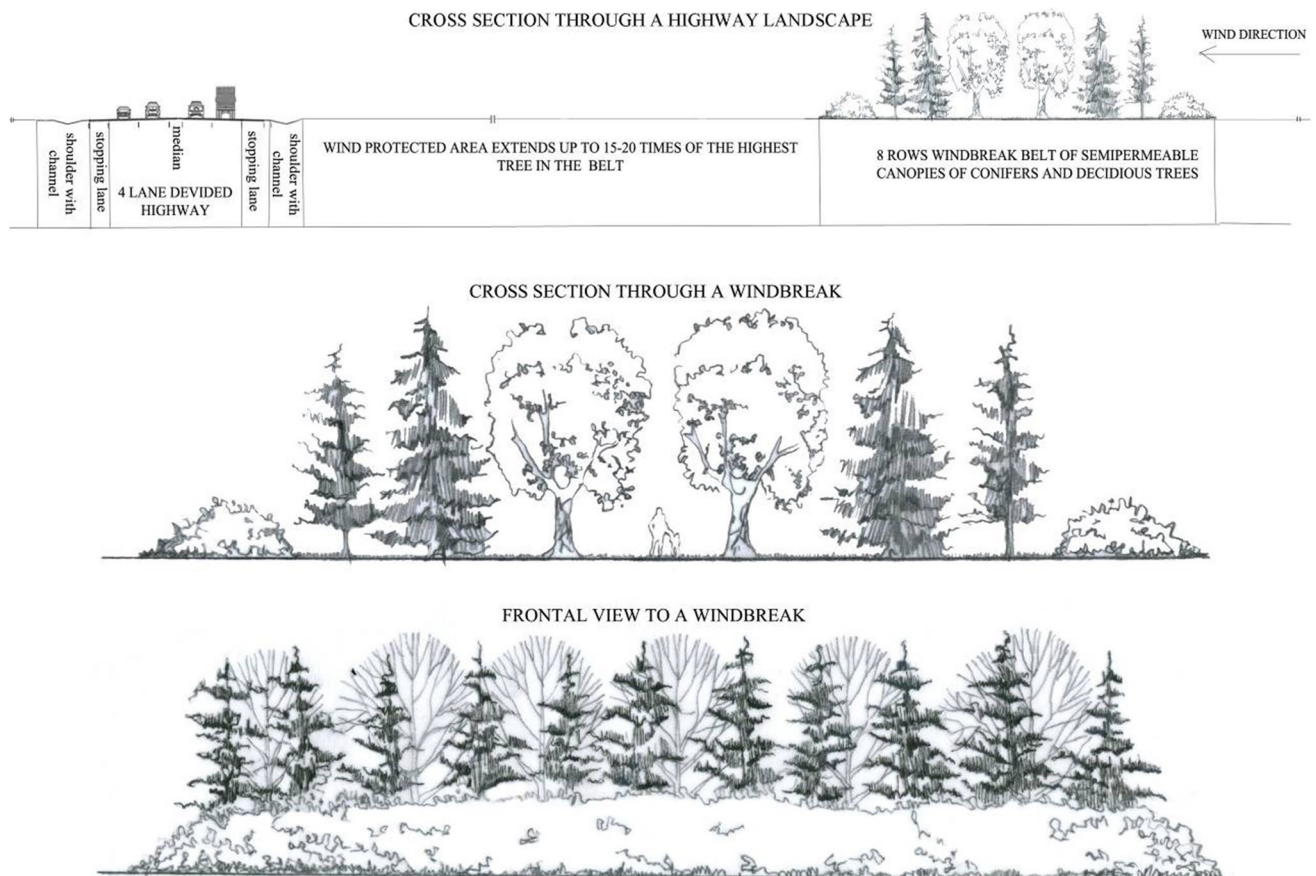
0 - absence

2 - present, could show good results in technical way

1 - present

3 - present, could show good results in ecological way

*Source: Table based on the data obtained from the entire fieldwork observation using the checklists method*

