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A ferry route in the Skagerrak optimised via VISIR-2

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Outline

→ *Introduction*

Methods

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Discussion

Weather routing for short sea shipping?

Shipping CO2 emissions: between 2.0 and 2.4% (with domestic emissions: 2.9%) of global ones

Emission reduction from International regulatory efforts (IMO 2023 Strategy, EU-ETS, FuelEuMaritime) will take time to materialise

slow-steaming, anti-fouling paintings, and weather routing are immediately available and can help with low-C fuels too

Large uncertainty on quantitative role of weather routing, especially for short sea shipping

open-source VISIR-2 model can help assessing quantitative savings in a systematic way

Case study route in the Skagerrak (red-hatched in map) ~70 miles

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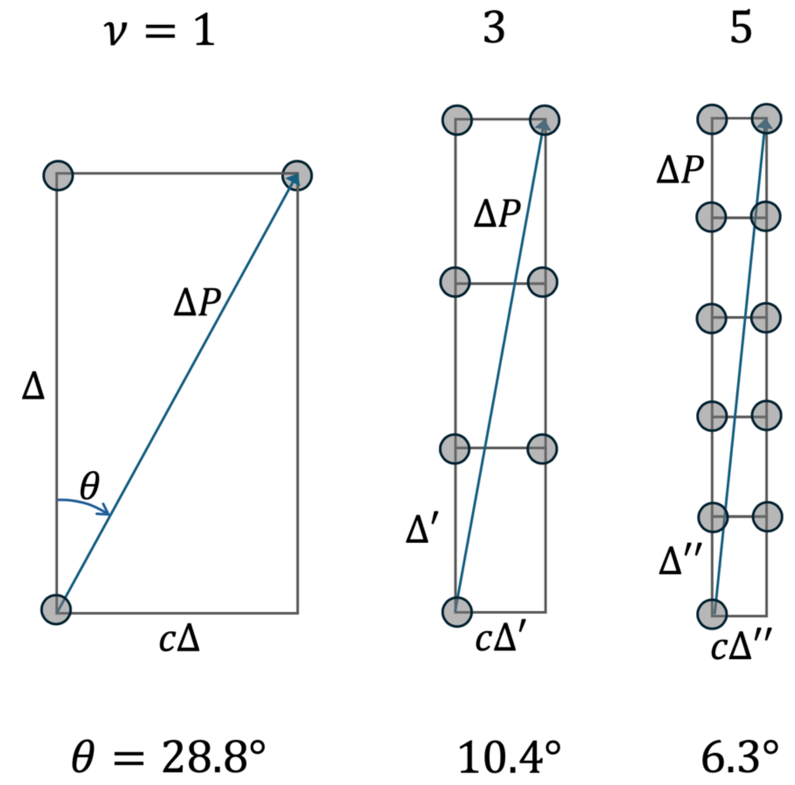
Graphs and route smoothness

VISIR-2 solution is based on a graph-search method

(graph edges connect nodes up to a given number of hops ν)

fixed ship's engine load χ → graph edge angle θ as sole control variable for the optimisation problem

