Statens vegvesen

Notat

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1 Introduction

In the sequence of an analysis of the availability of the Bjørnafjorden bridge for traffic, the Cowi report [1] estimated that 96% of the downtime was associated with weather conditions, and more specifically with strong winds. We have in this technical note investigated this more closely using the wind data obtained from the measuring campaign conducted by SVV in Bjørnafjorden, instead of the Slåtterøy fyr data used in the Cowi report [1].

The results from the Cowi report [1] were based on a target downtime of 99% of availability for traffic, which corresponds 87.5h of downtime per year. This includes external impacts, traffic accidents, maintenance and inspections, and wind/weather. From all those causes, 15.6h of downtime results from the time estimation of yearly occurrences of 10-minute mean wind speed from the eastern sector (60°-120°) and the western sector (240°-300°) exceeding 25 m/s at 66.74 m.a.s.l.
There are two aspects where we focus our attention on in this technical note which differs from the Cowi report [1]:

1. The source of the wind data. The wind used in the Cowi report [1] is taken from the measuring station of the Norwegian Meteorological Institute located at Slåtterøy fyr which is very close to the coast, where we expect to measure much higher wind speeds than at the more sheltered location of the fjord. From the measuring campaign conducted at the Bjørnafjord, we have more relevant data that can be analysed.

2. The closing criteria, which is not standardised, varies from bridge to bridge. We therefore have examined the closing criteria at different bridges and can therefore select relevant closing criteria.

2 Closing conditions

To find an estimation for the downtime of the Bjørnafjorden bridge, we analysed the data for different closing criteria that we expect to be relevant during the bridge's operation. The reason for this is that the closing (and opening) criteria for each bridge, thus far, has been set differently. Although there are some similarities, they are not constant nor uniform, but more dependent not only on local factors (such as experience obtained while operating the bridge), but also on what type of system for traffic control is installed (from manual to automatic). In Table 1, an overview of when different bridges are closed, obtained from VTS, as a reference.

Defining the downtime as the yearly number of hours the bridge is closed due to the wind, one must first clarify what characteristics for the wind are monitored to which we set thresholds that are relevant for the safety of running traffic, and that ultimately can result in closure of the bridge. The most common parameters to take into account is

- U_{10min}: 10-minute mean wind speed;
- U_{gust}: wind gust speed (3 second);
- Θ: wind direction.

The closure for the traffic is then activated when the wind measurements exceed a chosen threshold. Typical examples in use are

$$u_{10min} \geq U_{10min} \quad \text{Equation 1}$$

$$u_{gust} \geq U_{gust} \quad \text{Equation 2}$$

where U is the threshold for the time dependent measured wind.

As the closing criteria is based on the safety of the vehicle while in motion, the crosswinds can be the most representative for setting the threshold. For this reason, our analysis also addresses the component of the wind which is perpendicular to the bridge. When this case is evaluated, $u^{p}{}_{10min}$ and $u^{p}{}_{gust}$, will correspond to the 10-minute mean and gust wind component perpendicular to the bridge, respectively.

To simplify, we analyse three distinct locations on the bridge (Figure 1):

1. South: at the highest elevation point for the suspended bridge deck, we assume the traffic is at approximately 50 m.a.s.l. The data measured at Svarvhelleholmen, which is closest, is the most relevant for this point. The perpendicular direction to which we determine the wind speed (crosswind) is at approximately SW-NE (90+30 deg. and 270+30 deg, where North is at 0 deg.);

2. Mid-point: at the floating bridge, for an elevation of 20 m.a.s.l., this is where the absolute wind speed is expected to occur at the bridge [2]. The crosswinds correspond to the E-W direction

3. North: at the floating bridge, where we consider the traffic is at 20 m.s.a.l, the closest measurement data is from Synnøytangen. The crosswinds correspond approximately to the direction NE-SW (90-15 deg. and 270-15 deg. from North).

