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Traffic restrictions due to wind on the Fehmarn Belt bridge

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Abstract This report documents the calculations carried out in order to estimate the wind climate at the site where the Fehmarn Belt bridge is planned. Further, an estimate of how often and for how long traffic restrictions will be enforced according to stated criteria (sec. 3.2) is given. This estimate is given both as a total percentage of time and as a mean distribution of restrictions over the year. We perform the same analysis for the Øresund and the Great Belt bridge and compare the result with the actual fractions. Only during the last year of operation of the Øresund bridge the criteria are the same as used in this report and here the comparison is satisfactory.

We estimate that the prospective Fehmarn Belt bridge will be closed roughly 2% of the time for light roadway vehicles (unloaded trucks and caravans), corresponding to 7 days per year. This is slightly less than for the Fehmarnsund Bridge. For the Great Belt bridge the corresponding *actual* fraction is 1.5%, despite the fact that this bridge uses stricter criteria. The most important difference between the bridges in this connection is their orientation with respect to the prevailing wind direction. If all the large bridges (Øresund, Great Belt and Fehmarn Belt) used the same criteria the Fehmarn Belt bridge would be closed approximately twice as much as the two others. The majority of these restrictions are likely to take place in the winter time and can be significantly reduced with wind screens.

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1 Introduction

The purpose of this study is to estimate how often and for how long traffic on the projected bridge over Fehmarn Belt will be restricted due to strong winds. Of particular interest is whether and to which extent the Fehmarn Belt bridge would experience more restrictions than the Great Belt and Øresund bridges, which are of similar size. Since no meteorological wind measurements were taken close to the prospective bridge at its maximum height (80m), data from eight near-by masts in Denmark and northern Germany were used for the analysis. How these wind data were "cleaned" from effects caused by local conditions and then "moved" to the Fehmarn area is described in section 6 below. This transformation of data provides several virtual series of measurements taken at the Fehmarn Belt bridge location.

The transformed wind measurements were analyzed and the percentage of time when the traffic would be restricted due to strong winds was calculated.

In order to check the reliability of the method, the wind data was also transformed to the locations of the Great Belt and Øresund bridges. For these two locations, we could compare the actual fraction of time when the bridges were closed due to strong winds with the estimated fractions. The criteria for both bridges has been changing and adjusted since the openings of these bridges, and therefore, an exact comparison is difficult. We further investigated the inter-annual variability of estimated restriction time and how the yearly estimated restriction time varied when using data from different sites.

A sensitivity analysis was carried out to answer the question: How would a slight change in the Fehmarn Belt mean wind climate affect the fraction of time when the bridge would be closed due to strong winds? Finally, an analysis which shows the estimated seasonal distribution of the restrictions is presented.

2 Conclusions

Due to the direction of the Fehmarn Belt bridge and a large body of open water to the west of the bridge (see Figure 1), the Fehmarn Belt bridge is expected to be closed more often than the Great Belt and Øresund bridges. The bridge will be closed according to different closure criteria for different types of vehicles. Definitions of the closure levels used in this analysis are given in Table 1.

Table 1. Definition of roadway and railway closure levels. More details are given in section 3 below.

roadway	level 2	bridge is closed for light vehicles (unloaded trucks and caravans)
	level 4	bridge is closed for all roadway vehicles
railway	level 4	bridge is closed for cargo trains
	level 6	bridge is closed for cargo and passenger trains

We estimate that the bridge will be closed for light roadway vehicles (level 2) 2% of the time. This corresponds to almost 7 full days per year, which is roughly 1 to 2 days more than the level 2 closure time for the Great Belt bridge (170 hours versus 130 hours). The existing Fehmarnsund Bridge, which is lower and much shorter but oriented in about the same way as the Fehmarn Belt Bridge, is closed for light roadway traffic on average 8.3 days per year or 200 hours. The restriction criteria on the bridges differs, see section 3. Level 4 roadway and level 4 and 6 railway traffic on the Fehmarn Belt bridge will be

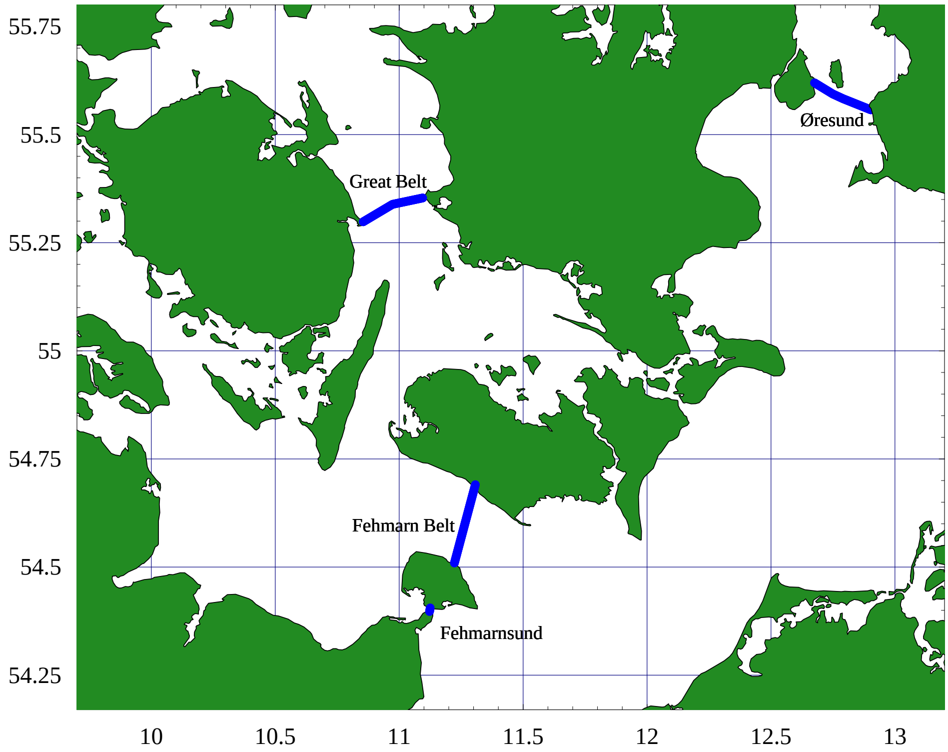

Figure 1. Great bridges in Denmark and northern Germany.

restricted less severely, but still (at least for level 4) slightly more frequently than for the Great Belt and Øresund bridge. This is equivalent to less than half a day of closure per year for cargo trains and a near zero closure fraction for passenger trains. We further find that most restrictions are likely to occur in the winter months (Figure 2) with roadway restrictions level 2 occurring on average 2 times per month in the summer and up to nine times on average in the winter months. The total monthly restriction time show a similar seasonal pattern, see figure 3. Most of the above numbers are summarized in Table 2.

Table 2. Estimated closure fractions for the Fehmarn Belt bridge and actual closure fractions for the Great Belt, Fehmarnsund and Øresund bridges. Closure fractions are given in mean number of hours per year.