multi-hop edges (ν > 1) → smaller θ → smoother routes



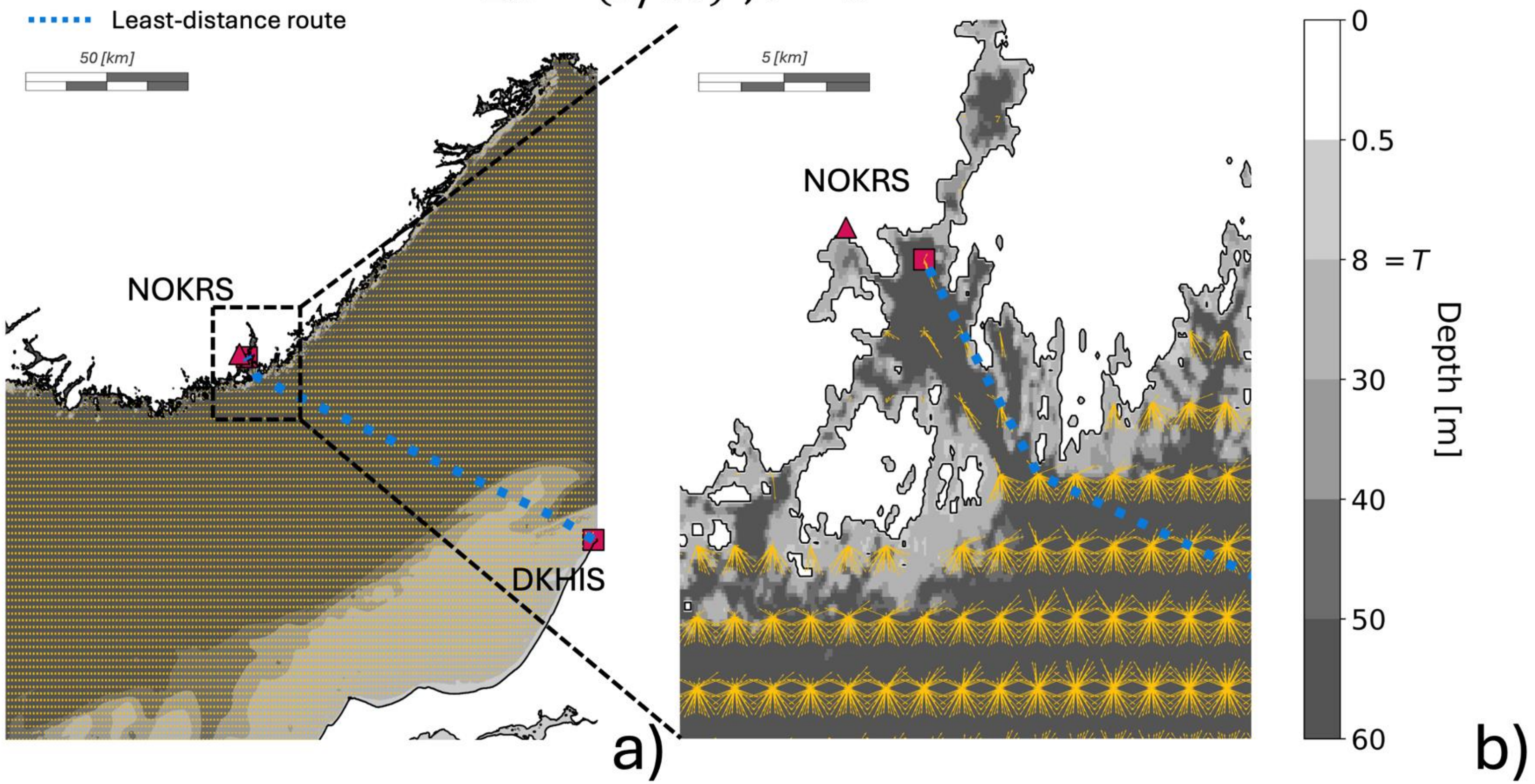
jagged ← → *smooth*

cf. Mannarini, Subramanani et al, IEEE Trans. Intell. Transp. Sys. (2020), doi.org/10.1109/TITS.2019.2935614

Avoidance of shallow waters

(2.2 km resolution in meridional direction)

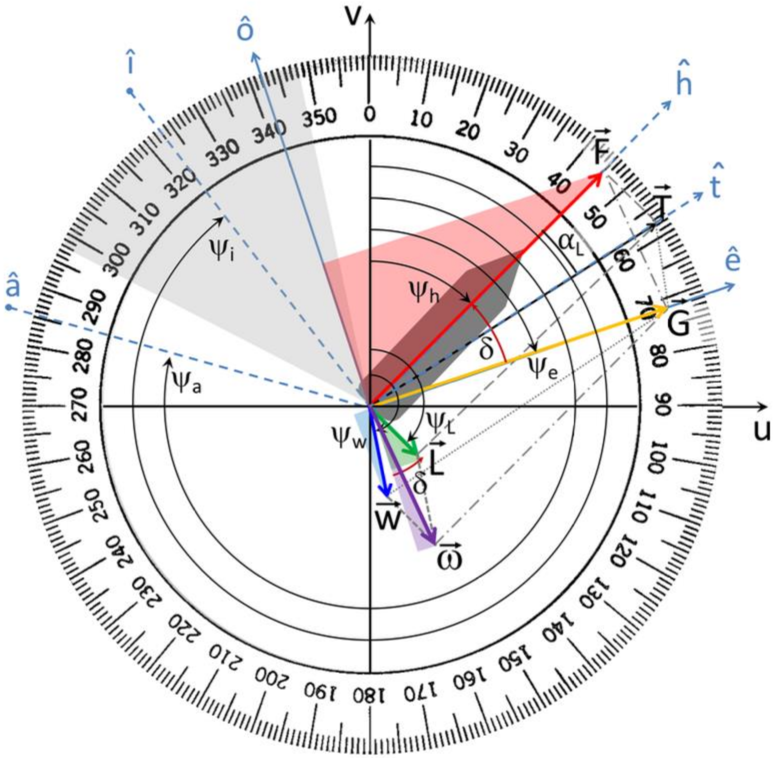
$\Delta x = (1/50)°, \nu = 5$



Edges with average sea depth less than ship draught are pruned from the graph:

→ ca. 1 million edges left per time-step

Shortest path and CO_2 savings



VISIR-2 features

- *Objective: least-distance, least-time, least-CO2 routes*
- *graph-search algorithm extended to use dynamic environmental fields at the edges*
- *linear superposition of currents and speed through water (STW) resulting from waves*
- *accounting for cross-currents via heading correction with respect to course ("drift angle")*
- *CO2 savings computed with respect to least-distance route:*

$$dCO_2 = \frac{CO_2^{(\mathrm{opt})} - CO_2^{(\mathrm{gdt})}}{CO_2^{(\mathrm{gdt})}}$$

validated vs. analytical benchmarks and intercomparison exercises

both pseudo-code and source code published

Mannarini , Salinas, et al., Geosci. Model Dev. (2024) doi.org/10.5194/gmd-17-4355-2024

