TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 1
March 2025

DOI: 10.12716/1001.19.01.17

Determining Port Wind Limiting Conditions for Safe Maneuvering and Berthing

M. Barić, I. Toman, N. Kostovic & L. Grbić
University of Zadar, Zadar, Croatia

ABSTRACT: This paper examines the influence of lateral wind forces on ferry operations within the port of Gazenica, situated on the Croatian Adriatic coast. Utilizing wind data collected from May 2017 to June 2024, the study identifies southeasterly (SE) winds as the most critical factor affecting ferry maneuverability due to their frequency and intensity. The research assesses wind-induced forces on three specific ferries—"Brac," "Ugljan," and "Juraj Dalmatinac"—comparing these forces against their maximum propulsion capabilities. Findings reveal that extreme SE wind conditions can surpass the thrust capacity of these vessels, elevating the risk of drifting and grounding, as illustrated by the grounding incident of the ferry "Cres". Consequently, the study highlights the necessity for advancements in ship design, propulsion systems, navigational aids, and port infrastructure to mitigate risks associated with high wind speeds. Implementing such measures is vital for ensuring the safety and operational reliability of maritime activities in the port of Gazenica and comparable settings.

1 INTRODUCTION

A thorough understanding of the impact of lateral wind forces on maritime vessels, particularly ferries, is essential for ensuring safe and efficient port operations. The port of Gazenica, situated on the Croatian coast of the Adriatic Sea, experiences distinct climatic conditions that significantly influence ship maneuverability. This literature review surveys previous research concerning wind forces acting on ships, examines design and operational strategies employed to mitigate these forces, and discusses the specific challenges encountered by maritime transportation within the Adriatic Sea.

Research investigating wind forces on ships has underscored the complex interplay between atmospheric conditions and vessel design characteristics. According to Schneekluth and Bertram (1998), the magnitude of lateral wind forces on a ship is contingent upon several factors, including wind speed, wind direction, vessel dimensions, and superstructure configuration. These authors formulated a set of empirical equations for estimating wind forces, which have gained widespread adoption within maritime engineering. A study conducted by Blendermann (1994) offered a comprehensive analysis of wind loads on ships, emphasizing the critical need to consider both steady and gusty wind conditions. Blendermann's research indicated that large vessels possessing substantial lateral plane areas exhibit particular vulnerability to drifting when subjected to high lateral wind forces.

To counteract the effects of wind forces, various design strategies have been investigated. Molland, Turnock, and Hudson (2011) discussed the significance of optimizing ship superstructures to minimize wind resistance. They proposed that streamlined designs and the application of advanced materials can markedly reduce the lateral wind force exerted on a vessel. Furthermore, Bai and Jin (2008) highlighted the crucial role of propulsion systems in opposing wind forces. Their work emphasized the necessity for adequate engine power and sophisticated thrust vectoring capabilities to ensure vessels can maintain control under adverse weather conditions. Operational strategies are fundamental to enhancing maritime safety in windy environments. Papanikolaou (2014) reviewed diverse navigational aids and real-time monitoring systems capable of assisting decision-making processes during extreme weather events. The utilization of real-time weather data, predictive modeling techniques, and automated control systems can substantially improve a ship's ability to navigate safely in high wind conditions.

The Adriatic Sea presents unique challenges for maritime transportation owing to its specific climatic characteristics. Besić, Mihanović, and Vilibic (2012) investigated wind patterns in the Adriatic, noting the prevalence of SE winds, which can attain considerable speeds and thereby impact maritime operations. Their research suggested these winds could generate significant wave heights, further complicating navigation and port activities. In a study concentrating on the Croatian coast, Kuzle, Grubisic, and Ljubicic (2010) analyzed historical wind data and its ramifications for maritime safety. They concluded that ports along the Adriatic, including Gazenica, must implement robust measures to address the escalating intensity of SE winds, potentially linked to climate change.

The existing literature concerning wind forces acting on ships emphasizes the importance of integrating vessel design, operational strategies, and real-time monitoring systems to guarantee maritime safety. The specific difficulties encountered by ferries operating in the port of Gazenica underscore the requirement for continued research and adaptation to mitigate risks posed by strong lateral wind forces. By applying insights gleaned from previous studies, maritime engineers and operators can enhance the safety and efficiency of maritime transportation within the Adriatic Sea.