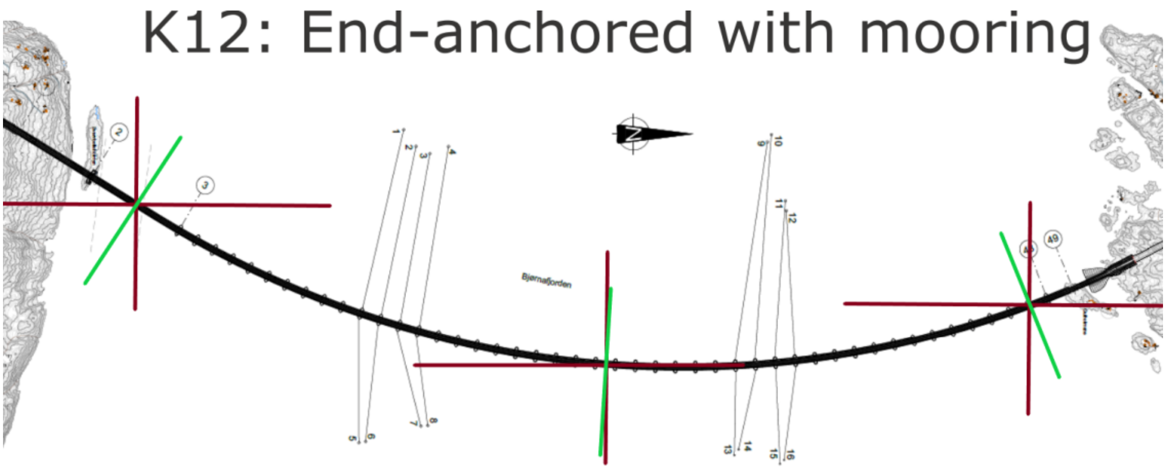

Figure 1 – Points of reference to estimate the yearly downtime hours. In green the crosswind directions.

For comparison, we will also look for the resulting estimated downtime if we consider the full wind speed, regardless of direction, which will result in higher downtime.

One additional factor that lacks clear definition, and depends on the local management of each bridge, is related to the opening criteria. For example, at the Øresund bridge the opening threshold windspeed is 2 m/s lower than the closing [3]. This will increase the total downtime if we account for such lag.

As a criterion, we follow the rules defined below, which are to be implemented in the western region of Norway. There are three levels of alarm, dependant on the measured wind gust:

1. Blinking yellow lights with wind gust of 22 m/s
2. Alarm to VTS with wind gust of 25 m/s
3. Closing with wind gust of 32 m/s

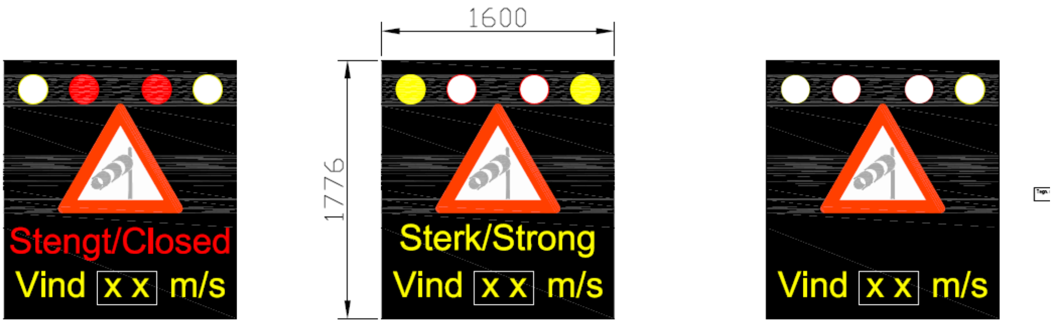

Figure 2 – Example for signs representing the possible alarm states visible to who is crossing the bridge. From left to right: closed, warning of strong winds (blinking yellow), and normal state.

However, there are at the present other closing criteria that are used. As an example, Table 1 shows the closing criteria for some of the bridges in the western part of Norway, where some are using limits on the gust and some on the 10 minutes mean, and some both.

Wind speed - [m/s]	U_{10min}	U_{gust}	**Z[m]-deck elevation**
Sotrabrua	25	-	50
Lysefjordbrua	-	32	50
Måløybrua	-	32	42
Hardangerbrua	25	30	55

Table 1 - Wind closure criteria for bridges monitored by VTS-vest at deck.

3 Data time series

3.1 Measured Data

We analysed the time series of the wind from three different locations: Ospøya, Svarvhelleholmen, and Synnøytangen, shown in Figure 3. The data is collected from the readings of the 50 m high masts sensors (Ospøya sensor is at 71.8 m.a.s.l. , Synnøytangen's is at 74.3 m.a.s.l., and Svarvhelleholmen's is at 57.3 m.a.s.l.). The time series data for Ospøya begins in November 2015, while Svarvhelleholmen and Synnøytangen ranges from the spring of 2015 until April of 2020.

Each data set consists of a time series of the 10-minute mean wind speed u_{10min}, a time series for wind gust u_{gust}, and the corresponding wind direction, θ.