Vessel performance modelling

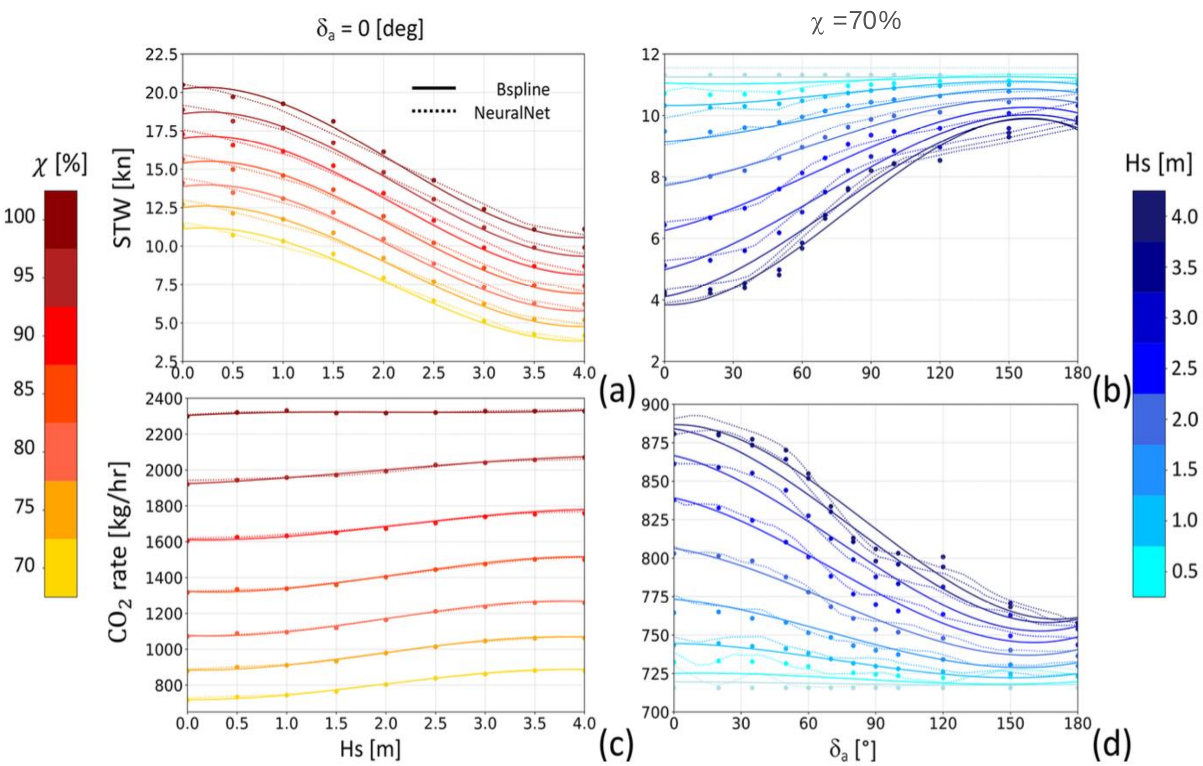
Ship considered: a ferry

vessel performance data (from simulator) available for a vessel smaller than MS Bergensfjord

Following the main engine power ratio, CO_2 emission rates are upscaled (6x)

	Simulator ferry	MS Bergensfjord
Length	125 m	170 m
Beam	23.4 m	27.5 m
Draught	5.3 m	6.3 m
Speed	19 kn	21.5 kn
Power	4,000 kW	24,000 kW

rescaled



← *STW decreasing with significant wave height Hs (more at low χ)*

larger reduction at smaller angle of attack of waves $|\delta_a|$

Emission rate Γ mainly depends on χ and $|\delta_a|$

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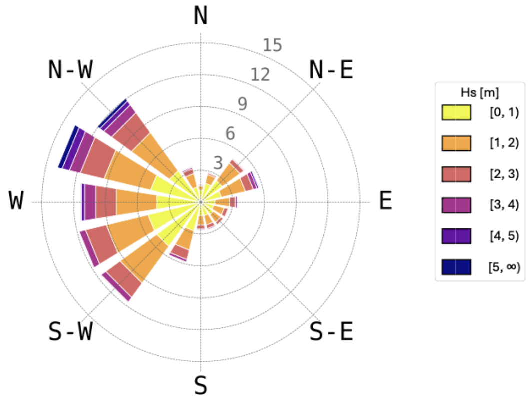
Optimal routes – individual case studies