Bridge	Type of traffic	level	Restrictions hours/year
Fehmarn Belt	roadway	level 2	170
	roadway	level 4	12
	railway	level 4	12
	railway	level 6	0
Øresund	roadway	level 2	98
	roadway	level 4	7
Great Belt	roadway	level 2	130[a]
	roadway	level 4	9
Fehmarnsund	roadway	level 2	200[b]

[a] slightly stricter criterion than Øresund
[b] quite different criterion, see section 3.2

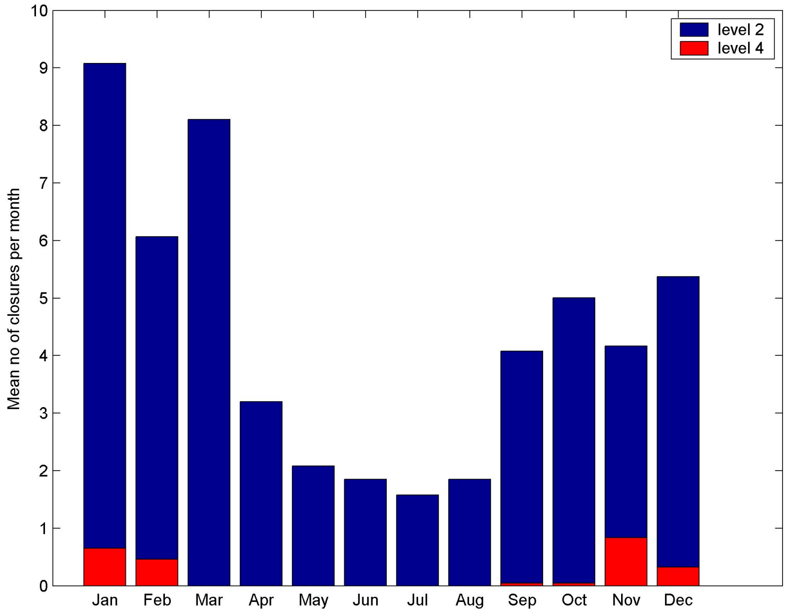

Figure 2. Mean number of restrictions per month as predicted for the Fehmarn Belt bridge. Blue is roadway level 2 and red is 4.

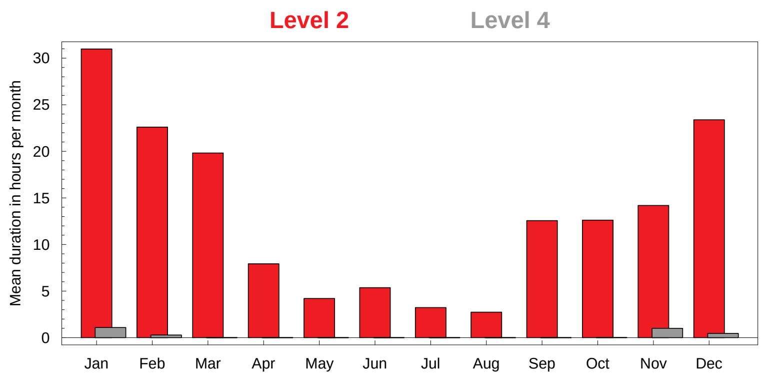

Figure 3. Mean duration of restrictions for each month predicted for the Fehmarn Belt bridge. Red is roadway level 2 and gray is 4. The analysis is based on Great Belt data.

As no measurements were taken at bridge deck height for the Fehmarn Belt bridge, a method was used, by which wind data from near-by masts in Denmark and northern Germany were transformed to the Fehmarn Belt bridge location. To check the validity of the method, data was also transformed to the location of the Øresund and the Great Belt bridges, where a comparison was possible between the estimated fraction of time when restrictions apply with the actual fraction since the bridges have been in operation. The criteria for both bridges has been changing and adjusted since the openings of these bridges, and therefore, an exact comparison is difficult.

When comparing the results from the different masts, we found a large variation for all bridges (Great Belt, Fehmarn Belt or Øresund). However, data from the five tallest masts gave results which were in good agreement. Data from the short masts, however, tended to give much higher closure fractions. In this case, we trusted the data from the taller masts, since it needed the least corrections when transforming to the high bridge locations.

The closure fraction for level 2 light roadway vehicles could be reduced from 2% to approximately 0.25% by using wind screens on the bridge. This corresponds to approximately one day or 24 hours of closure time per year.

3 Background

3.1 The Fehmarn Belt bridge

The Fehmarn Belt bridge is planned to connect the island of Lolland in southern Denmark with the island of Fehmarn in northern Germany. One possible technical solution for the Fehmarn Belt Bridge with a 4 lane motorway and a dual track railway line arranged in two levels is shown in Figure 4.

This solution comprises a southern approach bridge, a main bridge and a northern approach bridge with a total length of 18568 meter. The 3208 meter long main bridge is a cable stayed bridge with 3 main spans of 724 meter each and side spans of 278 and 240 meter. The maximum height will be 80 m above mean sea level.

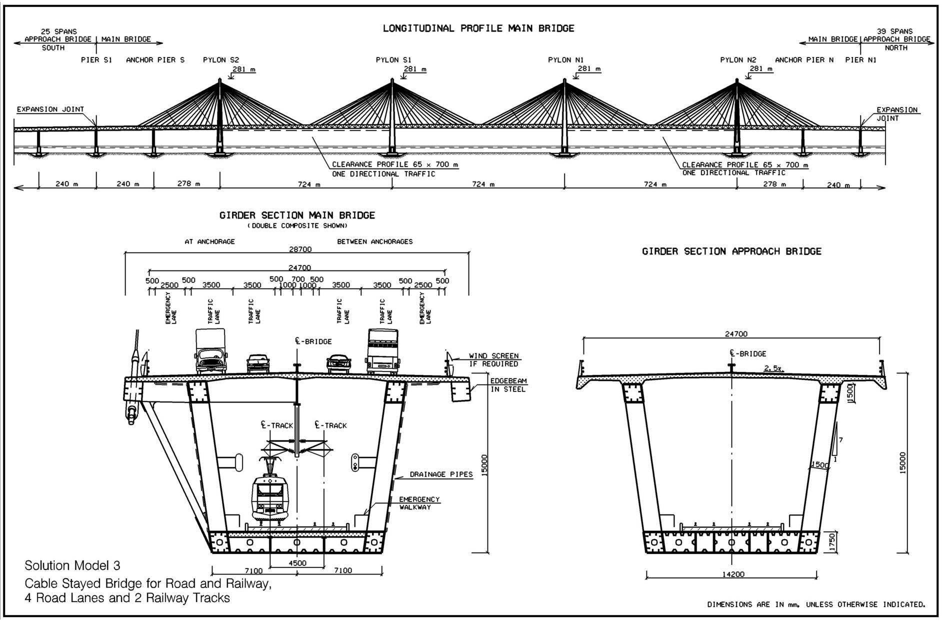

Figure 4. Sketch of the prospective Fehmarn Belt bridge.

3.2 Definition of traffic restriction levels for roadway and railway traffic due to strong winds

There are different traffic restrictions for bridges across Øresund, the Great Belt, and Fehmarnsund. At Øresund and Great Belt bridges the criteria have changed over time. The criteria involve measured winds averaged over differing periods and meteorological forecasts.