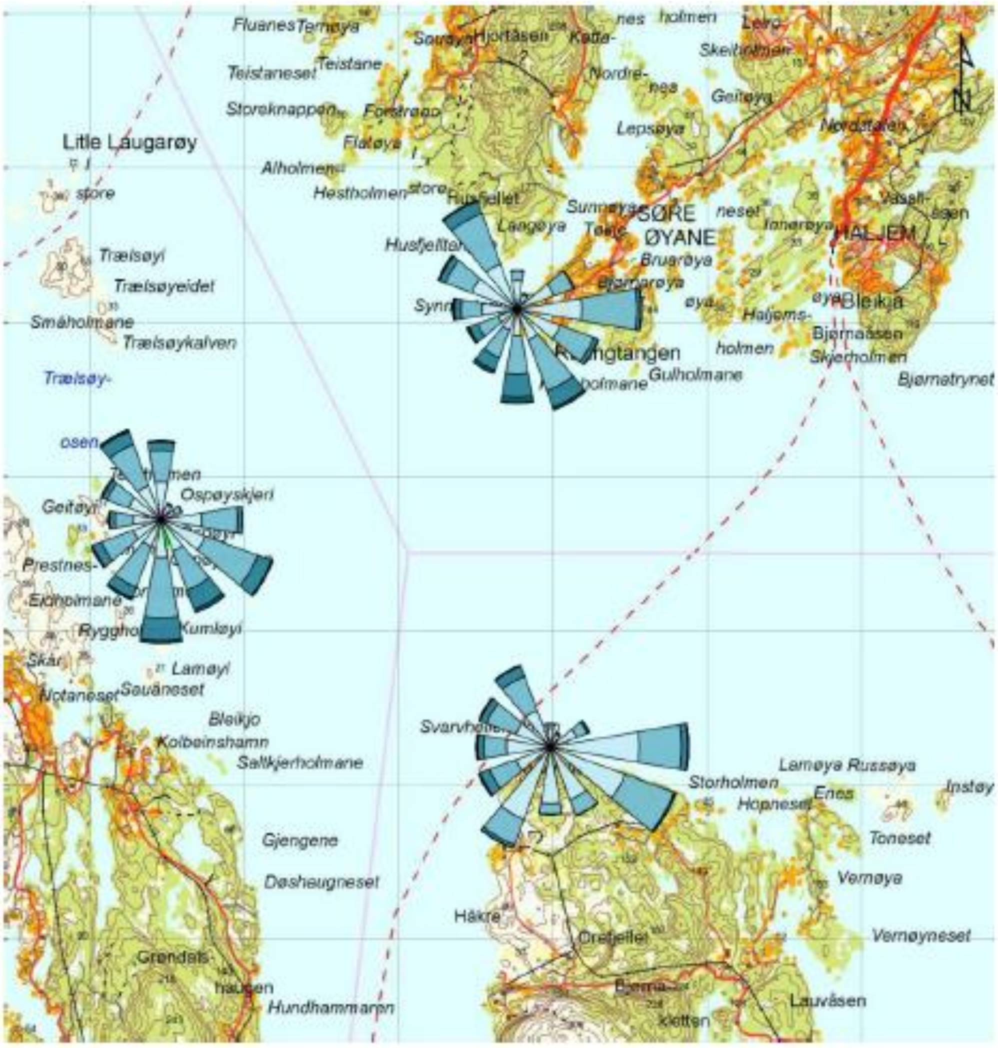

Figure 3. Location for the wind masts that collected the data for this analysis, seen in the wind roses. (Figure obtained from Kjellervindteknikk report KVT/MEH/2019/R073).

The Ospøya measurements, however, will only be used when not considering the cross winds. The reason for this is that while the wind speed measurements at this location are a good representation for the bridge mid-section, this is not true for the wind direction.

3.2 Simulation data -WRF model

For the mid-point of the bridge, since we do not have direct measurement at this location, we use the simulation data, generated by the WRF model (500m x 500m resolution), and correcting it for the elevation at the floating bridge. Given that the time resolution of the resulting WRF time series does not allow us to obtain the wind gust, this point is used only to compare with the 10-minute mean wind measured points at the two tops of the bridge, when analysing the crosswind.

3.3 Processed Data

As mentioned in Section 1, we are interested in the cross winds at the bridges three locations we defined above, which are expected to be the most unfavourable for the calculation of downtime. For this reason, we take the component of the wind speed data that correspond to the perpendicular direction relative to the bridge (as in Figure 1). Hence,

$$u^{p}{}_{10min} = u_{10min}\cos(\theta + \delta) \qquad \text{Equation 3}$$

$$u^{p}{}_{gust} = u_{gust}\cos(\theta + \delta), \qquad \text{Equation 4}$$

where δ is the angle correction. The correction parameters were set to $\delta\ (North) = -15\ [deg]$, $\delta\ (Middle) = 5\ [deg]$, and $\delta\ (south) = 30\ [deg]$.

The statistical wind data is based on the Weibull 3-parameter distribution:

$$f(u) = \frac{\beta}{\eta}\left(\frac{u-\gamma}{\eta}\right)^{\beta-1} exp\left\{-\left(\frac{u-\gamma}{\eta}\right)^{\beta}\right\} \qquad \text{Equation 5}$$

$$F(u) = 1 - exp\left\{-\left(\frac{u-\gamma}{\eta}\right)^{\beta}\right\}, \qquad \text{Equation 6}$$

where, η is the scale parameter, β the shape parameter, and γ is the location parameter.

