# RESEARCH RESULTS ON THE EFFECTIVENESS OF WIND PROTECTION STRUCTURES ON MOTORWAYS

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## Abstract

Motorway A1 in Croatia is exposed to the gusty north wind "bora", exceeding 250km/h. The motorway section situated on the slopes of the Velebit Mountain is sometimes closed for traffic, precisely due to safety requirements. This creates the need for adequate protection using specially designed structures. The paper describes the interdisciplinary approach of the research (meteorology, aerodynamics, structural engineering, road designing, etc.), presenting results of several research stages. At the beginning, significant results of mathematical model of wind speed and direction was provided detecting endangered motorway sections. Several types of wind barriers were tested in the recirculation wind tunnel. So called test sections were built along the motorway, in order to maintain the experimental field in scale 1:1. Different types of wind barriers built on the motorway embankment or viaduct are presented as well. In order to validate the presumed results, special method of dynamic measurements (DMV) of wind parameters is established. Efficiency of implemented structures is presented through the results of dynamic measurements along the motorway test sections.

*Keywords: gale, traffic safety, wind-protecting structures,*

## 1 Introduction

The relief and weather characteristics of Croatia strongly influence the process of design and construction of the motorway network in the country, as well as the ongoing of traffic on already constructed motorway sections. The connection of the continental and coastal parts of the territory requires that the motorway passes through a rough mountainous area where the continental and Mediterranean climates meat. That is why we can expect strong winds, especially the Bora, on the slopes of the Velebit Mountain. This paper tackles the problems relevant to strong gusts (Bora) on the A1 motorway section, from the south portal of the Sveti Rok Tunnel to the Maslenica Interchange.

## 2 Characteristic of Bora

The motorway runs along the slopes of the Velebit Mountain, and the very presence of the mountain enhances the occurrence of intensified turbulent winds of large vertical and horizontal shear, also known as Bora. [2]. Strongest Bora occurs during the winter although the summer also marks strong Bora winds. It is an unstable wind in speed and direction. Figure 1. shows the annual maximum wind speeds found at the Maslenica Bridge. We can see significant wind speed drop as we move toward the summer months and an upward, increasing wind speed trend as we move toward the winter months. The maximum recorded wind speed was measured in 1998 at the Maslenica Bridge, amounting to 69m/s=250km/h, which is the maximum recorded wind speed in Croatia [2].

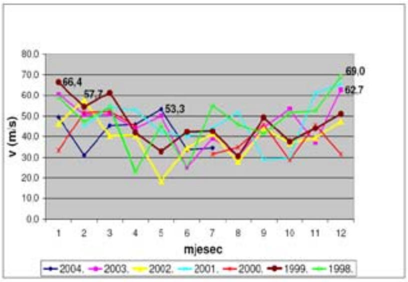


Figure 1 Maximum wind speed from 1998 to 2004 on Maslenica bridge

The wind speed during Bora (Figure 2) varies significantly. During high wind speeds, there is a difference between current wind speed, wind gusts and the maximum 10 minute speeds. During the maximum recorded wind speeds of approximately 70m/s, the maximum 10 minute wind speed was 40m/s. This factor has an important role in traffic safety and traffic control measures. For a detailed analysis of such an orograpfically very complex area as the one through which the motorway passes, we would need data on continuous, year long, wind

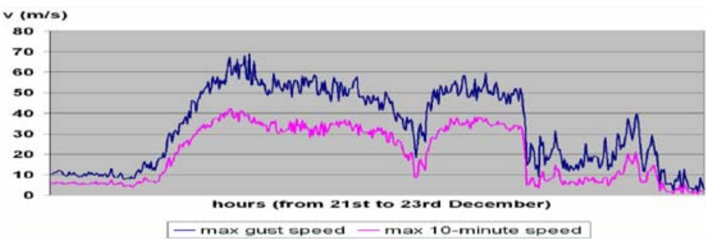


Figure 2 Maximum recorded wind speed: Maslenica bridge 22nd December 1998: 69,0 m/s = 248.4 km/h

speed and wind direction measurements at several locations. There are 11 measurement stations in the wider motorway area. In order to evaluate the level of traffic safety on the complete section, the method of wind interpolation according to the Wind Atlas and Application Programme (WA$^s$P) was taken, making it possible to calculate wind speeds at a series of representative points. For the complete subject section (Figure 3), based on 65 chosen representative points along the motorway, the average calculated wind speed is highest for the N-NE wind direction [2].


