Homogenization of driving conditions when incoming wind angles and intensity change significantly

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Abstract

Bora is a local, changeable wind that significantly decreases traffic security on the Zagreb-Split motorway on the south side of the Velebit Mountain. On the road section tunnel Sv. Rok - knot Posedarje, the wind velocity increases from near zero in tunnels up to wind gusts of 69 m/s near the bridges. The incoming wind direction varies from parallel to perpendicular to the road axes. As a result of such meteorological conditions, some incidents occur. For that reason the motorway has often been closed to certain categories of vehicle, or even to all traffic, during periods of strong wind. The goal of the described project was to design windbreaks that would decrease wind force and moment acting on the vehicles in such a way that the side wind does not exceed the prescribed value. In this paper a new procedure for homogenization of driving conditions when wind direction and intensity change significantly was developed. Four different types of windbreaks are proposed, based on the results of computer simulation and wind tunnel tests. The proposed windbreaks will significantly increase safety on the motorway during strong Bora.

Keywords: windbreaks, driving conditions, Bora.

1 Introduction

The newly built section of the motorway Zagreb-Split from the St. Rok tunnel to the Posedarje knot passes through the southern slope of the Velebit in the area where gale-force Bora often occurs with the strongest measured squalls of 69 m/s (248 km/h). Bora endangers traffic safety so the motorway is frequently
closed to the traffic. In order to diminish the periods in which the motorway is closed and at the same time to increase the traffic safety, special protective windbreaks have been designed.

The motorway section investigated is 17.7 km long, with 4 tunnels, 4 viaducts and the bridge across the Novsko ždrilo (Maslenica bridge) at a level of 90 m above the sea level. Complex conditions of the route result in the fact that wind velocity on the lane changes in very short time intervals and limited space from 0 m/s in tunnels to maximum squalls of 69 m/s, while the impact angle of wind changes from perpendicular to longitudinal, thus significantly diminishing traffic safety.

![Figure 1: Situation of the investigated section.](image)

2 Bora

Bora is a local, changeable wind that considerably differs from other winds. One of the main characteristics of Bora are great wind velocity fluctuations within a short time interval, or, as it is called in meteorological terminology, the Bora gusts.

From the synoptic standpoint, on the macroplane, it can be said that Bora occurs at locations where cold Arctic air masses reach the relatively warm boundary zones (seas or lakes). The most characteristic areas where the Bora blows (occurs) are the east coast of the Adriatic Sea, the Black Sea and the western coast of the Bajkal Lake [1].

Wind conditions are determined by geographical position, distribution of baric systems of global circulation, influence of sea and hinterland, season, time of day, height above sea level, exposure of constructions (viaducts, road sections) and other factors. From the meteorological point of view the observed section is in the very complex area, where, as a result of varied terrain, different atmosphere conditions meet in a comparatively small area. Great difference in height above the sea level and the vicinity of the sea are factors that cause strong and stormy wind in the area through which the motorway passes.
3 Homogenization principle

3.1 Meteorological model

In order to comprehend maximum velocity of wind (Bora) and its direction, as well as its incidence, a meteorological model was made. The analysis of flow regime was conducted based on the measured directional data available at the time, wind velocity in the wider motorway area, and the estimated wind direction and velocity distribution along the motorway route.

Interpolation of velocity fields was carried out by use of Wind Atlas and Application Programme (WASP) Model [2], and the statistical analysis, i.e. incidence determination, by Weibull’s distribution. For the detailed analysis 58 points along the route were selected [Fig. 2], less than 500 m apart. For each point maximum wind velocity with return period for 2, 5, 10, 20 and 50 years was defined.

![Figure 2: Characteristic points of the meteorological model along the motorway route [2].](image)

Results show that strong and gale-force winds may be expected along this motorway. On certain sections maximum wind velocity will exceed the maximum permitted wind velocity for traffic to proceed normally \( (v_{\text{max}} = 30 \text{ m/s}) \), lasting for 400-500 hours annually.

The results of meteorological model as well as meteorological measurements on the spot showed that velocity and direction of wind along the route differ considerably. Moreover, it should be stressed that wind direction is very rarely perpendicular to the traffic axis i.e. it is often at an acute angle in relation to the road and in some places vertical wind component also occurs.

Another considerable problem is the wind at an acute angle that, in case classic perforated rocks are put in, could be channelled and thus increase the
velocity on lanes by as much as 30%. Therefore windbreaks should have been designed and tested in order to protect vehicles from winds at an acute angle and longitudinal wind.