To estimate the windspeed at an elevation *z*, we use the wind profile power law,

$$U_2 = U_1\left(\frac{z_2}{z_1}\right)^{\alpha}, \qquad \text{Equation 7}$$

where α is the profile coefficient between two levels. The value for the parameter α is based on the extreme analysis report [4], resumed in Table 2, which was estimated for each of the angle sectors, where U_2 is the average wind speed of the five strongest storms at the height z_2, and U_1 is the average wind speed of the five strongest storms at the height z_1.

Position	0-75	75-225	225-255	255-285	285-345	345-360
Synnøytangen (North)	0.05	0.10	0.10	0.10	0.10	0.20
WRF (Middle)	0.09	0.06	0.12	0.12	0.08	0.08
Svarvhelleholmen (South)	0.10	0.11	0.13	0.12	0.08	0.11

Table 2 – values for the profile coefficient α for each sector, along the bridge, calculated from the five strongest storms at 18m and 58 m height.

For each of the 3 bridge locations in Figure 1, we analyse the following data:

- **North**: As seen in the Metocean specification [2], the variation along the bridge for the wind profile is relatively homogeneous, particularly towards the north, hence it is reasonable to use the Synnøytangen data for this point. To estimate the wind speed at the elevation 20 m.a.s.l., $U_2 = U_1\left(\frac{z_2}{z_1}\right)^{\alpha}$, Equation 7 is applied, using the form factor determined from the simulation in Table 2.
- **Middle**: the simulation data generated by the WRF model is adjusted for the 20 m.a.s.l. elevation, using $U_2 = U_1\left(\frac{z_2}{z_1}\right)^{\alpha}$, Equation 7.

- **South**: the data obtained from Svarvhelleholmen wind mast, which sensor is at 57.3 m.a.s.l, is representative to the deck of the suspension bridge.

Figure 4 shows the resulting Weibull distribution model fitting the measured omnidirectional data for the 10-minute mean wind speed (u_{10min}), and for the wind speed gust (u_{Gust}), at the three wind measurement locations (Synnøytangen, Svarvhelleholmen and Ospøya).