Figure 3 Wind speed interpolation points using WA$^s$P

# 3 Influence of Bora on traffic

## 3.1 General outline

According to current experiences, traffic control on the A1 motorway is done in two ways: by driving speed limits, and traffic bans for certain categories of vehicles. An ultimate control measure is traffic ban for all categories of vehicles. Critical wind speeds for implementation of certain traffic control measures are empirically determined and depend on the wind speed and condition of carriageway. There some researches on vehicle stability under wind influence, differing in limit wind and vehicle speed criteria, also pointed that the wind gust in the interval of 0.5 to 1s is sufficient to overturn a vehicle.
On the A1 motorway section, the mean 10-minute wind velocity at which the motorway is being shut for all vehicles is 108km/h, or approximately 30 m/s. Wind velocities exceeding 110km/h are expected during 50 to 100 hours a year, at certain locations even 400 to 500 hours a year, while the motorway would be closed [2]. Although the greatest wind influence on road closure occurs during the winter, estimates show [2] that the motorway would be closed for 1st category vehicles for approximately 120 hours even during the summer. At this time, the vehicle structure on the motorway is represented by camp trailers, which are very susceptible even to lower wind velocities. Therefore, installation of windbreak structures to decrease wind velocities at critical points, seems justified. Having in mind the very high wind velocities that can occur (up to 250km/h), it is not rational, and even not possible, to implement an absolutely foolproof windbreak system. The aim is to raise the critical wind velocity at which the motorway would be closed due to safety reasons.

## 3.2 Criteria and basic parameters for construction of windbreak structures


**Figure 4** Relief where strong bora blows

The critical wind velocity in the windbreak structure design for the A1 motorway section is 30m/s=108km/h. When the wind velocity exceeds 30m/s, motorway needs to be closed. An adequate windbreak structure system, can actually increase the critical closing wind velocity for approximately 40% [1]. At this point, driving conditions need to be homogenous, meaning that similar driving conditions need to be achieved at all critical points. This requirement is not easily met. Strong winds are susceptible to sudden change of direction and wind gusts. Current gust velocity (Figure 2) at high wind velocities can reach almost two times the value of 10 minute velocities. Another important factor is the road itself. The relief along the subject motorway section varies significantly (Figure 4), so the motorway passes through cuts and on embankments. Cuts can be sometimes considered as good natural shelter, where height of the cut and its length play a major role in the safety factor. A turbulence area can be created at the entrance and exit of the cut, due to the wind diffraction effect. Also a change in the motorway plan view elements in relation to the wind direction can create an area of turbulences even in the cut, especially if the wind acts under a small angle (from 0 to 30°) in relation to the centerline. In case of lateral wind direction, high embankments can cause strong turbulences at the edge surface (emergency lanes, windward carriageway parts). The number and width of traffic lanes and the central reserve are also changeable categories and influences the windbreak solution.

# 4 Windbrake systems on the A1 motorway

The task of the windbreak project is to ensure uniform driving conditions along the complete motorway section. This means that there can not be points or locations with strong lateral wind gusts.

## 4.1 Types of windbreak structures

Four types of windbreak structures have been applied on the trial sections:
1 Solid windbreak structure in the shape of artificial high embankment
2 Permeable windbreak structures with steel plates,
3 Permeable windbreak structure with transparent plates,
4 So-called segmental windbreak structure
According to the results of performance model tests for solid and permeable windbreak structures [3], the permeable windbreak is considered efficient up to 50% of its level of permeability. The level of permeability is defined as follows:

$$\Theta = \frac{A_{prop}}{A_{ukupno}} \leq 1{,}0 \qquad (1)$$

where: $A_{prop}$ - surface area of the permeable windbreak part,
$A_{ukupno}$ - total windbreak surface area.

Optimal permeability is within the following limits:

$$0{,}2 \leq \Theta \leq 0{,}5 \qquad (2)$$

One rule was applied on the test sections, this being that the windbreak height required for protection of one motorway carriageway is 4m, and for both carriageways this height is 8 m. There windbreak heights were chosen according to the model tests [4], but also as a result of the static analysis of structure.

## 4.2 Initial tests performerd in a wind tunnel

The windbreak system test sections were chosen on the basis of initial tests of the performance of certain types of windbreaks, which were done in a wind tunnel at the Faculty of Civil Engineering in Zagreb [4]. Their performance was tested with respect to the road width as well as the structural and spatial capacities for their application. The solid windbreaks type “high embankment” were tested, to protect the complete carriageway width, as well as permeable windbreaks, which protect each carriageway separately. The permeable, plate and segmental windbreak models were tested for different wind directions (angles): 30°, 50°, 70° and 90°. The wind speeds in front and behind the windbreak structure were measured, as well as tension measurements, to obtain the level of stress at the joints between the permeable and the solid part of the windbreak. The results of the wind tunnel tests showed that the expected decrease of wind speed profile occurs in the area behind the windbreak, which simulates the traffic lane (Fig. 5).