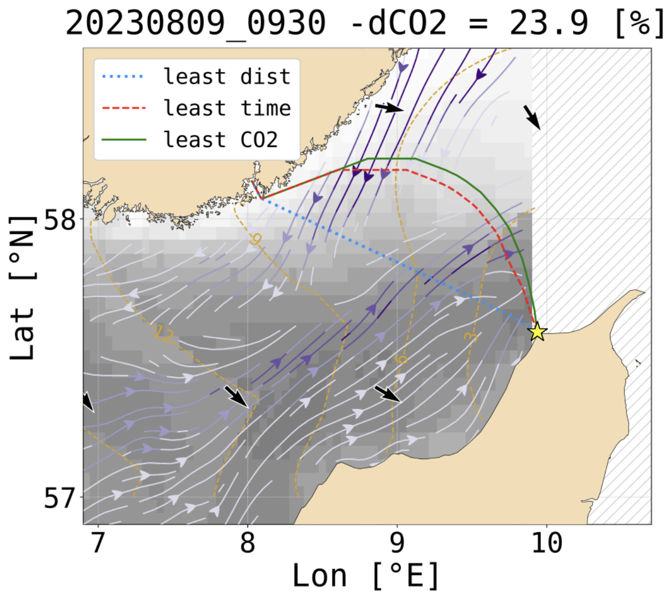
*Typical **sea circulation**:*

- *cyclonic (SW-bound Norwegian coastal current, NE-bound Jutland current)*

*Typical **sea state**:*

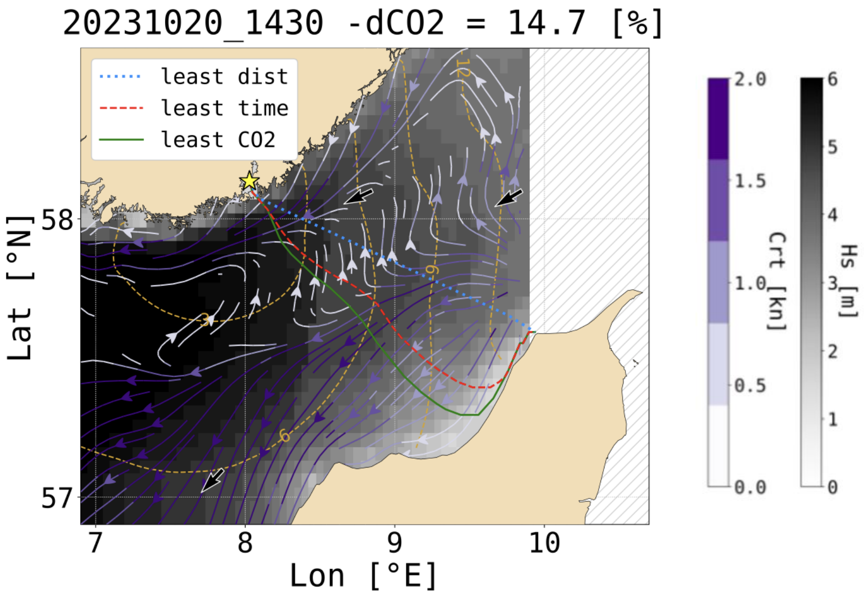
- *largest and most frequent waves are from NW*





*Optimal route **from Hirtshals**. Diversion is to NE:*

- *avoids head seas*
- *bypassess Jutland current*
- *exploits Norwegian current*
- *~24% CO_2 saving*