The operators of the Øresund bridge have found it appropriate to simplify the restriction criterion starting from September 30th 2003. The design of this bridge is similar to the projected Fehmarn Belt bridge, and we shall therefore use this new criterion to estimate the traffic restrictions at the Fehmarn Belt bridge.

New restriction criteria at the Øresund bridge

The wind speeds mentioned in the following are 10 minute averages.

Roadway traffic

level 2 applies for light vehicles

- Bridge closes when wind speed is above 21m/s or 17m/s for perpendicular winds.
- Bridge re-opens when the wind speed is below 19m/s and 15m/s for perpendicular winds.

level 4 applies for all roadway vehicles

- Bridge closes when wind speed is above 27m/s.
- Bridge re-opens when the wind speed is below 25m/s.

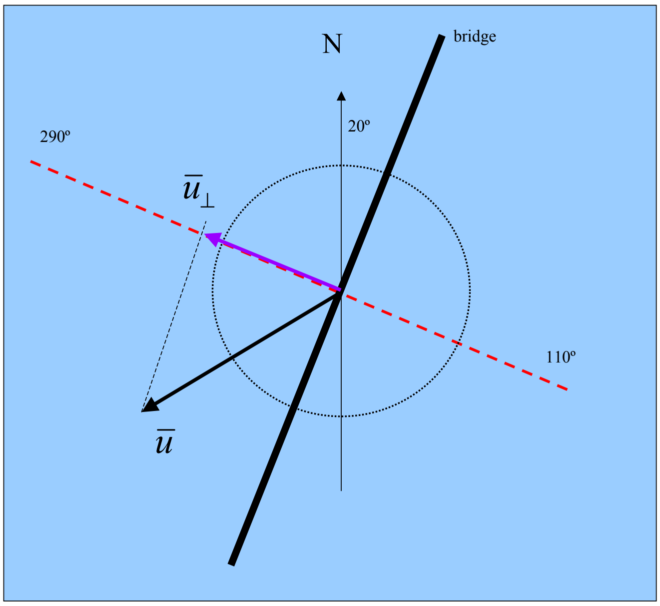

Figure 5. Illustration of how the perpendicular wind component $\bar{u}_\perp$ is calculated. The red dashed line is the axis 110-290°, which is perpendicular to the bridge angle.

Railway traffic

level 4 applies for cargo trains

- Bridge closes when wind speed is above 27m/s.
- Bridge re-opens when the wind speed is below 25m/s.

level 6 applies for passenger trains

- Bridge closes when wind speed is above 34m/s.
- Bridge re-opens when the wind speed is below 32m/s.

For level 2, closing and opening restrictions due to the perpendicular wind component are explicitly stated. From sketches of the Fehmarn Belt bridge, the bridge direction at its maximum height was estimated to be approximately 20°. The perpendicular mean wind component $\bar{u}_{\perp}$ is hence calculated as the projection of the mean wind vector $\bar{u}$ on the 110°-290° axis (Figure 5). The same procedure was used for the Great Belt and Øresund bridges, where the respective bridge directions were estimated to 77° and 117°.

Please note that railway and roadway level 4 closure and opening criteria coincide, which is why no distinction is made in the further analysis.

Restriction criteria for the Great Belt and Øresund (2000-2003)

At the Great Belt the criterion for level 2 traffic restriction is as follows. If the wind speed perpendicular to the bridge is larger than 15 m/s level 2 restrictions are enforced. However, the restrictions can also be enforced if the meteorological forecast is severe, or if measured gusts across the bridge reach a certain value. Similar criteria were used at Øresund before Sept. 30, 2003.

The level 4 criterion for these bridges are also similar to the new Øresund criteria, but again slightly more complicated.

Restriction criteria applied at the Fehmarnsund bridge

The decision depends on the wind measurements taken at the weather station in Westermarkelsdorf. The staff of the DWD station informs the responsible police station about the wind speed and direction as soon as the wind speed is above 17 m/s for more than 30 minutes respectively after a closure if it has been once below 17 m/s for more than 30 minutes. The police decides whether the bridge has to be closed. Restrictions refer to wind directions perpendicular to the bridge and to cars with trailers and unloaded lorries only.

4 Wind climate in the Fehmarn Belt area

The term climate covers how features of the experienced weather conditions are varying over decades. For the term wind climate, only aspects concerning wind speed and direction are included. The wind climate in the Fehmarn Belt area is largely dominated by strong westerly and south-westerly winds resulting from lows coming in from the North Atlantic area. The mean annual wind conditions are illustrated in figure 6. It shows the mean wind roses for the projected bridge based on the transformed Westermarkelsdorf and Sprogø data. The wind distribution based on Westermarkelsdorf data originate from hourly data from the period 1957 to 1996 at a height of 16.7 m above ground level. The Sprogø based rose use 10-minute measurements between 1977 and 1999 taken in 70 m agl. (above ground level). The wind roses show clear dominance of westerly winds. Whereas the wind directions independent of wind speed are more evenly distributed, a distinct preponderance of southwesterly winds appears for high wind speeds ($\geq$ 17 m/s). Although west winds prevail all through the year, the data series show a distinct annual course with lower wind speeds and a frequency increase of winds from Northwest in summer and higher wind speeds and an increase of Southwest winds in winter.

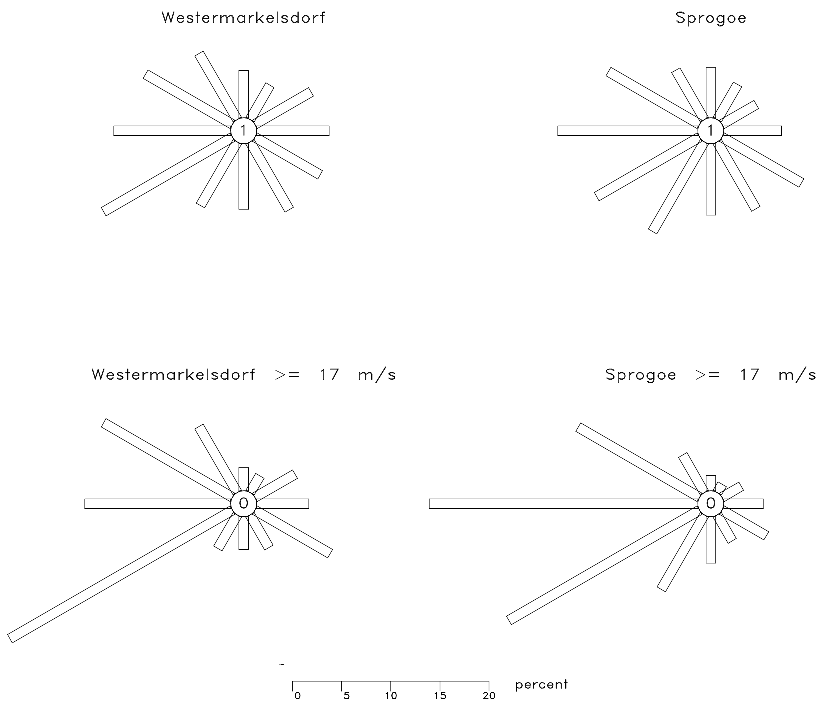

Figure 6. Annual mean wind direction distributions in percent for the Fehmarn Belt bridge position. Top: all wind speeds, bottom: wind speed above 17 m/s. Data originate from Westermarkelsdorf (1957–1996) and Sprogø (1977–1999).