2 WIND AND WAVES CHARACTERISTIC OF GAZENICA PORT

The Port of Gazenica is situated approximately 2 kilometers southeast of the main port of Zadar. The nearest meteorological station is positioned on Cape Puntamika, located 2 km northwest of Zadar port and 6 km northwest of Gazenica port. This station, operated by the Croatian Meteorological and Hydrological Service (DHMZ), provides the wind data utilized in determining limiting conditions for the area. Wind speed and direction are sampled at a height of 10 meters above ground level using both automatic instrumentation and human observations at hourly intervals. The recorded data represents sustained wind speed, averaged over a 10-minute period preceding the observation time. Due to the predominantly flat terrain in this coastal region, significant local topographical features are absent, minimizing differences in wind speed and direction between the measurement location and the Port of Gazenica. The analyzed wind data spans from May 2017 to June 2024 (a total of 7 years) and has been statistically compared with historical wind data from 1997 to 2006.

Table 1 presents the monthly wind distribution by speed and probability for the analyzed period. The data indicates that SE wind exhibits the highest average speed and probability, followed by NW and E winds. Notably, the NE wind, typically considered one of the most severe winds along the Croatian coast, demonstrates lower probability and speed compared to SE and NW winds in this specific location. Climatic studies of the Adriatic Sea confirm that NE winds are considerably less frequent in the Zadar Channel area compared to surrounding regions (Zaninović et al., 2008).

The wind speed distribution plot (aggregated across all directions, Figure 1) reveals that the most frequent wind speeds in the area range between 0 and 5 m/s. The relative frequency of wind speeds exceeding 5 m/s is lower, indicating that wind conditions are predominantly low to moderate.

Analyzing the relative frequency of wind speed by direction (Figure 2) shows that SE winds reach maximum values approaching 20 m/s. Wind speeds from all other directions generally do not exceed 10 m/s. This observation is corroborated by wind return period analysis. The calculated return period for wind speeds (from any direction) exceeding 21 m/s is 83.37 months (approximately 6.95 years). In contrast, wind speeds of 20 m/s occur with significantly higher frequency, having a calculated return period of 11.91 months (approximately 0.99 years). This disparity suggests that the maximum sustained wind speed for the analyzed period is approximately 20 m/s, with the highest probability associated with the SE direction.

Table 1. Monthly wind distribution analysis by direction, average wind speed “v” (m/s) and probability “%” from May 2017 to June 2024

Month	N		NE		E		SE		S		SW		W		NW		Calm
	v	%	v	%	v	%	v	%	v	%	v	%	v	%	v	%	%
1.	2,5	13,0	2,6	19,0	2,6	29,0	4,8	17,2	3,8	3,5	2,8	3,5	2,3	4,0	2,8	12,7	1,4
2.	2,9	12,0	3,1	14,0	2,3	23,4	4,6	24,4	2,5	2,4	1,8	3,2	2,1	4,2	2,7	14,4	1,6
3.	3,0	11,0	2,7	11,2	2,5	19,9	4,7	27,0	2,3	2,3	1,9	3,6	2,3	6,0	2,5	15,9	2,0
4.	2,9	10,1	2,8	10,3	2,4	15,5	4,1	27,2	2,7	3,3	1,8	4,3	2,2	9,0	2,3	17,3	2,5
5.	2,2	9,5	2,2	9,0	2,3	13,1	4,0	25,0	2,1	3,0	1,5	5,5	2,1	10,2	2,3	21,9	2,7
6.	2,4	11,0	1,9	7,0	1,6	9,0	3,1	20,7	2,2	3,3	1,4	5,0	2,1	12,2	2,4	28,6	3,5
7.	2,3	7,8	2,1	8,0	1,7	9,1	3,1	17,8	1,8	3,0	1,4	5,0	2,3	12,1	2,5	30,7	6,0
8.	2,2	8,9	2,2	7,5	1,8	12,4	3,6	16,8	1,9	2,9	1,4	5,0	2,2	12,0	2,4	28,4	7,0
9.	2,1	8,5	2,6	11,9	2,0	18,7	3,6	19,0	2,3	2,4	1,8	4,6	2,2	8,6	2,2	19,7	4,0
10.	1,8	12,0	2,2	11,2	2,1	25,9	4,9	22,0	2,3	3,0	1,8	2,9	2,1	7,0	2,3	15,6	3,0
11.	2,0	8,8	2,7	20,0	2,8	32,0	5,2	18,0	3,4	2,0	3,1	4,0	2,9	4,0	2,4	9,4	1,3
12.	2,3	9,3	2,4	15,0	2,6	33,0	5,4	20,0	3,8	2,7	2,5	3,6	2,3	3,0	2,7	9,5	1,0
Average	2,4	10,2	2,5	12,00	2,2	20,1	4,3	21,3	2,6	2,8	1,9	4,2	2,3	7,7	2,5	18,7	3,0