*Optimal route **from Kristiansand**. Diversion is to SW:*

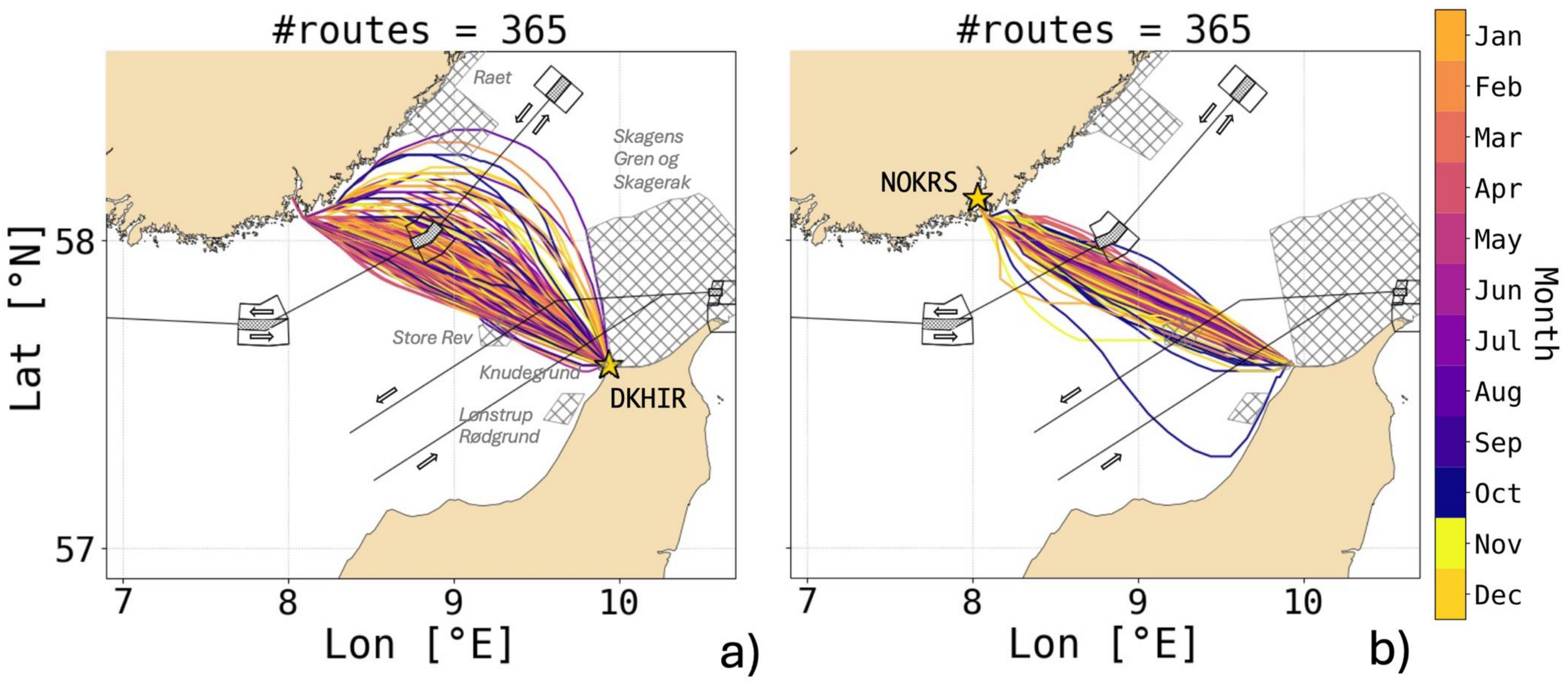
- *sea circulation disrupted by easterly wind*
- *avoids head seas*
- *calmer waters off Denmark*
- *~15% CO_2 saving*

Optimal routes over a full year

- *daily departures*
- *2 sailing directions*
- *4 engine loads: χ = {70,80,90,100}%*
- *with/without currents*

================

tot: 5,840 experiments



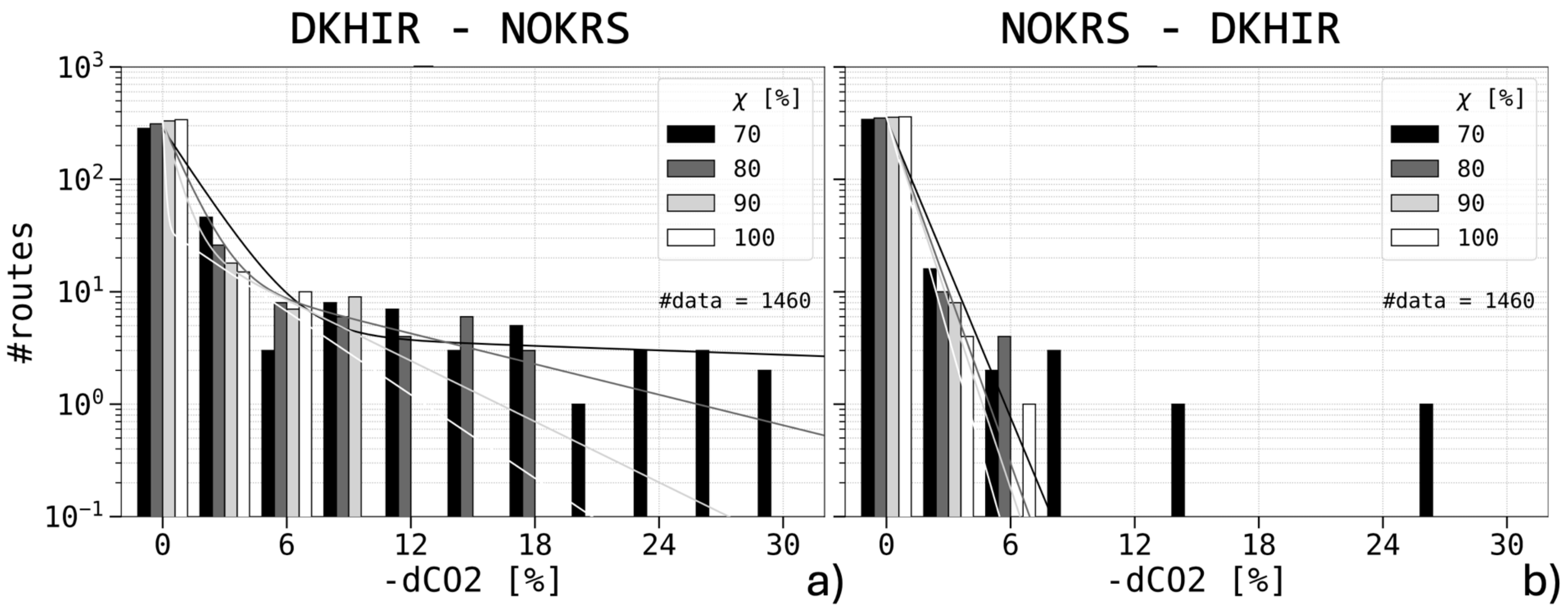
Traffic Separation Schemes and Natura 2000 (grey cross-hatch) areas not used for route optimisation