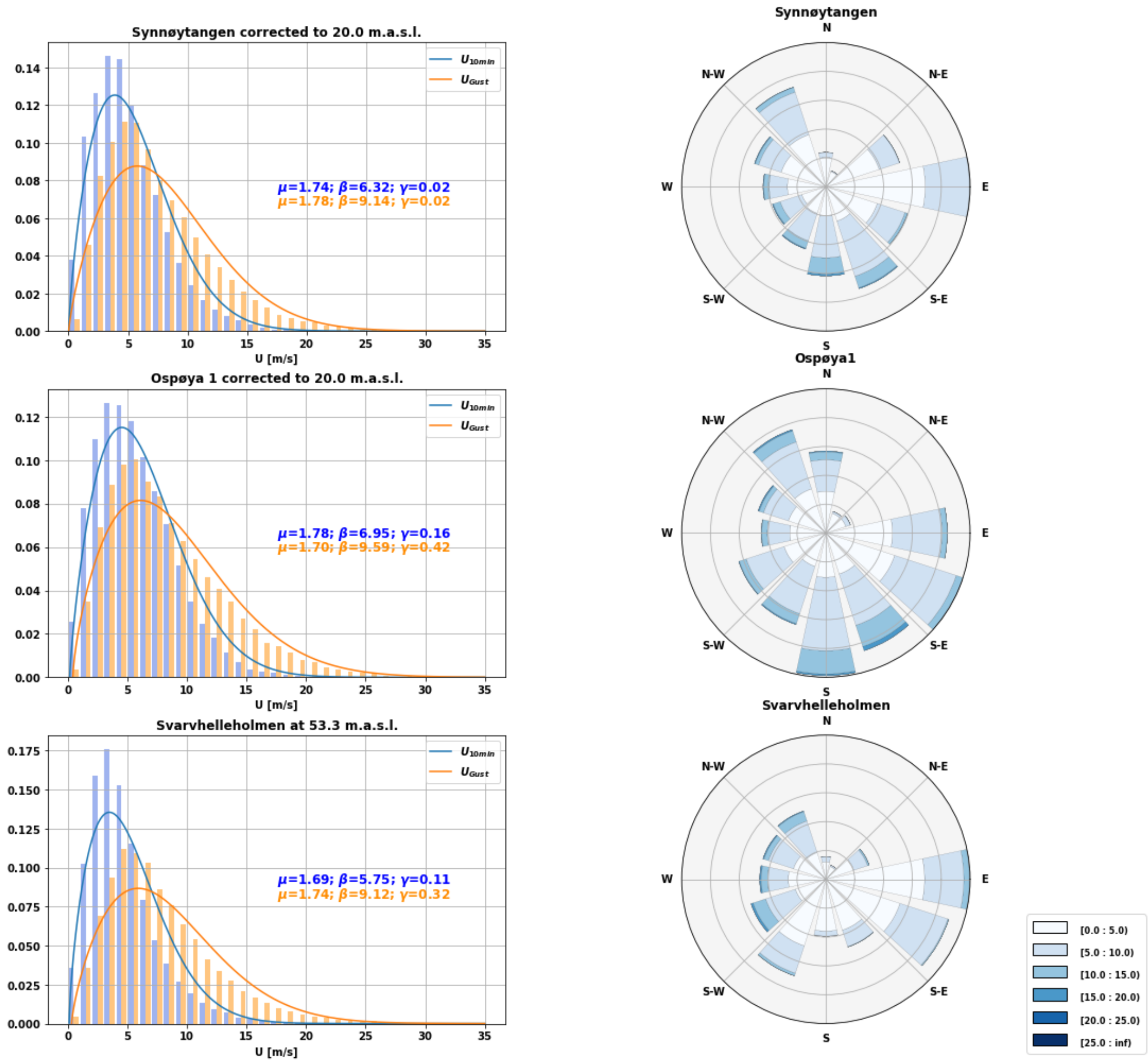

Figure 4 – left panel shows the Weibull distribution fit to the 10-minute mean wind speed histogram (in blue), and the wind speed gust (in orange), for the 3 measuring points (in rows). Right panel corresponds to the wind roses with 10-minute mean, for each of the three locations (in rows).

Figure 5 shows the resulting curve fitting to the Weibull distribution using the crosswind component of the wind speed measurements, as defined in $\boldsymbol{u^p}_{\boldsymbol{10min}} = \boldsymbol{u_{10min}} \boldsymbol{cos}(\boldsymbol{\theta} + \boldsymbol{\delta})$ Equation 3 and $\boldsymbol{u^p}_{\boldsymbol{gust}} = \boldsymbol{u_{gust}} \boldsymbol{cos}(\boldsymbol{\theta} + \boldsymbol{\delta})$, Equation 4. The time series correspond to the obtained from the two wind measurement locations (Synnøytangen, and Svarvhelleholmen) and the modelled data (WRF) at the bridge mid-section.