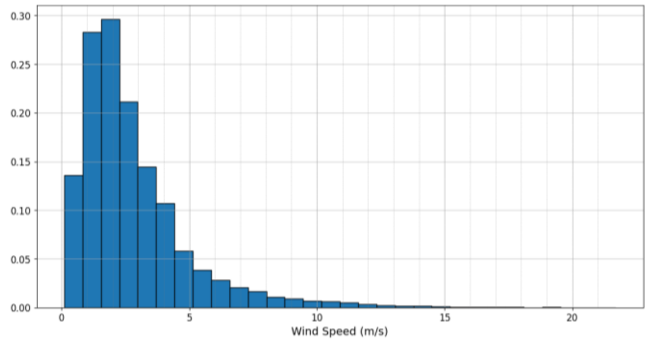

Figure 1. Histogram for wind speed regardless of direction in time period 2017 to 2024

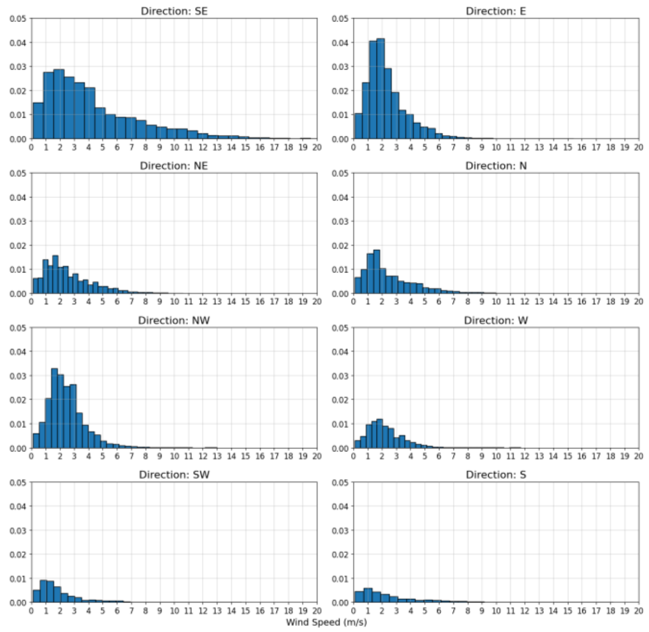

Figure 2. Histogram for wind speed distribution for each direction for time period from 2017 to 2024

The analyzed wind data was compared to historical data from the period 1997 to 2006, also represented in 10-minute intervals (Table 2). This historical data similarly indicates that SE wind is the most prevalent throughout the year and exhibits the highest speeds. On average, the highest recorded wind speeds in the historical dataset range from 14.8 m/s to 20.8 m/s. These historical maximum speeds correlate with the return period analysis, considering the 9-year duration of the analyzed historical period.

Based on the wind data and the area's geographical configuration, wave characteristics can be estimated using established forecasting techniques (e.g., Bretschneider & Tamaye, 1984). Calculating wave characteristics necessitates determining the wind fetch. The wind fetch was calculated for the dominant SE wind, corresponding to a main direction of 135°.

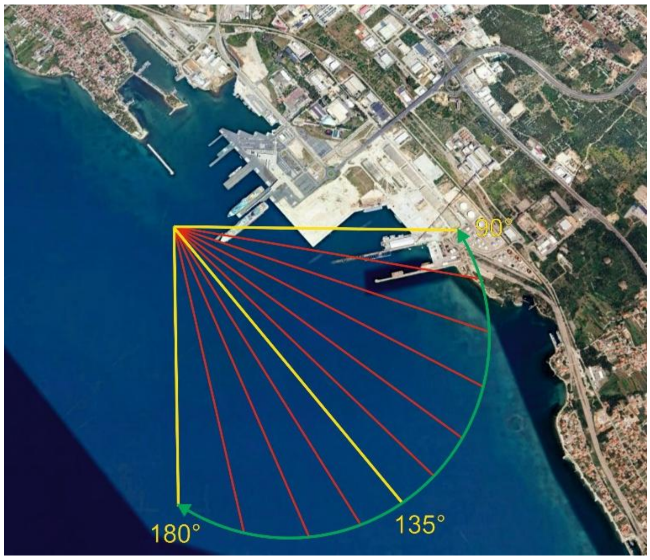

Figure 3. Direction of wind for effective fetch calculation

The calculation adheres to standardized methods, utilizing data from Table 3 and Equation (1):

$$Feff = \frac{\sum x \cdot \cos\alpha}{\sum \cos\alpha} \quad (1)$$

where the *Feff* represents the effective wind fetch in km.