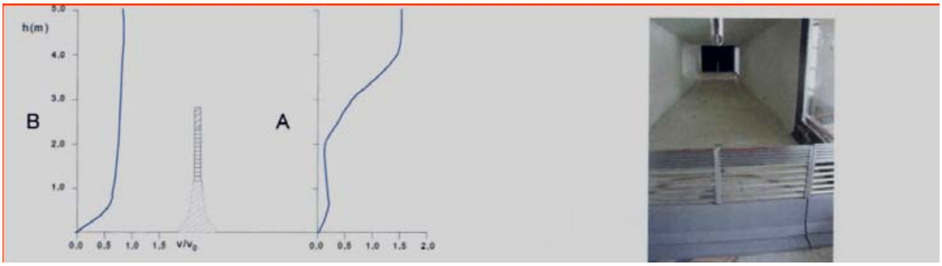


**Figure 5** Model testing of permeable windbrake structure, made in scale 1:5

### 4.3 Solid windbreak structures type "high embankment"

The windbreak structure type "high embankment" was installed at two test locations, where the terrain configuration allowed, using material from the nearby dumping site. The high embankment acts as a solid windbreak structure, 8m high, protecting the complete carriageway width. The leeward embankment side is made of gabions, to achieve as steep slope gradient as possible so that the embankment crown is as near as possible to the area being protected (Figure 6).


**Figure 6** Solid windbreak structures type "high embankment"

### 4.4 Permeable windbrake structures

According to the model tests of the efficiency of solid and permeable windbreak structures [3], [5] in decreasing the wind speeds, the permeable windbreak is considered effective up to 50% of porosity. The plate-like windbreak on the test section is given in Figure 7. Each carriageway is protected with one 4m high structure. The structure consists of a concrete safety fence in its lower part, with steel HEA profile posts mounted on the fence, and panels inserted between them. The panel fill elements are a "V" shaped cross section and at the top, the fill has a special shape that enables the air flow to be directioned upward, as far from the traffic ongoing area.

The concrete fence in the lower part is used as a windbreak and as a safety fence. Due to a significant load, the top of the concrete fence is a widened to enable a safe transfer of forces from the steel to the concrete structure part. The concrete fence foundations are made of piles because of different types of obstacles in the motorway body and the central reservation (buried utility installations, electricity, water, telecommunication, sewage, lighting posts), which are preserved this way.

**Figure 7** Plate-like windbreak structure

The permeable windbreak option with transparent panels was constructed as a test section on the Baričević Viaduct (Figure 8), not limiting the line of sight toward the sea. It consists of steel posts with transparent panels attached to them. Joints between the panels and the steel posts consist of steel seats with rubber inserts to reduce the vibrations of structural elements. Similar examples have been applied on viaducts Millau in France and the Črni Kal in Slovenia.

**Figure 8** The permeable windbreak structures with transparent panels

## 5 Measuring the wind parameters on trial sections

Measurements in actual conditions in the filed are done to verify assumptions and test the performance of windbreak structures. The testing program includes steady and dynamic measurements. Steady measurements are implemented on trial sections by means of an anemometer placed at different measuring points along the motorway. Steady measurements also include tensionmeter measurements on the panel windbreak structure.

### 5.1 Dynamic, DMV method measurements

Dynamic measurements are made by the vehicle (Figure 9) equipped with wind speed measuring devices (ultrasonic wind sensor) on the top. The vehicle moves at a speed of 40km/h along the driving lane, in both driving directions [1]. One measurement includes 4 drives in both direction. Multiple measurements serve to determine the permanent presence of wind on individual route segments. On critical sections with three traffic lanes (slow lane, driving and overtaking lanes) the measurements include drives along all three lanes, to determine the influence of windbreak structures on the wind velocity decrease, depending on the crosswise distance from the barrier. Wind velocity measurements were also done at different vehicle operating speeds, to determine the speed limit criteria in relation to wind velocity. An odometer which records the driving distance, is mounted on the car wheel. The one second wind velocity is measured, and the three second wind velocities are calculated to compare the dynamically measured and steady measured values.