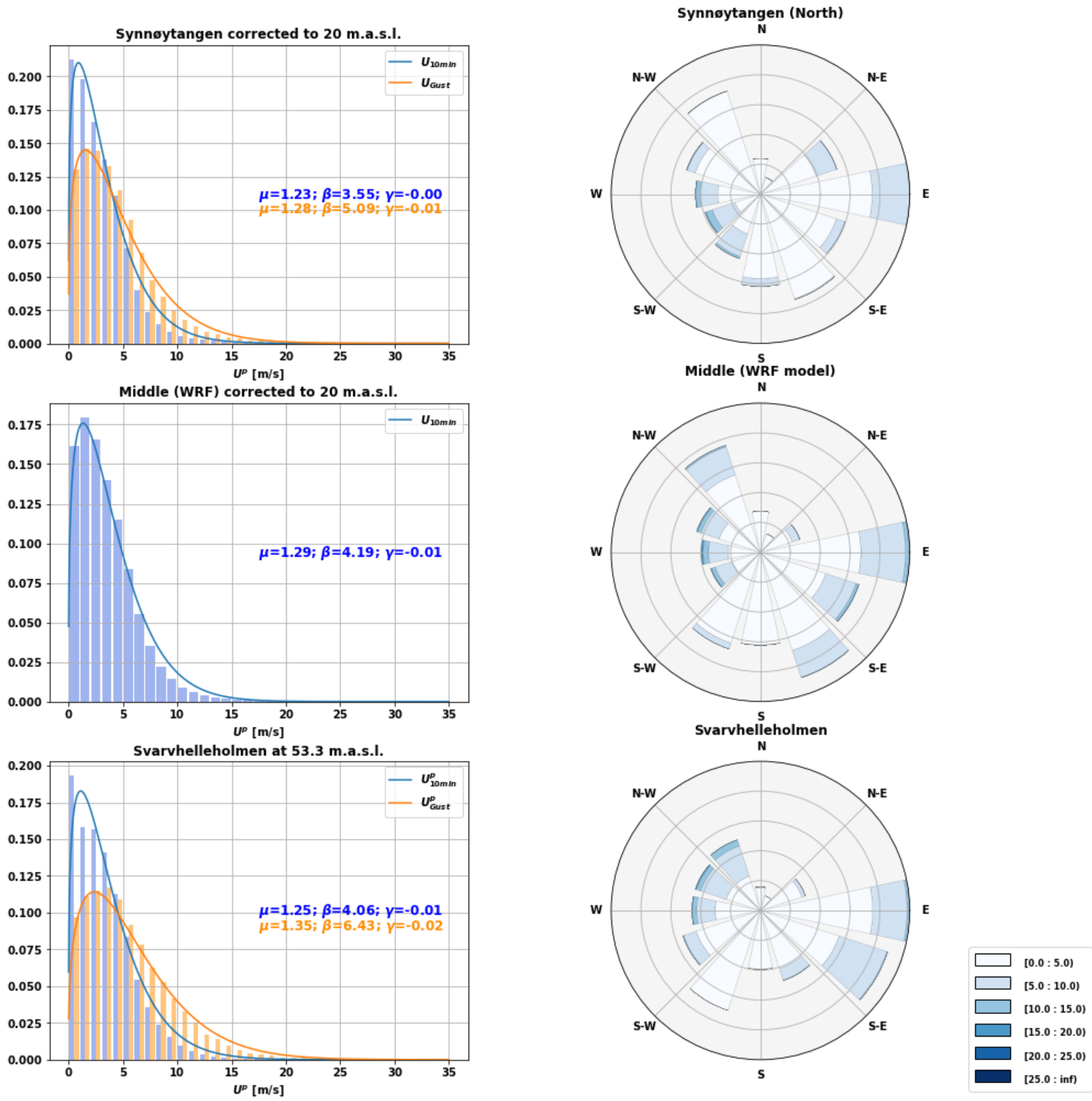

Figure 5 – Left panel shows the Weibull distribution fit to the 10 min crosswind component of mean wind speed histogram (in blue), for Synnøytangen, WRF data at the bridge mid-section, and Svarvhelleholmen. For the wind speed gust (in orange), only Synnøytangen and Svarvhelleholmen are available. Right panel corresponds to the wind roses with the crosswind component of the 10-minute mean speed, for each of the three locations.

4 Results

4.1 Thresholds for traffic closure

To determine the yearly downtime hours, we use the statistical models, namely the cumulative distribution function ($F(u) = 1 - exp\left\{-\left(\frac{u-\gamma}{\eta}\right)^{\beta}\right\}$, Equation 6), determined for each measuring dataset. The number of hours is then determined as

$$Downtime\ (h) = 8760\ (h) * F(u \geq U), \quad \text{Equation 8}$$

Where U is the threshold, and the value of 8760 corresponds to the number of hours in a year.

Figure 6 shows the evolution of the downtime hours with changing thresholds. This figure uses the absolute value of the wind speeds (10 minutes mean, and gust), while Figure 7 corresponds to the crosswind component. Note that with the lowering of the threshold, the yearly downtime grows exponentially. The values Figure 6 and Figure 7 were based on are summarized in Table 3.

In both plots of Figure 6, the black dashed line corresponds to the sum of the three curves. If the windspeed in each of these three locations were independent, the dashed line would correspond to the expected yearly closing time. However, since this is not the case, the dashed line corresponds to a ceiling for the expected yearly hours. In practice this means that if the wind gust exceeds the threshold at any of the locations at the bridge, the condition for any of the three alarms is met. Although this threshold may not be met in the other locations, the strong correlation of the wind along the bridge suggests that there is an overlap for these conditions to be met simultaneously in two or even all the measuring stations, thus the conservative nature of the dashed black line.