Table 3: Wind fetch calculation

Wind angle	Relative wind angle "α"	Cos "α"	Length of fetch "Xi" (km)	Xi × cosα
93°	42°	0,743	1,0	0,743
99°	36°	0,809	1,0	0,809
105°	30°	0,866	1,8	1,559
111°	24°	0,914	2,0	1,828
117°	18°	0,951	2,3	2,187
123°	12°	0,978	2,8	2,738
129°	6°	0,995	3,0	2,985
135°	0°	1,000	3,2	3,200
142°	6°	0,995	6,0	5,970
148°	12°	0,978	18,6	18,191
152°	18°	0,955	18,0	17,190
158°	24°	0,914	17,0	15,538
164°	30°	0,866	12,3	10,652
170°	36°	0,809	10,7	8,656
178°	42°	0,743	7,0	5,201
		Σ=13,512		Σ=97,447

The resulting effective wind fetch (Feff) is 7.21 kilometers. Significant wave height ($H_{1/3}$) can be calculated using Equation (2),

$$H_{1/3} = 0,283 \cdot \frac{v^2}{g} \cdot tanh\left(0,0125 \cdot \left(\frac{g \cdot F}{v^2}\right)^{0,42}\right) \quad (2)$$

and the significant wave period ($T_{1/3}$) using Equation (3).

Table 2. Monthly distribution of highest recorded wind speed (10-minute period) by direction for time period from 1997 to 2006

	January	February	March	April	May	June	July	August	September	October	November	December	Average
V10	15,7	18,4	16,2	17,5	16,9	16,9	20,8	19,7	15,1	14,8	19,6	19,7	20,8
Direction	SSE	SE	SE	SE	SE	SE	ESE	ENE	NW	SE	SSE	NE	ESE

$$T_{1/3} = 1,2 \cdot \left(\frac{2 \cdot \pi \cdot v}{g} \right) \cdot tanh \left(0,077 \cdot \left(\frac{g \cdot F}{v^2} \right)^{0,25} \right) \quad (3)$$

where the “v” is wind speed in m/s, “F” is effective wind fetch in meters and “g” is gravity constant. Input parameters for these calculations included the maximum recorded SE wind speed of 20.8 m/s and the effective fetch of 7.21 kilometers. The calculations yield a significant wave height ($H_{1/3}$) of 1.32 meters and a significant wave period ($T_{1/3}$) of 4.29 seconds. To characterize the significant wave shape, the wavelength (λ) was calculated using Equation (4),

$$\lambda = 16,78 \cdot H_{1/3}^{0,71} \quad (4)$$

resulting in a value of 20.46 meters. These results confirm that the prevailing SE wind, associated with the highest recorded speeds, can generate considerable forces on the above-water surfaces of ships and produce long waves of relatively large height.

3 MARITIME CHARACTERISTIC OF GAZENICA PORT

The inner mooring area for passenger ships within the port of Gazenica (Figure 4) is sheltered by a large cruise ship pier to the southeast, a land barrier to the northwest, and a breakwater to the west.

Figure 4. Configuration of port Gazenica

Although the inner passenger port offers good protection, challenges arise during port entry maneuvers. These difficulties are particularly evident during SE wind conditions, when vessels entering the port must orient their longitudinal plane nearly perpendicular to the wind direction. A comparison of vessel tracks derived from Automatic Identification System (AIS) data with the prevailing SE wind direction confirms that vessels are exposed to crosswinds during port entrance (Figure 5).