**Fig. 10** An example of 8-row windbreak



## 6 Discussion

Obtained results showed that the impact of wind is significant along the researched highway route throughout the year. Certain oscillations, depending on the period of the year, can be felt. The results are consistent with those of the previous studies (Baker and Reynolds 1992; Perry and Symons 1994; Edwards 1996), which addressed the impact of wind on traffic safety. One of the most cited references is the case of British Isles in the late 1980s and early 1990s. Authors Baker and Reynolds (1992) stated that in the abovementioned period, the area of British Isles was marked by the greatest losses of human lives in traffic accidents. Therefore, Edwards (1996) highlighted that identifying the parameters of climate elements in the traffic accident reports is crucial for traffic safety, with the aim of achieving adequate state-level monitoring of traffic safety by recognizing and confirming the link between traffic accidents and weather conditions. In this regard, the relevant institutions should be activated in taking appropriate safety measures. According to Musk (2003), this kind of traffic accident report has been in use in the UK since 1969, but there are certain omissions, since the report does not have the option to check the wind as the cause of the traffic accident. The results of research made by authors (Baker and Reynolds 1992; Perry and Symons 1994; Edwards 1996) determined that on highways, exposed to strong winds, the number of traffic accidents is also high. This emphasizes that the topic should be of concern and raised on a higher level. In Serbia, the awareness of studying the impact of climate elements on traffic safety (particularly the wind) is not suitably developed. There is no precise database on traffic accidents when the cause is a climate factor, especially the wind. As long as there is no designated institutional body that will collect data regarding traffic accidents caused by the climate factors, most of the information on the impact of wind on traffic safety will come from individual studies of extreme events, as it was the case with the British Isles. This has also been acknowledged by several authors (Perry and Symons 1994; Edwards 1996) and all of this slows further research on this topic.

In Serbia in January 2014, near a small plain settlement Feketić snowstorm hit a highway. According to the Meteorological Yearbook (RHMZ 2014), the meteorological station “Rimski Šančevi,” the closest station to Feketić (45 km far away), noted that in January 2014 there were 3 days with wind stronger than 6° of Beaufort scale and 5 days with snow (average value were calculated). Considering these data, there is no impression that in January 2014 were any conditions for some hazardous occurrences. The situation was a bit different on terrain. At the end of the month, wind with the intensity of a hurricane and snow crossed their

strengths and in just a few hours, the snowstorm caused a total collapse of traffic in that part of the Vojvodina. Over 1000 people were captured in their vehicles for almost 24 h. The snowstorm lasted for a couple of days [2]. The case Feketić is just one more example that confirms that climate elements must be studied at the micro-level since they could have harmful effects on the traffic flow. The fact is that daily extremes are caused by atypical weather conditions in the season and that their impact on traffic safety is not negligible. This is confirmed in numerous studies (Hassan and Barker 1999; Eisenberg 2004; Dupont and Martensen 2007; Bergel-Hayat et al. 2013; Sentić and Đorđević 2019). Also, combined climate elements can be extremely threatening to traffic (Brodsky and Hakkert 1988; Bergel-Hayat et al. 2013).

Considering the experience of other countries (Edwards 1996; Hermans et al. 2006), it can be said that the results of this research confirmed the significance of micro-level climate data observation. Since official meteorological stations are sources of macro data, it is necessary to find adequate access to microdata. There are various types of modern technologies used to collect microdata (Chen et al. 2010), also the interpolation method based on data from official meteorological stations was quite applicable in types of research (Yang et al. 2011; Luo et al. 2008; Wieringa 1986). In the case of developing countries, such as Serbia, where the installation of meteorological stations along highways is not achievable yet, the results of this research, usage of the CARPATCLIM database, distinguished as noteworthy but not without faults. This was the case in other relevant scientific papers as well (Cheval et al. 2014; Lakatos et al. 2016; Price et al. 2017).

The main fault is precisely related to the measurements at meteorological stations, because the CARPATCLIM database has just interpolated the abovementioned values. The lack of data on wind gusts is a big shortcoming because the results showed that these gusts are the most dangerous and the only ones that pose a significant danger because they exceed the limit values previously established by Baker and Reynolds (1992) and Hermans et al. (2006). As Košava represents a gusty wind whose gusts are not measured adequately at meteorological stations but only in the form of the number of days with the wind over 6 and 8B, by looking at the results we can already see the irregularity in the number of days with average daily wind speed over 5B which is highest in Novi Sad and the number of days with winds over 6 and 8B, which are far higher than the previous indicator and have the highest value in the vicinity of Belgrade, more precisely at the meteorological station Surčin. As we mentioned earlier, this is the only measure for wind gusts that are characteristic of Košava, and the explanation of this phenomenon was given by the authors Unkašević

et al. (1990). Lettau and Haugen (1960) pointed out that, for strong mean winds, the maximum wind speeds of short duration arise from mechanical turbulence. This was proved by the authors Unkašević et al. (1990) at the meteorological station Opservatorija in Belgrade by studying the interdependence of average, maximum daily, and *Košava* gusts during the longest period of *Košava* blowing in Belgrade. Although the danger and the main characteristics of the wind along the researched area (for the needs of landscaping which will in turn reduce the negative effects of wind) were analyzed in detail and the results show the regularity of the greatest wind gusts, it would be necessary to install adequate meteorological stations in the most endangered locations established by this study in order to establish a rapid alert system and implement adequate traffic measures in such situations (especially in the most endangered locations such as bridges for which we do not have accurate wind information).