5 Data material

5.1 Measurement sites

Data of wind speed and direction at three German and five Danish sites were analyzed. The location of the measurement sites and the duration of the measurement periods are shown in Figures 7 and 8 respectively. The data material show considerable differences with regard to distance from the planned bridge, measuring height and length of the data series. FS Fehmarnbelt, Westermarkelsdorf and Puttgarden are in close vicinity of the Fehmarn Belt bridge, whereas Sprogø is about 80 km away.

The tallest mast was located at the Sprogø site with wind measurements up to 70 m height. From the other Danish sites, mean wind measurements from 45-48 m were analyzed, whereas for the German sites, measurements were taken between 10 and 17 m height.

The longest measurement series comes from the German Westermarkelsdorf site, where the measurements started in 1957 and are still running. The measurement procedure at the site was changed in 1996. Since this change led to slightly different analysis methods, the Westermarkelsdorf series is sub-divided into two series. More details are given in Appendix A.

5.2 Instrumentation and data quality

All Danish sites are instrumented with Risø cup anemometers (Papadopoulos *et al.* 2001, Kristensen and Hansen 2002) for measuring the mean wind speed and Risø wind vanes for the mean wind direction. The Rødsand site was most properly attended to with regular re-calibration of the instruments. Since each re-calibration showed that the instruments

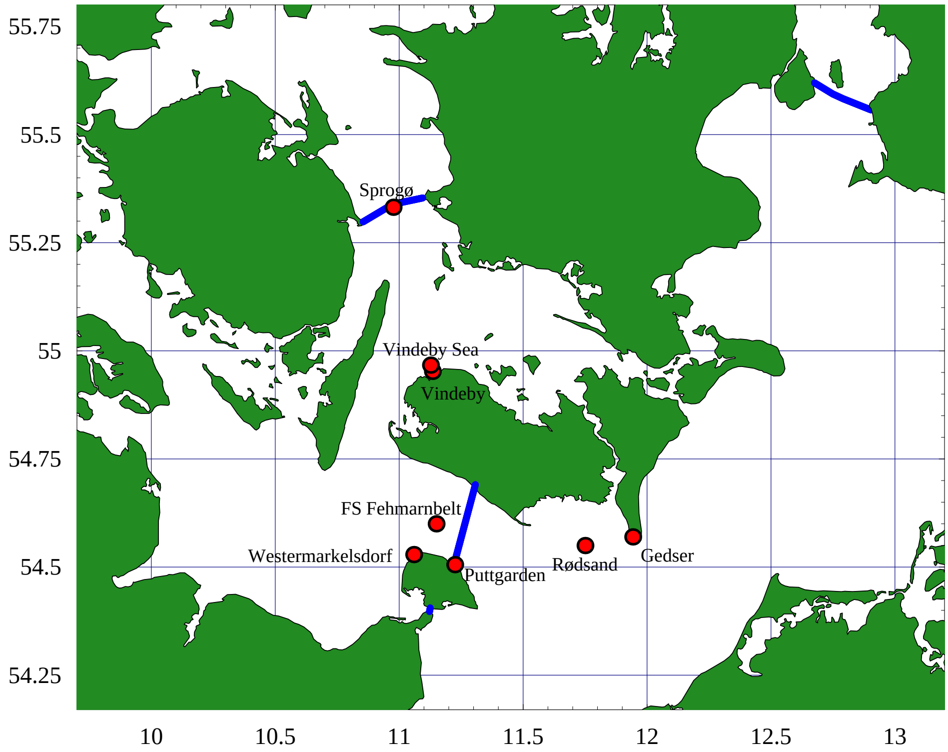

Figure 7. Map of the meteorological measurement stations, which are used to create a virtual wind database for the Fehmarn Belt bridge.

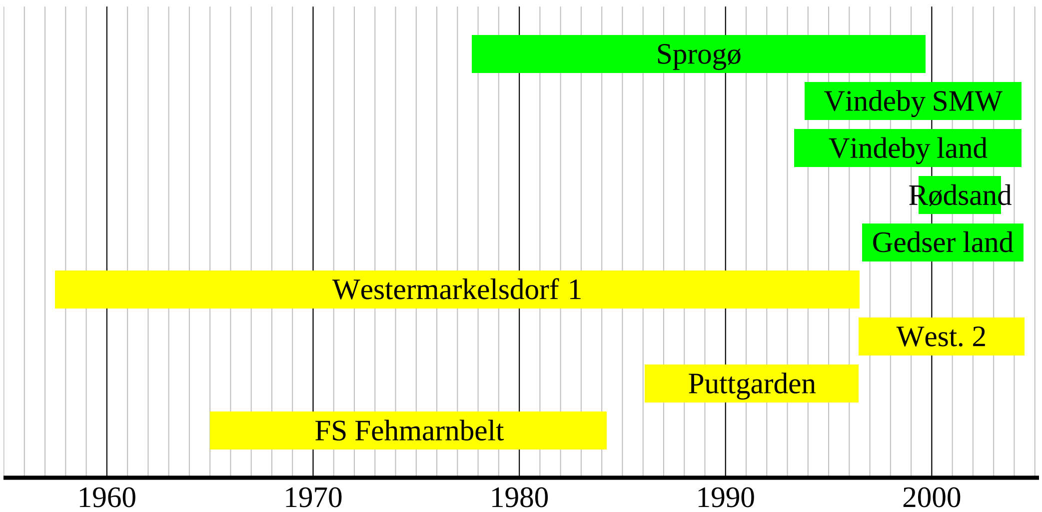

Figure 8. Time periods of the evaluated meteorological data.

were in good shape and needed minimal corrections, the instruments at the other Danish sites, which were re-calibrated less frequently, are trusted to give high quality data. This impression is further strengthened when comparing the different data series. No anomalies indicate that there is a calibration problem with the Danish data.

All data series have gaps and occasional measurements affected by errors. The gaps can be caused by lightning hitting the mast or computer problems, and the errors may be caused by instrumental problems. Additionally measurements of the light ship FS Fehmarnbelt were interrupted during periods of dockyard overhauls (September 1981) and heavy ice drift (winters 1966, 1970 and 1979).

All German data come from manned stations of Deutscher Wetterdienst. The instruments were regularly attended and re-calibrated according to the high-quality standard of the Service.

The failure frequency and the error-coding procedure for all sites are reported in Appendix A. Generally, all German sites have fewer samples missing due to errors and gaps in the series.

5.3 Data sampling

The wind measurements on the Great Belt and Øresund bridges are based on 10 minutes mean values of continuous measurements. This matches the Rødsand and the Sprogø sites. The other Danish sites give mean values over each half hour and Westermarkelsdorf up to 1996 hourly means. The data of the other German sites are sampled discontinuously: a 10 minute measurement period is followed by 50 or 170 minutes when no data are stored. In order to take these different sampling schemes into account when estimating the restriction frequency, the Sprogø site has been re-sampled to match the alternative sampling schemes.

The main analysis, which finds the periods when the bridge should be closed, is run on both the original Sprogø series (10 minute mean values) and the re-sampled Sprogø series. Correction factors χ, which are the ratio between the restriction time fractions for the differing sampling schemes can then be calculated and applied to data from sites with alternative sampling schemes.