**Figure 9** Dynamic measuring wehicle

### 5.2 Results of dynamic measurements

The recorded wind velocities are further divided to its lateral and longitudinal component. The diagram shows three second wind velocities measured at locations of the trial section with high embankments, panel windbreak structures along the carriageway edge and panel windbreak structures made of transparent elements on the Baričević Viaduct .
The Figures 10 and 11 show the results of initial wind velocity measurements measured by car, on December 19, 2006. The recorded wind velocities were not extreme, but rather usual for the subject location. The diagrams present the crosswise and longitudinal velocity component obtained through 4 drives in both directions. The exact locations of trial sections are marked by the "window". The diagrams show that the crosswise and longitudinal wind velocity component on the carriageway, on all three test sections is within admissible levels (below the critical velocity of 108km/h). This enables a safe drive within the protected area. The maximum incoming wind velocity on the subject date of measurement was 36m/s, or 130km/h (measured at the measuring stations). Wind velocity perpendicular to the direction of the car (marked "crosswise" on the diagram) in all three cases shows a significant decrease in the areas protected by windbreak structures in relation to the same component outside the protected area. The measurements also drew attention to the windbreak structure approach areas on the motorway, approximately 200m long, seen in Figure 10 where the lateral component of wind velocity is stressed. In the second stage and based on previous conclusions the area of protection was extended by additional construction of a gabion wall (embankment).

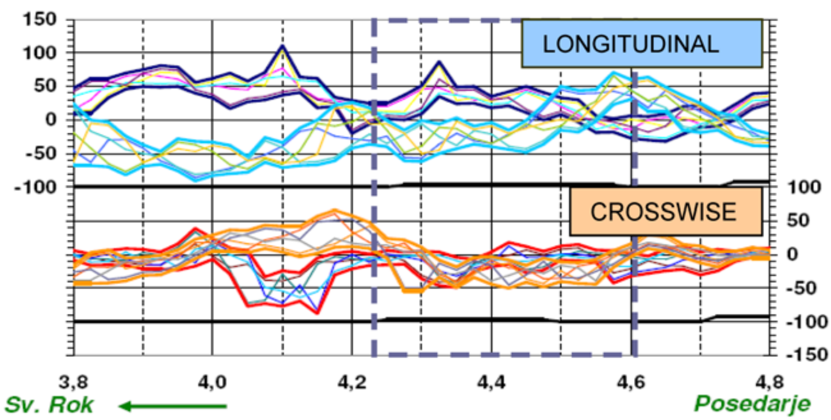


**Figure 10** The wind components measured by DMV method (embankment)

Figure 6 shows the area where the first part of windbreak embankment was constructed, and measurements implemented on this section are presented in Figure 10 ("face" of gabion wall extended toward the Tunnel Sveti Rok area later on). As anticipated, a transition area of flow was noted on all diagrams (Figures 10, 11), namely at the ends of windbreak structures. In this area, for approximately 50 to 200m, the wind flow velocity has increased due to diffraction around the windbreak. The area of turbulence is stronger with solid windbreaks, e.g. gabion walls than w permeable windbreak structures. This effect shall be alleviated by transitional windbreak structures, but after tests on numerical flow models (CFD).

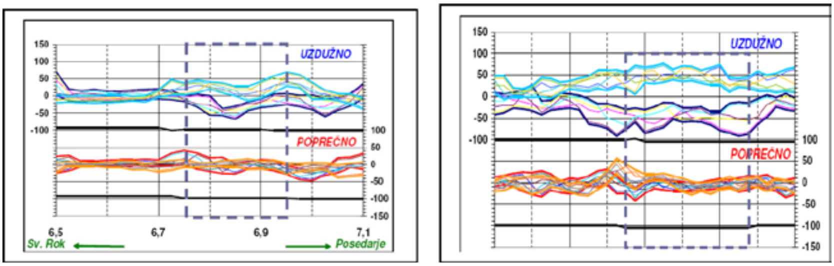


**Figure 11** Wind components measured by DMV: v. Božići - left, v. Baricević -right (longitudinal wind components-up, crosswise-down)

## 6 Additional testing by numerical simulation method (CFD)

Dynamic measurements of wind parameters on the motorway by means of the DMV method confirmed the efficiency of the windbreak structures on almost all protected areas of the trial sections. Likewise, on more complex location like the Vučipolje area, i.e. the area between the Čelinka Tunnel and Bristovac Tunnel, the subject method of measurement exposed a discontinuity in the protected part of the carriageway. This area is mostly along the boundary windbreak parts where we also have increased turbulence. These uneven driving conditions are increased by the fact that the location is in a curve, exposed to the north-northeasterly wind which, owing to the curved plan centerline, changes its angle (and direction) in relation to the motorway (Figure 12).