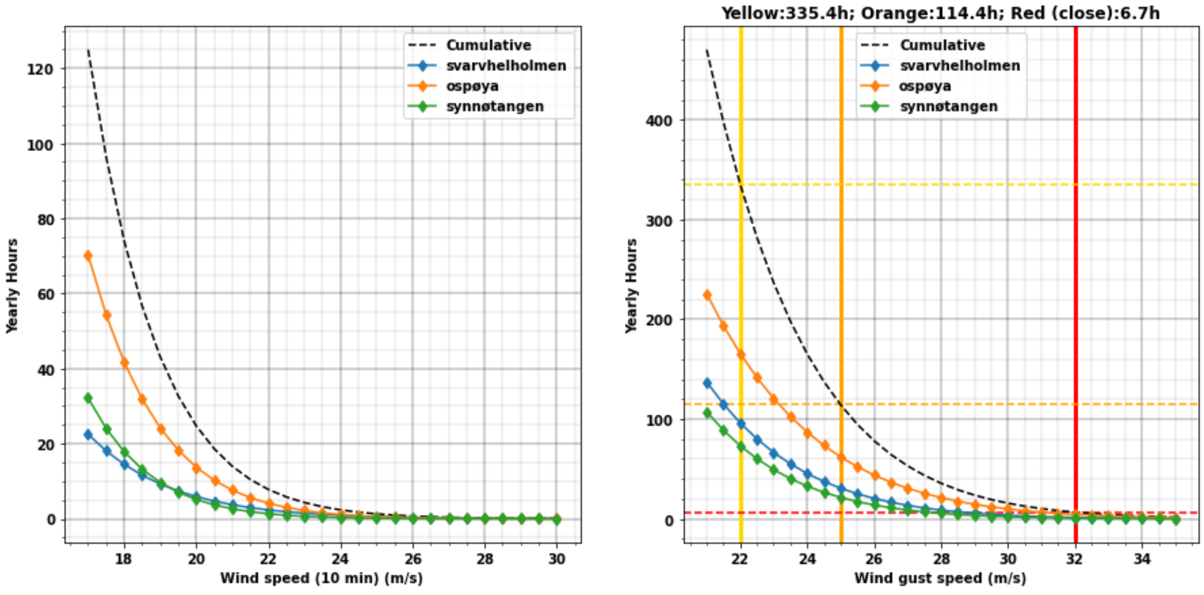

Figure 6 – Evolution of the yearly downtime in hours for each closing threshold. Left panel corresponds to the 10-minute mean wind speed, and the right panel is the wind gust. The vertical bars on the right panel correspond to a generic threshold set by VTS (red is to close all traffic, yellow is for warning the traffic, and the orange is for sending a warning to VTS). The black dashed line is the sum of the down hours for all three mast measurements. The coloured horizontal lines on the right panel are the intersection of the summation curve with the vertical alarm lines, which values are on the top.

If we use the statistical models determined from the crosswind data wind speed components, we obtain Figure 7. Ospøya wind gust measurements are not present, as explained in Section 2. The exponential growth of the number of closed hours as the threshold decreases is also observed with the crosswinds.

However, when compared with the omnidirectional windspeed, the downtime hours are always lower, as expected.

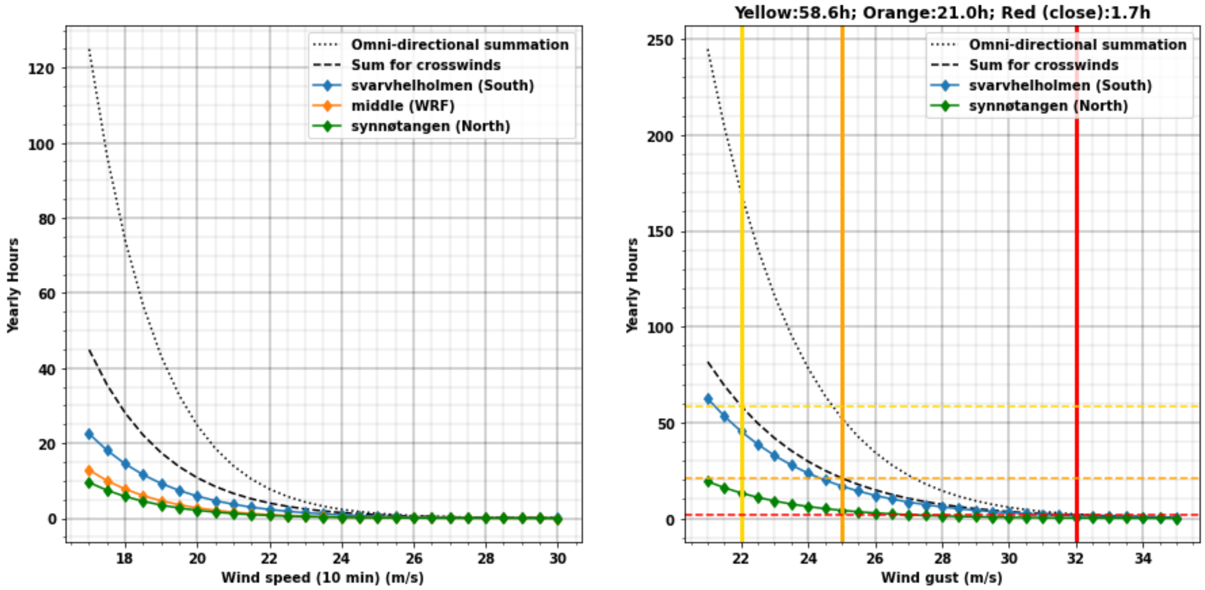

Figure 7 - Evolution of the yearly downtime in hours for each closing threshold (crosswind). Left panel corresponds to the 10-minute mean wind speed, and the right panel is the wind gust. The vertical bars on the right panel correspond to a generic threshold set by VTS (red is to close all traffic, yellow is for warning the traffic, and the orange is for sending a warning to VTS). The black dashed line is the sum of the closed hours for the Svarvhelleholmen and Synnøytangen (and WRF data when available). The dotted line corresponds to the omnidirectional summation of down time, for comparison.