6 Method of evaluation

6.1 Basic meteorology and WAsP Engineering

In the atmosphere the wind speed increases in general with height. It vanishes close to the ground, increases rapidly the first few meters, then more slowly. How sharply the wind increases with increasing height is connected with the aerodynamic roughness of the surface and the stability of the thermal layering. For the same large scale meteorological conditions the wind is stronger over the sea than anywhere else. Other surfaces, such as rural countryside, a forest, or a town, reduces the wind speed more efficiently. Terrain topography also affects the atmospheric flow. Risø has developed a program called WAsP Engineering (Mann *et al.* 2002) to take into account all these effects on the flow. By removing the local effects and imposing new conditions at another location, measurement data can be transformed from one place to another. One condition for performing such a transformation is that the two locations are sufficiently close to each other, *i.e.* that they experience the same background wind climate. However, within an area with the same wind climate, a single storm event will cause very different wind speeds depending on the exact storm track. WAsP Engineering can not transform information from one site to another for a single event, but only the statistical features of the flow. The long measurement series provided by the masts presented above describe with sufficient accuracy the mean wind climate in the Fehmarn Belt area. They are hence a good basis for the WAsP Engineering analysis.

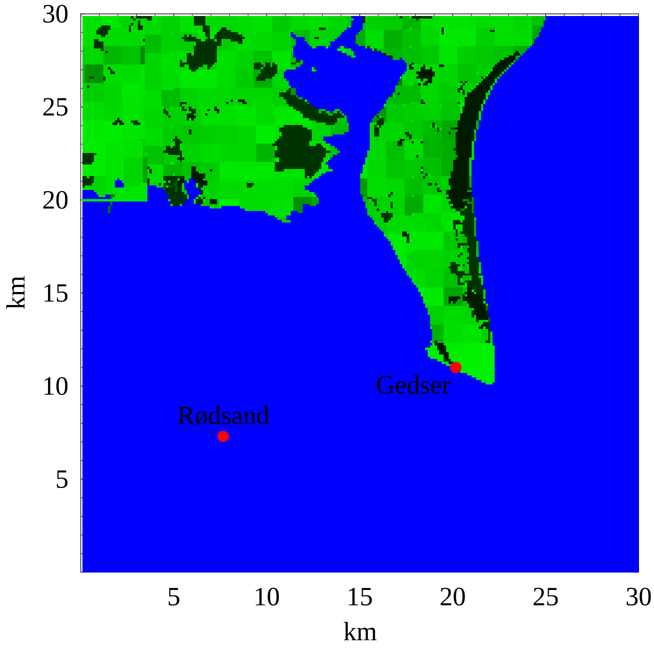

Figure 9. Map of the aerodynamic roughness, which is an input to the flow calculations, together with the position of the Risø meteorological masts Rødsand and Gedser.

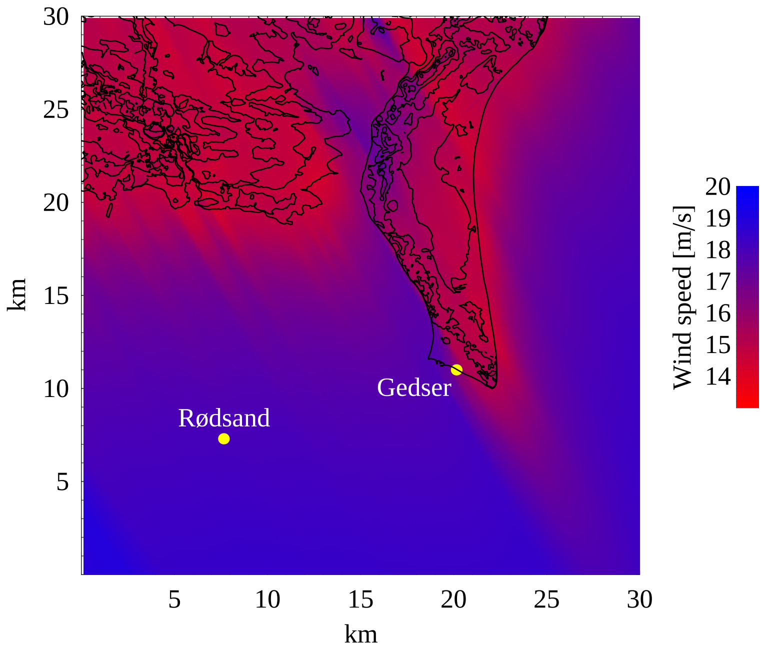

Figure 10. Height contours and the wind speed at 45 meter above the ground or sea level.

6.2 Creating the virtual Fehmarn Belt database

We use the WAsP Engineering flow calculations for the sites Rødsand and Gedser to illustrate how a virtual wind climate database for the Fehmarn Bridge location may be constructed. Figure 9 shows the aerodynamic roughness z_0 of the area surrounding the sites Rødsand and Gedser. The blue colour indicates the sea, where the roughness is low, less than 1 mm, but varies slightly with wind speed and distance to the coast. Going from

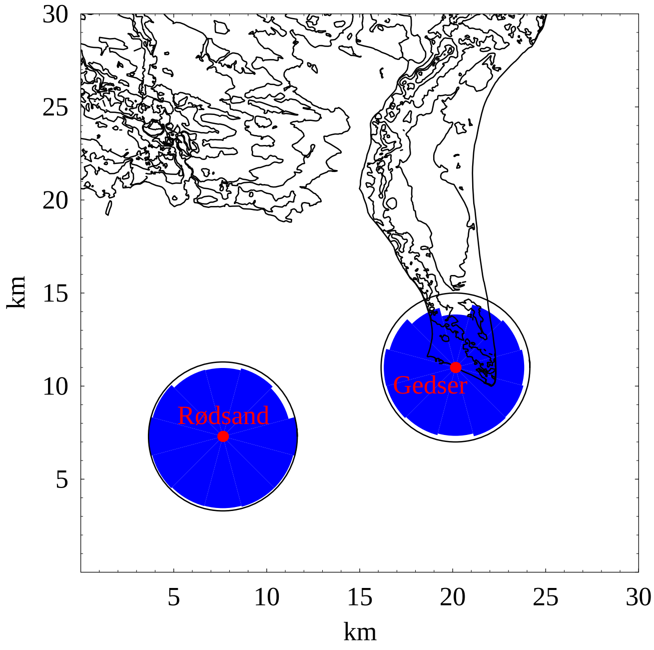

Figure 11. Calculated wind speed correction for each 30° sector at Rødsand and Gedser. The circle shows the free flow wind speed at 80 m above the sea and the blue area indicates the reduced wind speed measured at the sites due to the measuring height and the surrounding terrain.

light green to dark green the roughness increases from that of open country ($z_0 \approx 0.03$m) to towns or forests with $z_0 \approx 0.5$m. The topography shown in Figure 10 plays only a minor role because the areas surrounding the masts in this study are rather flat. Superimposed is the wind speed calculated with WAsP Engineering for a meteorological condition which gives 20m/s from the direction 330° at 80m above open sea. The wind speed is shown at 45m above the terrain corresponding to the height of the Gedser mast. Not surprisingly, the wind speed is everywhere less than 20m/s. At the Rødsand site, more than 10 km from the coast the wind speed is 18 m/s and the effect of the upstream presence of Lolland has almost faded away. At Gedser, however, the wind speed is only 16 m/s and influence of the higher roughness of the land is certainly felt. All wind speeds observed at Gedser from this direction is thus multiplied by 20/16 in order to "translate" the Gedser wind speeds to what would have been observed at a height of 80 m over the open sea corresponding to the Fehmarn Belt Bridge.