CO_2 savings – statistical distribution

from Hirtshals: bi-exponential distribution («fat tail»)

from Kristiansand: single exponential distribution

considering also currents: doubling of CO2 savings



	χ [%]	*wave* total [t]	*wave* savings [t]	*current & wave* total [t]	*current & wave* savings [t]
DKHIR - NOKRS	70	9,973	216	10,043	357
	80	11,638	135	11,695	218
	90	13,947	77	14,000	127
	100	16,638	53	16,689	91
NOKRS - DKHIR	70	9,461	30	9,443	83
	80	11,198	18	11,179	47
	90	13,608	14	13,584	34
	100	16,314	14	16,288	30

← compare to:

- *average, per-ferry pre-COVID-19 annual emissions in the European Economic Area (*) → 37,432 tons CO2*
- *annual CO2 emissions of a European citizen → 6.9 tons CO2*

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Missing modeling components

	issue	impact	fix
1	*Vessel performance modeling not specialised for the actual ferry*	*unrealistic route durations and savings*	*use metocean data and AIS or sensor data*
2	*Auxiliary engine neglected*	*overestimation of savings*	*modify emission rate Γ*
3	*Marine protected areas not considered*	*found routes potentially shorter than feasible*	*use static masking*
4	*Intact stability constraints neglected*		*dynamic filtering needed*
5	*Analysis fields of sea state and sea circulation used but just forecasts available in operational practice*	*suboptimal solutions*	*for deep sea shipping, rereouting (not available for short sea shipping)*
6	*Ferry routes must adhere to strict schedules for both departure and arrival times*	*not all optimal routes computed may be practically relevant*	*develop a given-duration, least-CO2 algorithm*

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Take-home messages

- ❑ *crucial to consider currents (if not, halved CO_2 savings)*
- ❑ *(due to wave direction in the Skagerrak) routing is particularly beneficial for voyages from Denmark*
- ❑ *CO_2 savings distribution is (bi)-exponential*
- ❑ *max savings: 26% from Kristiansand, 30% from Hirtshals*

Conference Paper:
doi.org/10.1088/1742-6596/2867/1/012003

VISIR-2 repository:
https://zenodo.org/records/10960842

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Appendix

Choise of graph resolution

How resoluted should a graph be?

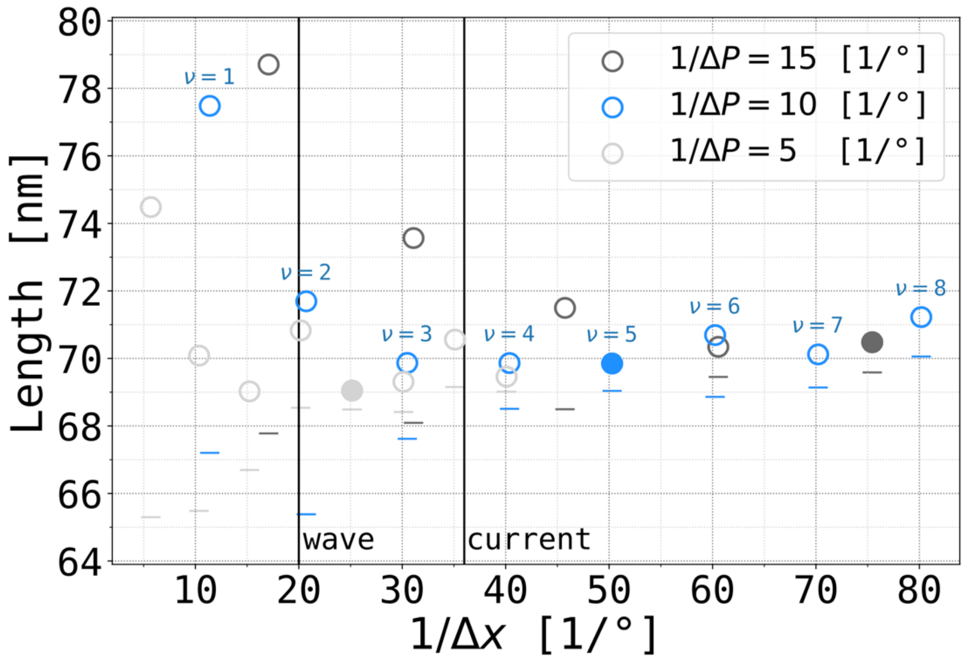
- *vary number of hops (ν) and spatial resolution ($1/\Delta x$) keeping edge length (ΔP) fixed:*

$$\Delta P/\Delta x = \sqrt{c^2 + \nu^2} \approx \nu$$
$$c = \cos \overline{\varphi}$$

with c = cosine of mean latitude

- *compare the length L of resulting least-distance route*

- *for the Hirtshals-Kristiansand route, convergence of L (within error ~1%) achieved for ν=5 and Δx=(1/50)°*



cf. Mannarini, Subramanani et al, IEEE Trans. Intell. Transp. Sys. (2020), doi.org/10.1109/TITS.2019.2935614