3.2 Relevant wind strains

By legal regulatory rules mean wind velocities have been set down (10 minute average) at which ban of traffic for certain vehicle categories should be introduced. In case of dry roadway traffic is banned for all vehicles at wind velocity of 30 m/s. Measurements on the spot showed that maximum mean 10-minute wind velocities exceed 41 m/s, with squalls up to 69 m/s.

Data collected by the use of anemograph provide the insight into the most frequent wind direction and its mean velocity. Within the 10-minute interval a considerable percentage of data (velocities) deviate from the mean wind velocity and most frequent direction, as a consequence of turbulences, i.e. big whirlpools.

By the present regulatory rules only the maximum mean 10-minute wind velocity at which the traffic could follow the normal course has been defined, while no consideration was paid to the angle between the wind impact direction and the direction in which the vehicles move. It is well-known from the experience that side-wind impacts are significant for traffic safety; therefore in this paper relation between longitudinal and cross wind components has been defined in order to rationalize protection from the unintended wind effect.

Figure 3: Definition of forces and moments acting on a vehicle (after [6]).

Most bridges and viaducts span channels and river valleys; consequently, dominant wind direction is mainly perpendicular to the traffic axis. For that reason side-wind, relevant for the traffic safety, often occurs. In case the wind
blows in the same direction in which the vehicle moves, if the circulation were laminar, no side-wind would occur, so dominant wind influence would be only on vehicle acceleration or slowing down. However, because of turbulences, even if the wind blows in the same direction the vehicles move, side-wind component should be taken into consideration.

When observing and describing turbulences it is very often assumed that turbulence is isotropic ([3], [4], [5]). At the meteorological station installed near the Maslenica Bridge that is critical point of the whole section, per second values of wind velocities and directions have been measured. Based on the measured data about per second values of wind velocity and direction, maximum side-wind blows were calculated.

The first approach of establishing maximum side-wind impacts is based on the analysis of the per second values and comparison of mean and maximum values.

The analysis shown is based on the processing of data collected by use of the anemograph on December 23, 2002 during the gale-force Bora. On the basis of the collected data mean wind velocity ($v_{SR}$) and mean angle ($\alpha_{SR}$) were calculated, while maximum per second wind impact and its direction ($v_{MAX}$ i $\alpha_{MAX}$) were singled out. These data were used to establish maximum side-wind component ($v_{B,MAX}$) occurred in the observed period.

\[ v_{B,MAX} = v_{MAX} \sin (\alpha_{MAX} - \alpha_{SR}) = 57,2 \sin 26 = 25,07 m/s \]  
\[ v_{B,MAX} = 43,83\%v_{MAX} \approx 0,5v_{MAX} \]  

where:

- $v_{B,MAX}$: maximum side-wind impact
- $\alpha_{max}$: direction from which maximum wind impact was registered
- $v_{MAX}$: velocity of the maximum side-wind impact
- $\alpha_{SR}$: direction of the mean wind velocity

The adopted value of the side-wind impact coefficient is 0.50, thus defining the side-wind impact as half of the mean wind velocity. After having carried out statistical analysis of the obtained results it was concluded that maximum squalls are by 47% bigger than the mean value. If this deviation is presumed to be a result of turbulence (which is adopted as being isotropic) it could be concluded that side-wind impacts would equal 47%.

Another approach of determining side component is based on the presumption that circulation is turbulent, while the turbulence itself is isotropic. If we adopt the fact that the mean value of the side component of the velocity vector equals zero, and that standard deviation of the side component equals standard deviation of the longitudinal velocity component, maximum side-wind impacts (with 99.7% probability) could be calculated as triple value of the standard deviation. Processing of the measured values has shown that standard deviation equals $\sigma = 9.69$ m/s and that maximum side-wind impacts equal:
By including the triple standard deviation into the calculus, the value of the side wind is obtained, that will not be surpassed in 99.7% cases.

Based on the two demonstrated analyses it can be adopted that a side-wind component of the wind blowing from an undefined angle is defined by the equation:

\[ v_{B,MAX} = 0.5 \cdot v_{MAX} + 0.5 \cdot v_{MAX} \cdot \sin \alpha \]  \hspace{1cm} (3)

where \( v_{MAX} \) stands for the maximum per second incoming wind velocity and \( \alpha \) for the angle between wind velocity vector and road axis. This equation will be used in further work for homogenization reasons.

Based on the adopted presumptions for homogenization conditions, the following equation has been acquired:

\[ v_{HOM} = c_B \cdot (0.5 \cdot v_{MAX} + 0.5 \cdot v_{MAX} \cdot \sin \alpha) \leq 30 \text{ m/s} \]  \hspace{1cm} (4)

where:
- \( v_{HOM} \) homogenized velocity
- \( v_{MAX} \) expected maximum wind velocity calculated by the meteorological model (m/s)
- \( c_B \) decrease of the wind velocity behind windbreaks
- \( \alpha \) relative wind direction

On the basis of this equation particular types of windbreaks have been selected in order to reduce wind velocity along the entire observed route to less than 30 m/s.