	Total hours downtime			
Threshold	Omnidirectional		Crosswind	
Wind [m/s]	10min	Gust	10min	Gust*
17	124.9	1625.2	51.1	294.6
18	74.1	1212.8	32.2	215.4
19	43.2	894.5	20.2	156.7
20	24.7	652.2	12.6	113.4
21	14	470.3	7.8	81.7
22	7.8	335.4	4.8	58.6
23	4.3	236.7	2.9	41.8
24	2.4	165.4	1.8	29.7
25	1.3	114.4	1.1	21
26	0.7	78.3	0.7	14.8
27	0.4	53.1	0.4	10.4
28	0.2	35.7	0.2	7.3
29	0.1	23.8	0.1	5.1
30	0.1	15.7	0.1	3.5
31		10.3		2.4
32		6.7		1.7
33		4.3		1.1
34		2.7		0.8
35		1.7		0.5

Table 3 – Estimated yearly total of hours downtime based on the wind speed threshold. The total number of downtime hours in the columns correspond to the crosswind and omnidirectional wind 10-minute mean and wind gust. The crosswind gust values correspond, however, to the sum of two curves, instead of the three at the other columns.

5 Discussion

As the results show, the downtime is, as expected, highly dependent on the threshold for closing the bridge, increasing exponentially as this threshold lowers. When considering the omnidirectional windspeed instead of the crosswinds, as shown in Figure 7, the obtained downtimes are higher.

To be on the most conservative side for the counting of the total number of downtime hours we may use the black dashed curves on Figure 6, which correspond to the omnidirectional wind gust downtime hours in Table 3. For these, it is assumed that the windspeed measured at any of the three reference locations crosses the threshold, triggering the closing of the bridge, at different times, and never overlap. It also assumes that the direction of the wind is not relevant, when it is known [3] that it is in fact the crosswinds that are most critical for the driving conditions.

For a direct comparison with the results from the Cowi report [1], choosing the threshold for closing as the 10-minute mean crosswind speed at 25 m/s, the expected yearly downtime hours, from Table 3, is no higher than 1.1h. However, if we chose the other typical wind criteria for closing showed in Table 1, for a crosswind gust of 32 m/s, the total amount of expected yearly downtime hours is no higher than 1.7h, and for a crosswind gust of 30m/s, the total expected downtime is of 3.5h.

With the most conservative approach, using the omnidirectional values in Table 3, the 10-minute mean wind at 25 m/s would result on an expected yearly downtime of 1.3h, and for a wind gust of 32 m/s the expected yearly downtime would be 6.7h, which are still below the 15.6 yearly hours estimated in the Cowi report. For a yearly downtime hours similar to the estimated in the Cowi report [1], the threshold for the wind gust would have to be 30.0 m/s, omnidirectional, and, if crosswind, close to 25.5 m/s; while for the 10-minute mean, it would have to be close to 21m/s and 20m/s for omnidirectional and crosswind, respectively.

The difference in the results from this analysis to the ones in the Cowi report [1], as the report itself points out, suggests that the location of the measured time series from which the study is based on has a significant impact. The time series used in this analysis were obtained from locations at the Bjørnafjord and therefore can more accurately describe the wind characteristics that are more relevant to the future bridge.

As mentioned in Section 2, the closing conditions can vary according to the characteristics of each specific bridge, including its operational aspects. Although we use typical values of wind gust, as showed on Table 1, for a generic analysis of the downtime, this criterion may be adjusted such that the safety conditions for traffic are guaranteed while optimizing its operation so that the traffic flow is maximized. More on these conditions for Bjørnafjorden can be found in [3]. There, it summarizes the results of simulations and tests to study aspects such as the effect of wind on vehicles. The effects depend greatly on the type of vehicle (lorries, buses, small cars, etc.) and its speed. One of the control parameters for the bridge operation, for example, can be the management of the lanes, being the outer lanes the most sensitive to wind effects, instead of a full closing of the bridge, a partial closing can be a policy, preventing overtaking, or acting on the speed limit.

6 References

[1] COWI, “Bjørnafjorden floating bridge (K12) - RAM analysis A205696-COW-RAM-004,” November 2020.

[2] StatensVegVesen, “MetOcean Specification SBJ-01-C4-SVV-01-BA-001,” 2020.

[3] Statens VegVesen, “Motion criteria for E39 Bjørnafjorden based on simulated driving conditions SBJ-32-C5-SVV-90-TN-002-0,” 2020.

[4] H. K. Fuhr, “SBJ-01-C4-SVV-01-TN-006 Vind Bjørnafjorden – fase 5,” Statens Vegvesen, 2018.