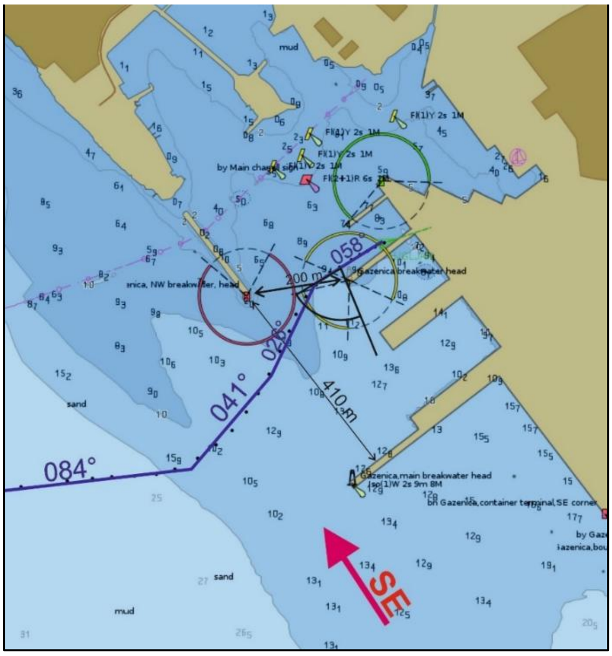

Figure 5. Vessel track during port entrance from AIS compared to SE wind

Analysis of vessel AIS tracks indicates that ships approaching from the Zadar channel typically maintain a course of approximately 084°. Subsequently, they execute turns to courses of 041° and then 026°, following a route close to the breakwater. The most critical phase during this approach occurs during the turn from 084° to 041°, where the SE wind acts perpendicularly to the ship's side. The average approach speed of vessels during this phase is approximately 6 knots. To quantify the wind's influence on the ship, it is necessary to determine the relative wind direction with respect to the ship's course.

The relative wind direction (αR) can be calculated using Equation (5),

$$\alpha_R = arcsin \left(\frac{v \cdot sin(180 - \alpha)}{Vr} \right) \quad (5)$$

where “v” is ship speed (m/s), “V_r” is relative wind speed (m/s) and the “α” is angle of the wind compared to ship headline. The calculated results for each leg of the approach are presented in Table 4.

Table 4. Calculation of relative wind direction

Ship course	True wind direction compared to ship headline	Relative wind direction
084°	51°	50°
041°	94°	81°
026°	109°	70°
058°	77°	69°

The data presented in Table 4 confirms that the most critical phase of the approach corresponds to the leg with a ship course of 041°, during which the wind acts almost perpendicularly to the vessel's heading. This orientation generates the largest lateral force, potentially causing the vessel to drift off its intended course.

4 ANALYSED SHIPS CHARACTERISTICS

The analyzed section of Gazenica port primarily serves passenger traffic, predominantly local ferry lines. The vessels employed on these routes are typically ferries characterized by large capacities for both vehicles and passengers. Key technical specifications of the analyzed ferries are detailed in Table 5.

Table 5. Technical characteristic of analysed ferries

Ferry	Ferry 1 "Brac"	Ferry 2 "Ugljan"	Ferry 3 "Juraj Dalmatinac"
Length over all (LOA)	99,80 m	102,20 m	87,6 m
Length between perpendiculars (LBP)	89,10 m	91 m	80 m
Breadth (B)	17,50 m	18 m	17,5 m
Draught (T)	2,40 m	2,70 m	2,40 m
Type of propulsion	Azimuth Schottel	Azimuth Siemens	Azimuth
Power and number of propulsors	4 x 445 kW	4 x 478 kW	4 x 537 kW
Gross tonnage	3827	2925	3193
Deadweight	759 t	758 t	569 t

To analyze the wind forces acting upon these ships, determining their frontal (lateral) and longitudinal plane areas is essential. These areas can be obtained either from ship plans or through established calculation methods. One such method utilizes statistical data and regression analysis (Akakura & Takahashi, 1998). This statistical approach provides Equation (6) for estimating the ship's lateral and longitudinal plane areas (A):

$$A = \alpha \cdot X^{\beta} \tag{6}$$

In equation (6) "α" and "β" are coefficients depending on ship type (Table 6), where "X" is ship deadweight or gross tonnage.

Table 6. Coefficients and ship data for calculation of the ship's plane surface area

Ship type	X	Lateral plane area		Longitudinal plane area	
		α	β	α	β
Cargo ship	DWT	0,592	0,666	3,213	0,616
Bulk carrier	DWT	8,787	0,370	16,518	0,425
Container ship	DWT	1,369	0,609	2,614	0,703
Tanker	DWT	2,946	0,474	3,598	0,558
Ro-Ro ship	DWT	10,697	0,435	28,411	0,464
Passenger ship	GT	8,842	0,426	3,888	0,680
Ferry	GT	5,340	0,473	3,666	0,674
LNG/LPG ship	GT	2,649	0,553	5,074	0,613

Calculated plane area surfaces using this method were compared against measurements derived from the actual ship plans for each analyzed ferry. Ferry 1, "Brac" (built 2014), has a capacity of 616 passengers and 145 cars (Figure 6).

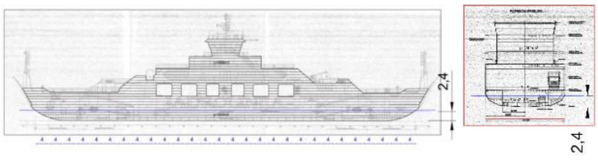

Figure 6. Longitudinal and lateral plane area of ferry 1 „Brac"

Ferry 2, "Ugljan" (built 2009), is the largest among the analyzed vessels, with a capacity of 600 passengers and 107 cars (Figure 7). Its reduced car capacity relative to its size is attributed to the absence of underdeck garages.