Another concern is that the data obtained by interpolation seem inaccurate for point no. 5. Errors in databases of this type made for large areas from a network of only a few meteorological stations can often lead to errors at the level of one or two points (depending on the interpolation methods). Therefore, like any result of interpolation of climatological data, this database should be used with caution.

Finally, when the impact of wind is perceived as one of the threatening elements for traffic safety, it is necessary to find ways to reduce its intensity and to allow traffic to proceed smoothly. Author Lorenz (1980) wrote extensively about the importance of vegetation in the highway landscape and its role in creating a safe driving environment. For sure, the issue of highway landscape should be seen a little broader (Ziakopoulos and Yannis 2020) and as the authors Perry and Symons (1994) and Alemu (2016) emphasized, the windbreaks could play an important role in reducing wind intensities. According to the Law on Roads of the Republic of Serbia (“Official Gazette RS” no. 41/2018, 95/2018), only area up to 40 m from the highway is considered to be a protective buffer zone in the landscape. Such narrow observation of the buffer zone cannot bring any greater comfort in the process of highway landscape design, and therefore, the possibility to control high-intensity winds using vegetation is minimized. So appropriately designed windbreak in the highway landscape slows down the wind and reduces its intensity (Alemu 2016). Therefore, traffic safety through vegetation control has been raised to a higher level which is shown in the results of this paper.

## 7 Conclusions and further research

The impact of climate elements can be to some extent adapted to the needs of man, but it can never be completely eliminated, and therefore, it must not be neglected. The

impact of wind on traffic safety has not been enough studied in the literature, so the results of this research can be used for better understanding of the highlighted issues. The average values of wind, as climate factor on a weekly, monthly, and even annual basis reduce the importance of this issue. As a result of that, high-intensity winds that occur for only 1 h during the day can cause numerous traffic accidents, where a fatal outcome is not excluded. Therefore, daily and hourly data processing should be pursued in order to have a clear insight into the danger to which drivers are exposed to in open windy areas. Setting the points for wind monitoring along the highway should certainly be the goal to be pursued, but in the absence of adequate conditions to achieve that, the methodology presented in this research may be a step in bridging the path from macro- to micro-level and even implementing the proposed model of highway landscape design.

Recording the weather conditions in traffic accident reports should be made obligatory. It is not easy for police officers to accurately record wind conditions, but certainly, it should be possible for the competent authorities to establish a special body to collect information on wind-related accidents in cooperation with the police (ordinary or with the help of modern technology). Although this research was conducted on a particular highway route, it opens the possibility for further research of the impact of wind on traffic safety, both in Serbia and beyond, in the countries with similar geographical features and climate characteristics.

It is clear that extremes are the ones that cause fatal outcomes in the traffic. Therefore, their recording and monitoring is of great importance in the process of adequate highway landscape design as well as establishing adequate safety measures. One of the measures for mitigation of the impact of wind on the road is landscape vegetation. Vegetation in the highway landscape is a topic that has not been widely discussed, and this paper raises more questions than just the role of vegetation windbreaks. For example, how vegetation regulates the impact of other climate elements on traffic or how the highway landscaping increases the cultural aspect of the area. We believe that further research should go in the direction of the impact of these windbreaks on *Košava* impacts that have proven to be very variable at micro localities. There is also a question of how big is the drivers’ awareness regarding the traffic safety and highway landscapes that they are driving through. However, these can be the subject of some future research.

**Author contribution** IS: conceptualization, methodology, investigation, writing – original draft, visualization, supervision; TD: methodology, software, writing – original draft, validation, visualization; JĐ: conceptualization, methodology, writing –original draft, supervision; ML: investigation, writing – review & editing; JČ: investigation, writing – review & editing.

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**Data availability** Not applicable

**Code availability** Not applicable

#### Declarations

We declare that this research paper has been composed solely by ourselves and that it has not been submitted, in whole or in part, in any other journals. Except where states otherwise by reference or acknowledgment, the work presented is entirely by our own.

**Ethics approval and consent to participate** The paper does not include work on animals and humans, and it is not subject to ethics board approvals. Consent to participate is not applicable.

**Consent for publication** Not applicable

**Conflict of interest** The authors declare no competing interests.

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