Similar calculations are done in twelve 30° sectors as shown in Figure 11. Here it is seen that for Gedser the northerly wind directions are sheltered by land, while for Rødsand the sheltering is still visible but almost disappeared. All time series from all site are converted in this way and it must be kept in mind that the the closer the anemometer is to the condition 80 m above the open sea surface the smaller the uncertainty in this procedure.

6.3 Determination of closure periods

For the main analysis, a numerical algorithm searched the individual virtual Fehmarn Belt series and selected the samples for which the bridge would be closed according to the different restriction levels. The percentage of time for which the bridge would be closed was calculated as

$$r_{closed} = \frac{No\,of\,closed\,samples}{Total\,no\,of\,samples} \cdot 100 \cdot \chi, \qquad (1)$$

where χ transforms any sampling scheme of a site to the standard format of 10 minutes consecutive mean values (see section 5.3).

7 Results and discussion

7.1 Fehmarn Belt prediction

By using all the nine measurement series, the total estimated percentage of time when the roadway traffic (level 2) would be restricted is on average 2.1%. The standard deviation of the estimates in table 3 is 1.2%. All estimates are based on 10 minute mean wind estimates as calculated from the original sampling frequency (see section 5.3). The high variation is largely due to the series based on the Fehmarnbelt light ship measurements and the Vindeby sea series. The original Vindeby sea series is most likely influenced by an off-shore wind turbine park, which could not be taken into account in the analysis. For the Fehmarnbelt light ship, a significant systematic measurement error due to the fact that the ship acts as an obstacle on the sea can not be excluded. When removing these two series from the analysis material, the result for the remaining series changed to 1.9 $\pm$ 0.7%. Another source of the variation is that many of the time series are rather short, and, as explained in section 7.4, this gives rise to a quite a large scatter. The estimates based on the two longest times series, Sprogø and Westermarkelsdorf 1 (see figure 8), are quite close: 1.8 and 2.1%, respectively. This indicates that the uncertainty on the closing fraction averaged over many years may be even smaller than the 0.7% given above.

For the level 4 analysis, when all virtual wind data is included, we get a total estimated restriction percentage of on average 0.06% with an even larger variation . This variation can be explained by two factors: (1) the events of these high wind speed are very rare and due to geographical variation and pure statistics, it is hard to get representative values for the wind climate and (2) The Puttgarden series indicates a value of r_{closed}, which represents a tenfold increase compared to the rest. The latter factor may partly be due to a problem with the flow calculations. Of all the sites, the measurements at Puttgarden are taken at the lowest height (10m) and the landscape in which the mast is located is compared to the other sites aerodynamically rough. Hence, we make a large correction for this site, when creating the virtual database for the Fehmarn Belt bridge. In addition, as the station does not exist any more, the estimation of the roughness or any disturbances of the flow cannot be properly reconstructed. Small errors in the method or the calibration of the instruments may hence be amplified to give an extreme result.

The level 6 analysis resulted in a near zero closing fraction using data from all Danish sites and Westermarkelsdorf 1. The fraction was higher for the remaining German sites.

7.2 Øresund prediction and comparison

For the Øresund bridge, the level 2 analysis based on the same station material as in Table 3 yields a restriction fraction for level 2 of 1.2 $\pm$ 0.5%, whereas the actual restriction fraction based on the year October 2003 – September 2004 (see section 3.2), where the restriction criteria used in this report was in use, was 1.1%. In light of the large yearly variation (see section 7.4) this good comparison can be pure luck. During the period with different a criterion (Oct. 2001 – Sept. 2003) the average level 2 restriction fraction was 2.9%.

For level 4 we estimate a restriction fraction of 0.05% with a large uncertainty. The actual fraction is 0.05% for the single year with identical criterion and 0.15% for the previous years. For level 6 both the predictions and the actual values are very close to zero.

Table 3. Results for the virtual Fehmarn Belt data series, estimated restriction time r_{closed} in percentage.

Original site	r_{closed} (%)			
	roadway		railway	
	level 2	level 4	level 4	level 6
Sprogø	1.8	0.032	0.032	0.00045
Rødsand	1.5	0.030	0.030	0
Gedser	1.5	0.012	0.012	0
Vindeby sea	0.8	0.011	0.011	0
Vindeby land	1.2	0.016	0.016	0
Westermarkelsdorf 1	2.1	0.034	0.034	0.0015
Fehmarnbelt light ship	4.6	0.078	0.078	0.0037
Westermarkelsdorf 2	2.2	0.063	0.063	0.0057
Puttgarden	3.3	0.27	0.27	0.014

7.3 Great Belt prediction and comparison

Again by creating a virtual wind measurement series from all nine sites for the Great Belt location, we can get a comparison between our estimate and the *actual* restriction frequency as reported by Sund og Bælt, since the bridge has been operational in 1998.

The mean result for level 2 is 0.9± 0.3 %, whereas the actual fraction of time when the bridge was closed between 1998 and 2003 is 1.5%. Here it should be remembered that the level 2 restriction criterion at the Great Belt is stricter than the criterion used here. This can probably explain the difference.

The actual restriction fraction value for level 4 was 0.1% whereas the prediction is less that 0.05%. Again the actual criterion is stricter than the modelled.

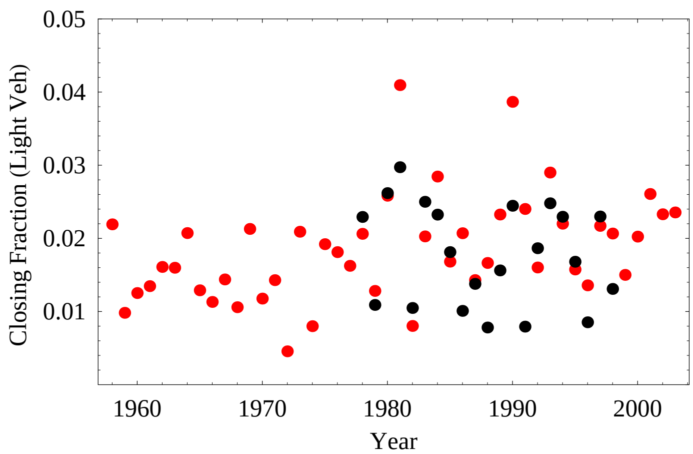

Figure 12. Annual level 2 restriction fractions predicted for the Fehmarn Belt bridge based on data from Sprogø (black) and Westermarkelsdorf (red).