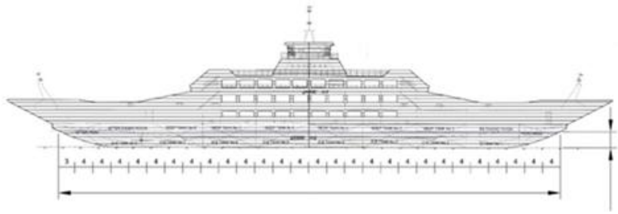

Figure 7. Longitudinal plane area of ferry 2 „Ugljan"

Ferry 3, "Juraj Dalmatinac" (built 2007), accommodates 1200 passengers and 138 cars, possessing the largest passenger capacity and gross tonnage of the three (Figure 8).

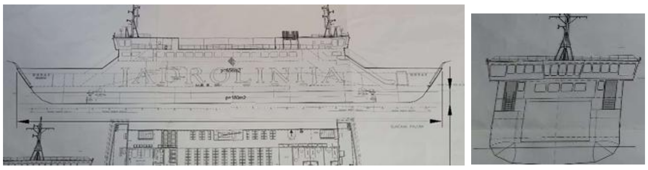

Figure 8. Longitudinal and lateral plane area of ferry 3 „Juraj Dalmatinac"

Discrepancies between the calculated and measured plane areas are presented in Table 7.

Table 7: Differences between calculated and measured lateral and longitudinal plane surface area

Ship	Lateral surface			Longitudinal surface		
	Measured	Calculated	Difference	Measured	Calculated	Difference
Ferry 1 "Brac"	241 m^2	264 m^2	+10 %	888 m^2	953 m^2	+7%
Ferry 2 "Ugljan"	256 m^2	232 m^2	-10 %	890 m^2	795 m^2	-11%
Ferry 3 "Juraj Dalmatinac"	256 m^2	243 m^2	-6%	658 m^2	843 m^2	+28 %

For Ferries 1 and 2, the differences generally fall within ±10%. However, Ferry 3 ("Juraj Dalmatinac") exhibits a larger discrepancy of +28% for the longitudinal plane area. This deviation might be attributed to fewer side openings compared to the other ferries, which significantly reduces its measured longitudinal surface area relative to the statistical estimate. All analyzed vessels are equipped with azimuthal thrusters, enabling thrust generation in any direction. Based on their installed engine power, the maximum calculated total thrust is 233.8 kN for Ferry 1 ("Brac"), 250.47 kN for Ferry 2 ("Ugljan"), and 281.39 kN for Ferry 3 ("Juraj Dalmatinac").

5 WIND FORCE CALCULATION

The wind force (Fv) acting on a vessel can be calculated using Equation (7) (PIANC, 2014),

$$F_v = Cv \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \tag{7}$$

which incorporates the coefficient of ship body wind resistance (Cv), air density (ϱ), relative wind speed (v), and the relevant ship plane area (A). The wind resistance coefficient (Cv) can be determined using the regression methodology presented in Equations (8) and 9 (Yamano & Saito, 1997).

$$Cv = \sum_{n=1}^{3} C_{yn} \cdot sin\varphi_{vj} \qquad (8)$$

where value "C_{yn}" represents regression coefficients calculated using equation:

$$C_{Yn} = C_{Yn0} + C_{Yn1} \cdot \frac{A_{V,L}}{Lpp^2} + C_{Yn2} \cdot \frac{X_L}{Lpp^2} + C_{Yn3} \cdot \frac{Lpp}{B} + C_{Yn4} \cdot \frac{A_{V,L}}{A_{V,F}} \quad n = 1,2,3 \qquad (9)$$

The value "$A_{V,L}$" and "$A_{V,F}$" represents longitudinal and lateral ship plane areas (m^2) and XL is the distance of the longitudinal plane area's center of gravity from the stern. The values for the regression coefficients are provided in Table 8.

Table 8. The values of regression coefficients

Coefficient „n“	Coefficient C_{Ynj} for j = 0 do 4				
	C_{Yn0}	C_{Yn1}	C_{Yn2}	C_{Yn3}	C_{Yn4}
1	0,509	4,904	0	0	0,022
2	0,0208	0,23	-0,075	0	0
3	-0,357	0,943	0	0,0381	0

The ship-specific wind resistance coefficient (Cv) was calculated for the different relative wind directions encountered during the port approach. The relative wind angles derived previously (Table 4) were used as input for these calculations. The resulting Cv values for both longitudinal and lateral resistance are shown in Table 9.