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Along route information

DKHIR - NOKRS

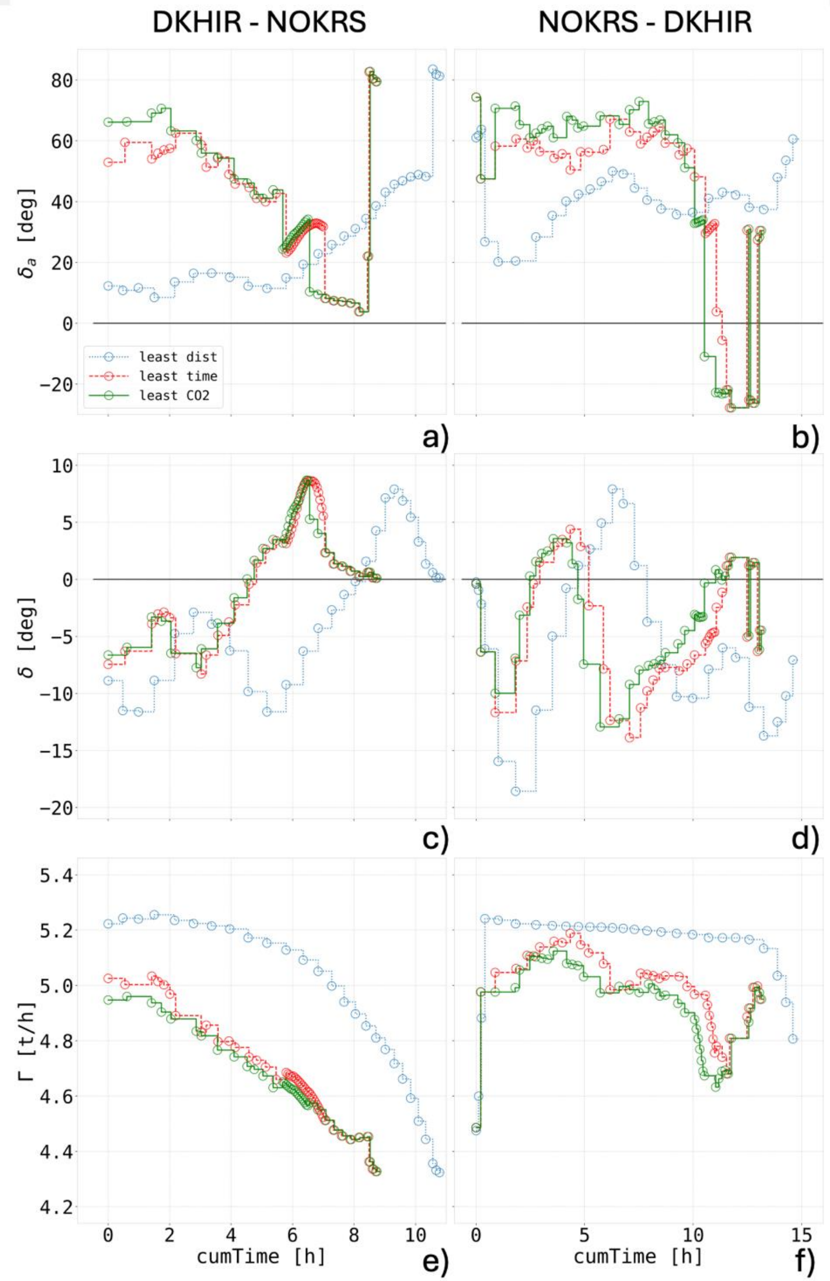
- *large angle of attack of waves $|\delta_a|$ @ 0-5 h*
- *small course-heading deviation $|\delta|$ @ 4-5 h*
- *large voyage-mean longitudinal current $w_{||}$ and $|\delta_a|$*
- *small voyage-mean significant wave height H_s and $|\delta|$ ➔ low emission rate Γ*

	Route type	$\langle H_s \rangle$ [m]	$\langle \lvert\delta_a\rvert \rangle$ [deg]	$\langle w_{\parallel} \rangle$ [kn]	$\langle \lvert\delta\rvert \rangle$ [deg]	$\langle SOG \rangle$ [kn]	$\langle \Gamma \rangle$ [t/hr]	T^* [hr]
DKHIR - NOKRS	least-dist	2.4	32.3	-0.24	5.3	7.7	4.9	10.9
	least-time	1.8	37.7	0.49	4.8	10.6	4.7	8.8
	least-CO_2	1.7	37.9	0.53	4.3	10.9	4.6	8.9
NOKRS - DKHIR	least-dist	4.2	42.5	-0.67	7.2	5.4	5.1	14.9
	least-time	3.5	45.5	-0.50	5.3	6.9	5.0	13.2
	least-CO_2	3.3	48.8	-0.45	4.2	7.6	4.9	13.2