7.4 Inter-annual and geographical variations

Figure 12 shows the predicted level 2 restriction fraction for the Fehmarn Belt Bridge based on data from Sprogø and Westermarkelsdorf. It is seen that the inter-annual variations are very large ranging from 0.5% to more than 4%. Furthermore, when the restriction fraction predictions from the years covered by both data series are plotted versus

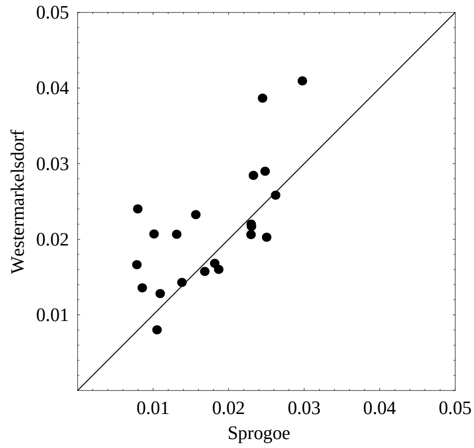

Figure 13. Annual restriction fraction predictions based on data from Sprogø versus Westermarkelsdorf.

each other as in Figure 13, individual years show large geographical variation.

The following conclusions may be drawn from these plots:

- It does not make sense to predict the average restriction fraction from one year of data.
- A restriction fraction based on one year of data can not be used to predict that years restriction fraction for a bridge 100 km away.
- Averaged over many years the the restriction fractions predicted from the two sites agree well and there seems to be no clear trend in the data.

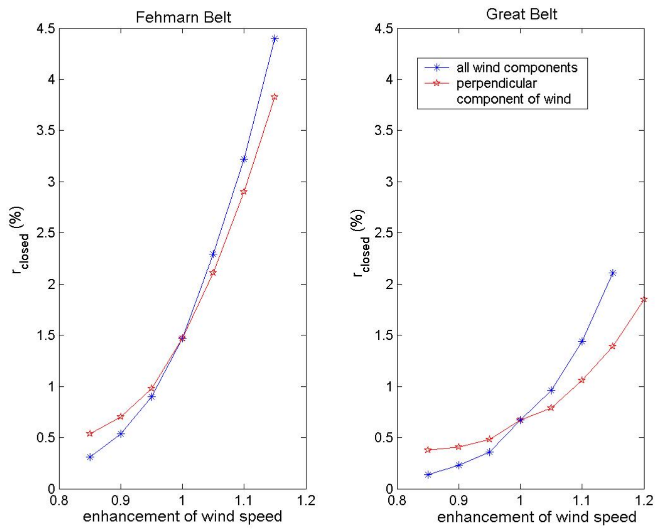

Figure 14. Sensitivity analysis which shows how the level 2 traffic restriction fraction at the Fehmarn and Great Belt bridges would respond to changes in the wind climate or a speed up/speed down effect caused by the bridge.

7.5 Fehmarn and Great Belt sensitivity analysis

The virtual wind climate databases from the transformed Rødsand data was used to estimate how small changes in the wind may affect the level 2 restriction of the Fehmarn and Great Belt bridges. The wind measurements were multiplied by a factor and the effect of varying this factor on r_{closed} was studied.

The analysis was performed, firstly, for all components of the wind ($\bar{u}$) and, secondly, the component of the wind perpendicular to the respective bridge only ($\bar{u}_{\perp}$). The first method corresponds to a general change in wind climate due to for example the greenhouse effect, and the second method to the effect of the bridge on the perpendicular winds. When the wind encounters an obstacle like a bridge, its speed will increase to compensate for the smaller cross section where the wind can pass. This effect is called speed up. The result for both methods is presented in Figure 14.

There is a difference between the reaction of small enhancement factors for the Fehmarn and the Great Belt bridges. The restriction fraction will increase more dramatically for the Fehmarn Belt bridge compared to the Great Belt bridge. This result can be explained with the orientation of the bridges. Since the traffic restrictions are more severe for perpendicular winds, the north-south orientation of the Fehmarn Belt bridge makes it very sensitive to strong westerly winds typical for Northern Europe.

7.6 Seasonal distribution of level 2 and 4 restrictions

Figure 15 shows the expected seasonal distribution for level 2 and 4 closing based on the data transformed Sprogø data (Table 3). Most restrictions are expected during the winter months. The length of the expected restriction periods were further investigated and the result is plotted in Figure 16. The restrictions will be dominated by rather short periods all through the year.

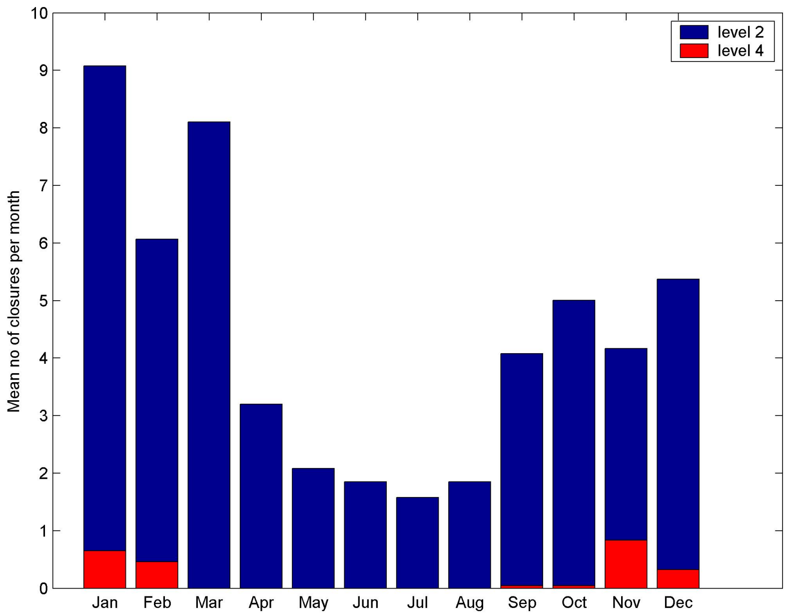

Figure 15. Mean monthly distribution of level 2 (blue) and 4 (red) restrictions regardless of duration as predicted for the Fehmarn Belt bridge. The analysis is based on the Sprogø wind data set.

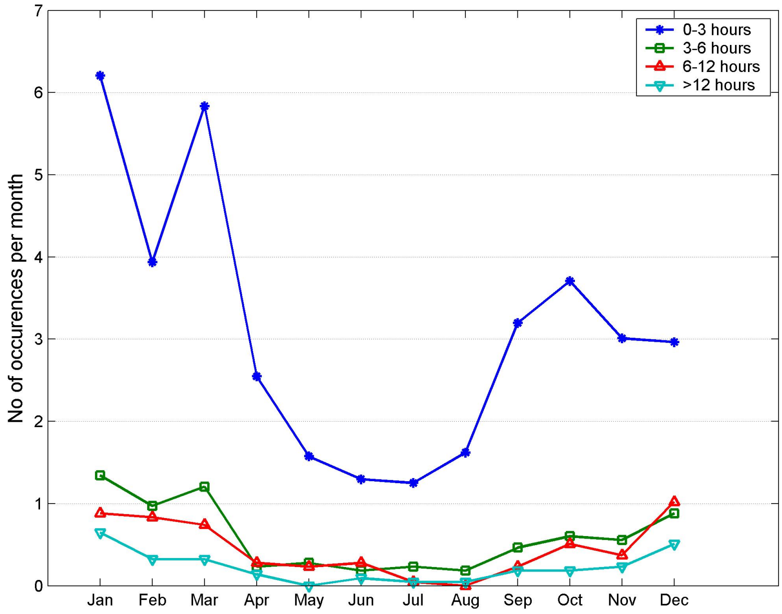

Figure 16. Expected frequencies of level 2 restrictions for four different time intervals.