Table 9. The values of calculated ship body wind resistance coefficient „Cv“

Relative wind direction compared to ship headline	Longitudinal ship body wind resistance coefficient " Cv"			Lateral ship body wind resistance coefficient " Cv"		
	Ferry 1 "Brač"	Ferry 2 "Ugljan"	Ferry 3 "Juraj Dalmatinac"	Ferry 1 "Brač"	Ferry 2 "Ugljan"	Ferry 3 "Juraj Dalmatinac"
50°	0,853	0,993	0,784	0,780	0,912	0,761
81°	1,179	1,379	1,136	0,196	0,233	0,199
70°	1,105	1,292	1,053	0,433	0,504	0,435
69°	1,096	1,281	1,043	0,453	0,528	0,455

The analysis indicates that the largest longitudinal resistance coefficient occurs at a relative wind direction of 081°, while the largest lateral coefficient corresponds to a direction of 050°. Among the vessels, Ferry 2 ("Ugljan"), being the largest ship with extensive plane areas, exhibits the highest resistance coefficients.

Utilizing Equation (7) and the calculated coefficients, the wind force acting on each ship was determined for the different approach legs. The resulting lateral wind pressures and forces are presented in Table 10.

As anticipated, Ferry 2 experiences the largest lateral pressure and resultant wind force due to its significant plane area surface. The maximum lateral force occurs when the ship is on the 041° course leg, where the wind acts nearly broadside to the vessel. Comparing the calculated maximum lateral wind force against the maximum available engine thrust reveals potential vulnerabilities, particularly in extreme wind conditions (Table 11).

Table 11. Comparison of maximum lateral wind force to maximum lateral engine trust

Ship	Sila vjetra (kN)	Maximum engine force (kN)	Difference (%)
Relative wind angle	081°		
Ferry 1 "Brac"	282,9	281,39	-1
Ferry 2 "Ugljan"	331,5	250,47	-24
Ferry 3 "Juraj Dalmatinac"	201,9	233,8	+14

The results demonstrate that extreme wind speeds can indeed overwhelm the available engine power for some vessels, creating a risk of drifting towards the breakwater. Specifically, Ferry 1 operates near the limit of its engine capacity under these conditions, while Ferry 2 appears underpowered relative to the potential lateral wind force. Under such circumstances, Ferries 1 and 2 lack sufficient power reserves to counteract the calculated extreme lateral forces. An incident illustrating this risk occurred on December 28th, 2020, when the ferry "Cres" (a sister ship to Ferry 1 "Brac") grounded on the breakwater due to high SE winds. Figures 9 and 10 show the recorded AIS track of the mentioned accident (provided by MarineTraffic).

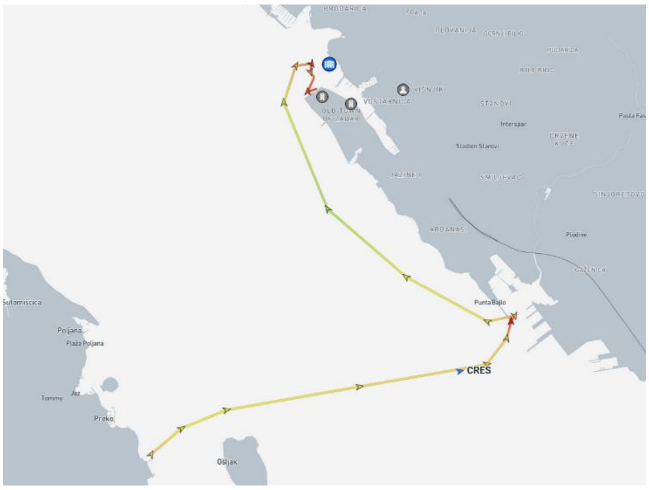

Figure 9. AIS track of the ferry "Cres" departing from Preko (Island of Ugljan) towards Gazenica port. After grounding on the breakwater at 44.092334°N, 15.252184°E due to strong SE winds, the master abandoned further attempts to berth in Gazenica and diverted to the Zadar old town port area, which offers better shelter from SE winds.