13.17
13.24

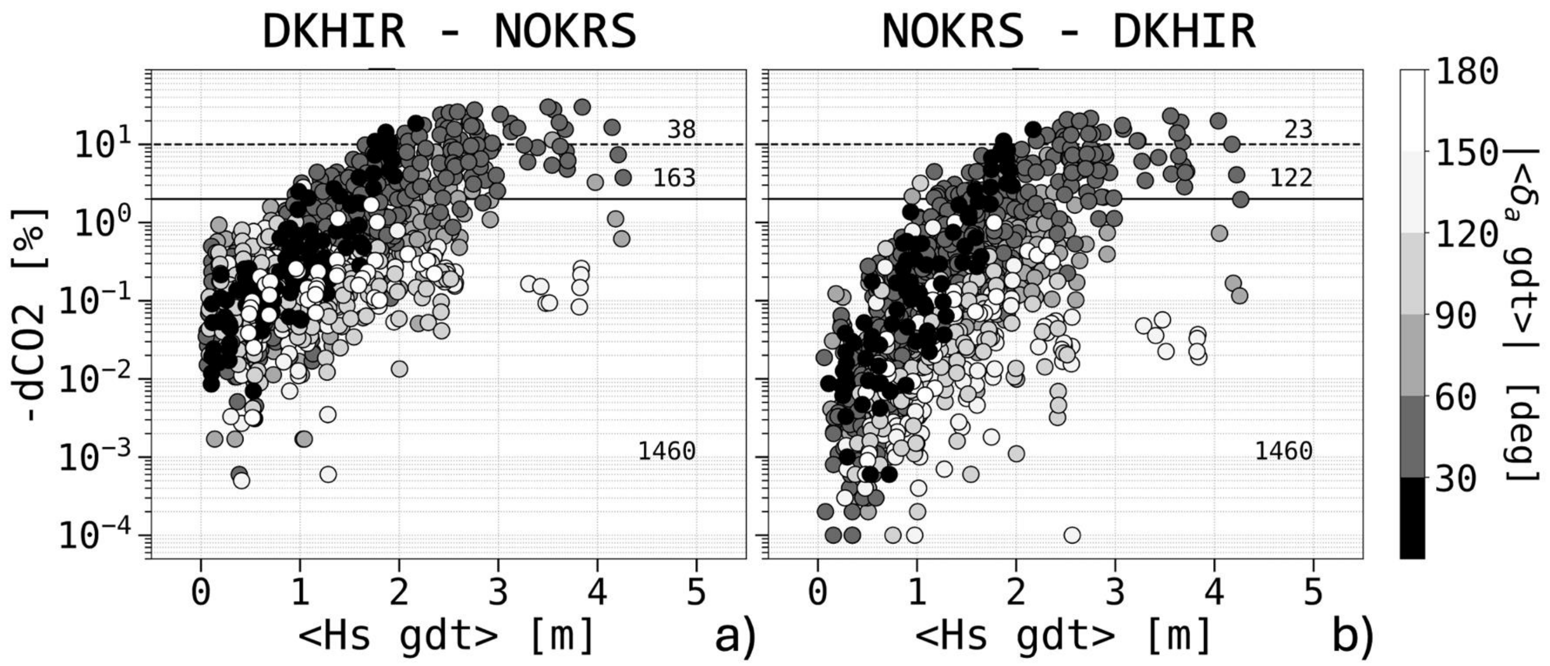
NOKRS - DKHIR

- *larger $|\delta_a|$ @ 0-10 h*
- *smaller Hs*
- *least-CO2 vs least-time:*
  - *less negative $w_{||}$*
  - *smaller cross current (smaller $|\delta|$)*



CO_2 savings throughout one year

- *minimum acceptable saving in our case: 2%*
- *threshold 10% saving was exceeded in 38 (23) experiments out of 1460 for routes from Hirtshals (Kristiansand)*
- *max CO2 saving was 30 (26)% from Hirtshals (Kristiansand)*
- *Note: a study (*) found that route length reduction of just 0.65% can make optimisation profitable*



voyage / χ	wave 70	wave 80	wave 90	wave 100	current & wave 70	current & wave 80	current & wave 90	current & wave 100
DKHIR - NOKRS	1.3	0.8	0.4	0.3	2.1	1.3	0.7	0.4
NOKRS - DKHIR	0.2	0.1	0.1	0.1	0.6	0.4	0.2	0.2

- *currents lead to higher annual-average CO2 savings*
- *savings are more significant at smaller engine loads*
- *Voyages from Denmark yield larger savings (3-5 x)*