7.7 Discussion of error sources

Several factors may influence the results: (1) calibration of instruments and instrument construction, (2) method errors (transforming data from one site to another), (3) speed-up caused by the bridge construction and (4) a human factor.

For the first issue, we have strong reasons to trust most of the wind data. Neither should method errors be significant for the tall mast data, since the creation of the virtual data bases for the Fehmarn and the Great Belt bridges include relatively small corrections. When transforming data from the low mast sites, the corrections are larger and a small calibration error may be magnified. The speed-up caused by the bridge was previously mentioned in the section with the sensitivity analysis and here we find a reason to believe that our method, which predicts the free wind speed, would tend to underestimate the perpendicular component of the bridge wind speed. The fourth factor mentioned above includes uncertainties concerning how strictly the bridge operators follow the restriction criteria. It is possible that due to practical reasons, the bridge restriction periods are of longer duration than is stated by the criteria.

8 Measures for reducing the expected traffic restrictions

In the Fehmarn Belt feasibility study, reported in 1999, it was foreseen that it could be necessary to introduce measures for reducing the expected traffic restrictions. The bridge design therefore includes wind screens of the entire length of the bridge.

The following is a quotation from the Fehmarn Belt feasibility study, Investigation of Technical Solutions: "Wind screens might be necessary to protect the light traffic from strong cross wind. Wind screens can be provided either over the entire bridge length

Figure 17. Wind screens on the Millau Bridge in Southern France. The bridge opened December 2004 and is the tallest bridge in the world.

or partly around the pylons where the wind screens will smooth the transition for the light traffic, first exposed to cross wind before passing the structure, then sheltered when passing and finally after passing suddenly exposed to wind again.

Wind screens can be designed either as shields composed of longitudinal or horizontal equispaced bars or perforated plates with holes. An example of the former is shown in figure 17. Wind tunnel test indicate that the shape of the openings is of minor importance for the efficiency of the screen. The porosity however, i.e. the ratio of openings to the total screen area, is of significant importance to the shelter provided and to the additional drag loading generated by the screens on the bridge.

Wind tunnel test have shown that wind screens of porosity of 0.4-0.5 are suitable for bridge design, because they offer a reasonable compromise between shelter efficiency (50-75% reduction in onset wind speed) and the drag loading on the bridge."

When extrapolating the blue curve in Figure 14, it is estimated that a 50% reduction of the wind speed would reduce the closure fraction from 2% without wind screens to less than 0.25% with wind screens.

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A Data information for all sites

A.1 Danish sites

We use data from the following sites: Sprogø, Vindeby sea mast west, Vindeby land mast, Rødsand and Gedser.

Table 4. Danish wind measurement sites

Site	Averaging time [min]	Measurement period	Anemometer height [m]	Vane height [m]
Sprogø	10	197709131435-199909080715	70	67.5 or 70
Vindeby SMW	30	199311051700-200405092358	48	43
Vindeby land	30	199304301900-200405092358	46	38
Rødsand	10	199905121500-200305091502	50	46
Gedser	30	199608151600-200406062330	45	30

The Vindeby sites were originally not error coded for a failure in the wind direction measurement. However, it was evident that errors were present for times when the measurements were identical over a longer time period. To detect these periods, a running mean filter over six hours was applied to the series. If the measured wind direction over this period did not deviate from the mean value, the sample was error coded. The time period of six hours was chosen to avoid that random samples, which accidentally had the same value as the running mean value were excluded from further analysis.

Further, the Gedser series had a flaw in the direction measurement in the spring of 2000 (5846 samples), when the measurements were within 10 degrees for approximately 4 months. The series was compared with the Rødsand direction measurements. The comparison made the extent of the period easily distinguishable and it was error coded.

The Sprogø wind direction measurement had an error during a very long time. The new direction series contains data from two instruments: one at 67.5 m (until May 1988) and one from 70 m (from 1989).

Table 5. Data quality overview for the Danish sites

Site	Number of samples			
	possible	actual	in error	Missing (%)
Sprogø	1 156 564	1 156 277	55 173	4.7
Vindeby SMW	184 238	161 512	12 148	6.4
Vindeby land	193 353	167 889	6 056	3.1
Rødsand	209 952	209 917	19 224	9.4
Gedser land	136 806	130 509	6 125	4.5

Generally the missing samples (error coded samples divided by the total possible number of samples) corresponded to around 5% of the data set.

The relatively high percentage of error coded samples at Rødsand corresponds to errors in the measurement series between the end of March to the beginning of July 2000 (13 392 samples).

A.2 German sites

Details on the German sites are given in tables 6 and 7.

All German data series, except for Westermarkelsdorf1, are discontinuous. A ten minute measurement is recorded every hour or every three hours.

Table 6. German wind measurement sites

Site	Averaging/stride [min]	Measurement period	Anemometer height [m]	Vane height [m]
Westermarkelsdorf 1	60/60	195707010000-199606302300	16.7	16.7
Westermarkelsdorf 2	10/60	199606140600-200406302300	10	10
Puttgarden	10/60	198601290800-199606101200	10	10
FS Fehmarnbelt	10/180	196501010000-198403292100	13.5	13.5

Table 7. Data quality overview for the German sites

Site	Number of samples			
	possible	actual	in error	Missing (%)
Westermarkelsdorf 1	341 880	340 392	398	0.6
Westermarkelsdorf 2	70 529	70 296	17	0.4
Puttgarden	90 844	89 450	367	1.9
FS Fehmarnbelt	56 224	55 166	15	1.9

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23	7	17	3

Abstract (Max. 2000 char.)

This report documents the calculations carried out in order to estimate the wind climate at the site where the Fehmarn Belt bridge is planned. Further, an estimate of how often and for how long traffic restrictions will be enforced according to stated criteria (sec. 3.2) is given. This estimate is given both as a total percentage of time and as a mean distribution of restrictions over the year. We perform the same analysis for the Øresund and the Great Belt bridge and compare the result with the actual fractions. Only during the last year of operation of the Øresund bridge the criteria are the same as used in this report and here the comparison is satisfactory.

We estimate that the prospective Fehmarn Belt bridge will be closed roughly 2% of the time for light roadway vehicles (unloaded trucks and caravans), corresponding to 7 days per year. This is slightly less than for the Fehmarnsund Bridge. For the Great Belt bridge the corresponding *actual* fraction is 1.5%, despite the fact that this bridge uses stricter criteria. The most important difference between the bridges in this connection is their orientation with respect to the prevailing wind direction. If all the large bridges (Øresund, Great Belt and Fehmarn Belt) used the same criteria the Fehmarn Belt bridge would be closed approximately twice as much as the two others. The majority of these restrictions are likely to take place in the winter time and can be significantly reduced with wind screens.

Descriptors

Wind climate, Fehmarn Belt bridge, closure fraction

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