Table 10. Results of lateral wind pressure and force for each analysed ship

Ship course	Relative wind direction	Air density (kg/m^3)	Wind relative speed (m/s)	Lateral wind pressure Fv (N/m^2)			Lateral wind force Fv (kN)		
				Ferry 1 "Brac"	Ferry 2 "Ugljan"	Ferry 3 "Juraj Dalmatinac"	Ferry 1 "Brac"	Ferry 2 "Ugljan"	Ferry 3 "Juraj Dalmatinac"
084°	50°	1,22521	21	230,4	268,2	211,8	204,6	238,7	139,4
041°	81°	1,22521	21	318,6	372,5	306,9	282,9	331,5	201,9
026°	70°	1,22521	21	298,6	348,9	284,6	265,1	310,6	187,3
058°	69°	1,22521	21	269,0	345,9	281,8	262,8	307,9	185,4

Figure 10. Zoom of the view from the Figure 9 at the position of the grounding.

6 RESULTS AND DISCUSSION

The analysis of wind data for the port of Gazenica from May 2017 to June 2024 confirms the dominance of SE winds regarding both frequency and intensity. The SE wind, exhibiting the highest recorded speeds and greatest probability, presents considerable challenges to maritime operations within this area. A calculated effective wind fetch of 7.21 kilometers for SE winds corresponds to potentially substantial wave heights and periods, which can adversely affect ship stability and maneuverability.

The findings indicate that all three analyzed ferries possess adequate engine power to manage moderate wind forces. However, during extreme SE wind events, the forces exerted on the ferries can approach or even surpass their maximum thrust capabilities. For instance, Ferry 2 ("Ugljan"), with its larger plane area, is subjected to the highest wind forces, signifying an elevated risk of drifting and loss of control under severe wind conditions.

The grounding incident involving the ferry "Cres" serves to underscore the practical significance of these findings. The fact that "Cres" grounded due to high SE winds highlights the imperative for robust design considerations and operational procedures to mitigate such risks effectively. While the calculated return period for winds exceeding 20 m/s indicates such events are relatively infrequent, their potential impact is severe, demanding adequate preparedness and resilient vessel designs.

7 CONCLUSION

The analysis of lateral wind forces affecting ferries in the port of Gazenica underscores the substantial operational challenges presented by extreme wind conditions, particularly strong SE winds. The findings demonstrate that certain ferries, especially those with larger lateral profiles, are vulnerable to drifting as wind forces can approach or exceed their maximum engine thrust capabilities under severe conditions. This vulnerability was notably demonstrated by the grounding of the ferry "Cres" during high SE winds. These results emphasize the need to re-evaluate vessel design specifications and propulsion systems to ensure adequate power reserves for managing extreme weather. Furthermore, the study highlights the critical importance of developing sophisticated operational protocols and enhancing port infrastructure to bolster navigational safety. Future research should prioritize the integration of real-time meteorological data with predictive modeling systems to optimize vessel routing and port operations, thereby improving the overall safety and efficiency of maritime transport in the Adriatic Sea.

LITERATURE

[1] Akakura, Y., & Takahashi, H. (1998). "Analysed Ships Characteristics"

[2] Bai, Y., & Jin, W.-L. (2008). Marine Structural Design. Elsevier.

[3] Besić, A., Mihanović, H., & Vilibić, I. (2012). Wind-induced waves and currents in the Adriatic Sea. Oceanologia, 54(4), 601–620.

[4] Blendermann, W. (1994). Parameter identification of wind loads on ships. Journal of Wind Engineering and Industrial Aerodynamics, 51(3), 339–351.

[5] Bretschneider, C. L., & Tamaye, E. E. (1984).Coastal Engineering Manual.

[6] Kuzle, I., Grubisic, M., & Ljubicic, A. (2010). Analysis of wind effects on maritime safety along the Croatian Adriatic coast. Pomorstvo: Scientific Journal of Maritime Studies, 24(2), 45–60.

[7] Molland, A. F., Turnock, S. R., & Hudson, D. A. (2011). Ship Resistance and Propulsion: Principles and Practices. Cambridge University Press.

[8] Papanikolaou, A. (2014). Risk-Based Ship Design: Methods, Tools and Applications. Springer.

[9] PIANC. (2014). Harbour Approach Channels Design Guidelines,

[10] Schneekluth, H., & Bertram, V. (1998). Ship Design for Efficiency and Economy, Butterworth-Heinemann.

[11] Yamano, T., & Saito, Y. (1997). "Wind Force Calculation"

[12] Zaninović, K., Gajić-Čapka, M., Perčec Tadić, M., et al. (2008). Climate atlas of Croatia 1961–1990, 1971–2000. Državni hidrometeorološki zavod, Zagreb. 200 stranica. ISBN: 978-953-7526-01-6.