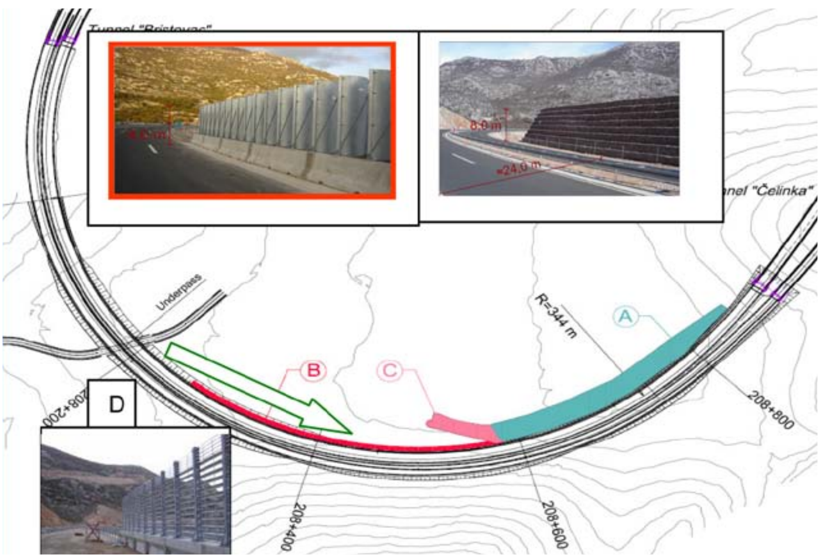


**Figure 12** Windbraking stages on test section Vučipolje

Improvement of the system and the aim to achieve homogenous driving conditions was based on the research of several options by means of numerical simulation, using the "Fluent" computer software [6]. Based on a three dimensional terrain model and the motorway interpolated into it according to the three- dimensional conceptual design, several options of the end of the gabion windbreak were modeled ( Figure 13). This was followed by modifications of the gabion wall edges according to the chosen option The same principle was adopted for the other discontinuities during the homogenization of driving conditions along the test section.

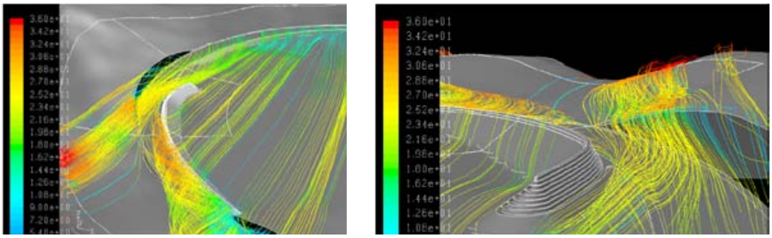

**Figure 13** CFD modeling of gabion windbrake, stage C on Figure 12.

## 7 Conclusion

In the areas with significant altitude differences, e.g. the south slopes of the Velebit Mountain, strong gusts can be expected, which can have negative effects on the safety of traffic along the motorway or the future railway line. In order to ensure safe and uninterrupted traffic operation, windbreak structures shall be designed and constructed. The wind protection systems shall be designed on the basis of year - long analysis and measurements of the direction and speed of wind on a large number of measuring stations, as well as on the basis of present knowledge in the field of Fluid Mechanics. Numerous data in literature refer to the need of a comprehensive research for each of the subject locations.
We can witness significant changes in the speed and angle of wind along the motorway route, which increases the complexity of the traffic safety design. This complexity requires a multidisciplinary and iterative approach to the solution. As part of the research on the traffic safety along the motorway section from the Tunnel St. Rok to Posedarje, results of measurements using anemometers were used, obtained in a wind tunnel on a CFD model, on a test site, as well as measurements using a specially equipped vehicle. Based on the model tests in a wind tunnel, provisional solutions are formed and degree of efficiency of safety systems is examined. Provisional solutions reached model testing in the wind tunnel are insufficient for a complex solution of the overall protection system for each location. Provisional solutions need to be supplemented by numerical simulation (CFD), especially in along the windbreak structure edges. Homogenous driving conditions are tested by means of dynamic measurements on each of the subject locations. The dynamic measurement method (DMV) proved its effectiveness by recording the wind parameters at locations with complex route geometry elements which influence permanent change of wind angle in relation to the motorway centerline. By comparing the results of steady and dynamic wind velocity measurements on the test sections, it can be concluded that the achieved decrease of wind velocity due to windbreak structure systems is within the limits determined by model tests in the air tunnel. The combination of DMV and CFD methods determines the area of discontinuities in the windbreak system and enables creation of homogenous conditions.
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