### 3.3 Windbreaks

Having taken into consideration very heterogeneous wind conditions along the route, in order to establish approximately equal driving conditions it was necessary to provide for a number of windbreaks of different shapes and heights. Four basic types of windbreaks were used. Their efficiency and stability was tested by use of physical and mathematical models.

Basic windbreak type that protects from side wind was composed of horizontal steel laminas. In the bottom part steel laminas are designed in such a way that they dissipate energy in the lower part, and they redirect airflow above the vehicle. For protection of traffic on bridges and viaducts windbreaks made of transparent horizontal laminas are anticipated in order to provide better perception of the surroundings.

The two described windbreak types are appropriate for traffic protection if the wind blows approximately perpendicularly to the traffic direction. In case of the
significant component in the traffic direction airflow could be channelled and wind velocity in traffic lanes increased.

The third type is a windbreak in the form of a honeycomb (hexagon) that directs the incoming airflow in vertical direction; consequently the incoming airflow is partly dissipated and partly redirected above the traffic lane. This windbreak type was proved good for the wind blowing at the angle of $45^0$ to the vehicle direction.

The fourth type of windbreak consisted of segment windbreaks in the form of bowler, adapted to the protection of the wind blowing at the angle of $20-30^0$ to the traffic direction. For this type of windbreak no efficiency data existed so it should have been tested.

The lack of satisfactory analytical solutions to the Navier-Stokes equations in the highly turbulent flow in the region of a windbreak has inevitably led to a preference for empirical description of windbreak airflow, based on field and wind-tunnel data.

The newly designed windbreak type demonstrated satisfying efficiency for traffic protection on the Maslenica Bridge having the wind impact angle of $27^0$.

Figure 4: Windbreak model scheduled for the Maslenica Bridge (air-tunnel test and full-scale model).

4 Project for wind protection of traffic on the motorway section

Based on the results of the research a project for protection of the motorway section from the St. Rok tunnel to the Posedarje knot was made. For each motorway segment (ca 20 m long) homogenization of driving conditions is based on the adopted expected maximum 10-minute wind velocity for the 10-year return period acquired by the described meteorological model ($v_{max}$). If wind velocity on the observed section exceeds 30 m/s installation of windbreaks is
planned. Based on the existing data on the efficiency of particular windbreak type (past tests and results have been published) efficiency coefficient $c_B$ is adopted. By including values of maximum expected wind velocity ($v_{\text{max}}$) of the 10 year return period, windbreak efficiency coefficient ($c_B$) and angle between wind direction and traffic axis $\alpha$ into equation (4) homogenized wind velocity is obtained that should not exceed the permitted 30 m/s.

If the originally planned protection (windbreak) satisfies this criterion as well as other established criteria (installation feasibility, aesthetic and visual criteria) their installation is proposed. In case one of these criteria is being not fulfilled, testing is carried out for other windbreak type.

In the above mentioned procedure the acquired maximum permitted wind velocity of 30 m/s is based on the previous experience and present road traffic regulations. On rest areas, it is necessary to enable safe moving of the pedestrians; based on the literature pedestrians are safe at wind force 7 - 8, that is at wind velocity of 20 m/s.

![Figure 5: Diminishing of maximum Bora squalls along the motorway route.](image)

### 5 Conclusion

After the section of the Zagreb-Split motorway from the St. Rok tunnel to the Posedarje knot was built it was found out that strong Bora diminishes considerably traffic safety. During the exploitation several traffic accidents caused by strong wind have taken place. Therefore, in order to increase traffic safety it was defined that the road should be closed if the wind velocity exceeds...
30 m/s. Because of the strong winds the motorway is closed as much as 800 hours per annum.

In order to increase traffic safety and diminish the period in which the motorway is closed for the traffic, windbreaks have been designed. As a result of changeable wind intensity and direction in relation to the traffic axis, considerably different driving conditions occur along the route.

In this paper a newly developed algorithm for designing traffic protection from the unwanted wind influence has been shown. The used equation takes into consideration windbreak efficiency, turbulence and the wind impact angle. By using the equation during windbreak designing the influence wind could be considerably diminished and homogenized, and consequently shorten the periods in which the motorway is closed for the traffic and increase traffic safety.

In order to protect traffic from the wind blowing at an acute angle to the traffic axis, a new windbreak type was developed, tested in wind tunnel, on CFD model and on testing field. The newly designed windbreaks have demonstrated considerable efficiency in these specific conditions.

References


