

Data Analytics for Improving Energy Efficiency in Short-Sea Shipping (iHelm Project)

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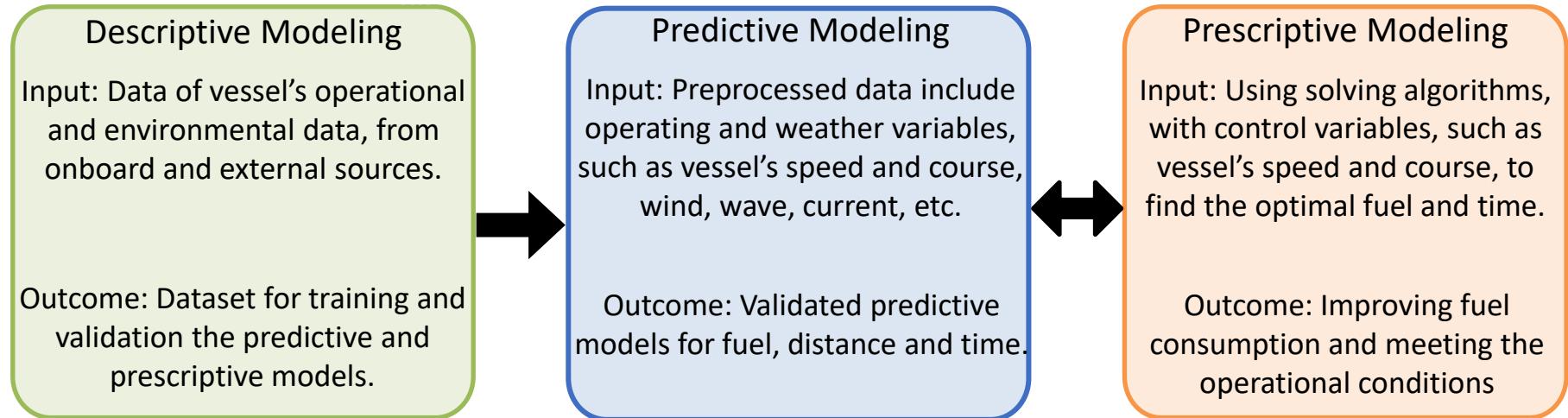
Center for Applied Intelligent Systems Research (CAISR)
Halmstad University
2022

Data Analytics for Improving Energy Efficiency in Short-Sea Shipping

Descriptive
Analytics

Predictive
Analytics

Prescriptive
Analytics



Workflow for Improving the Vessel's Energy Efficiency

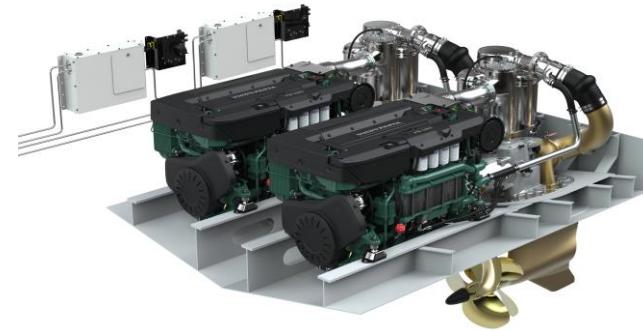
The ship's onboard data have been received from our industry partner CetaSol AB in Gothenburg [1]. It has been gathered over the entire year of 2020. It has a 3Hz frequency and records about the ship's position, course direction, and speed. It is also including some of operational and meteorological data.

Ship name: Buro; Type: passenger ship,

Size:(Length by Breadth) 19m * 6.41m; Average speed is 8.2 knots(4.2 m/s)



Buro ferry Photo by Owe Johansson [2]

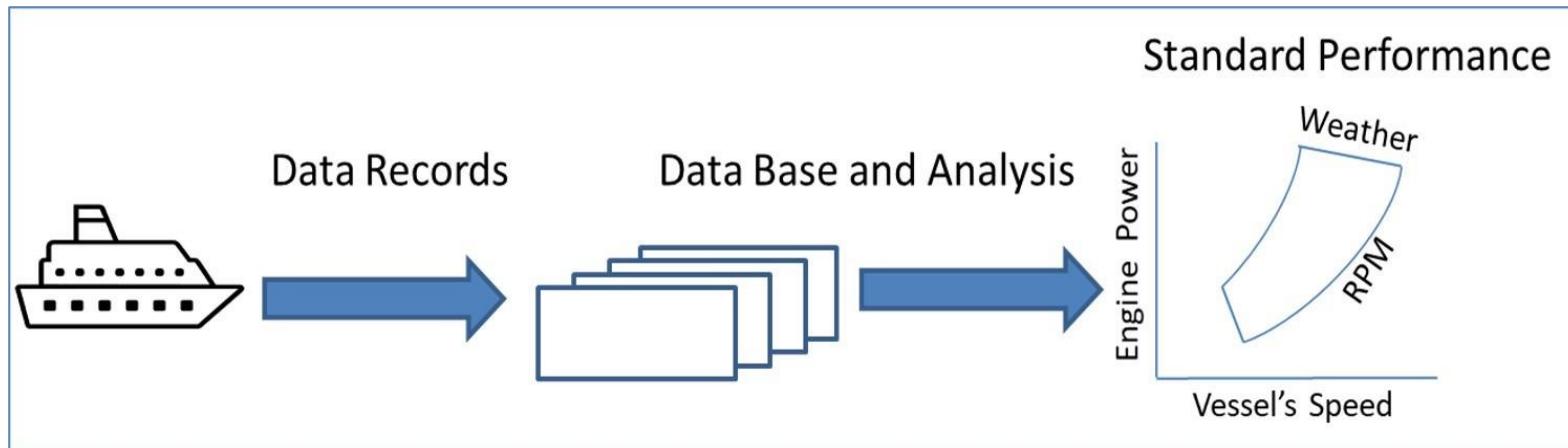


Engine Volvo Penta [3]

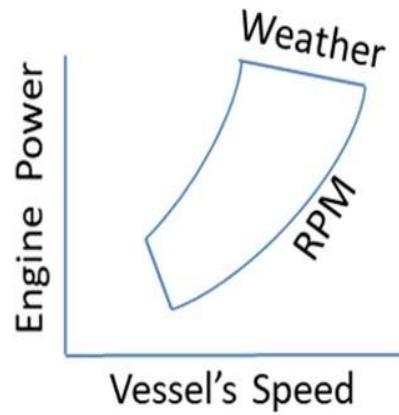
[1] CetaSol AB ." [Online]. Available: <https://cetasol.com/>

[2] <https://www.marinetraffic.com/>

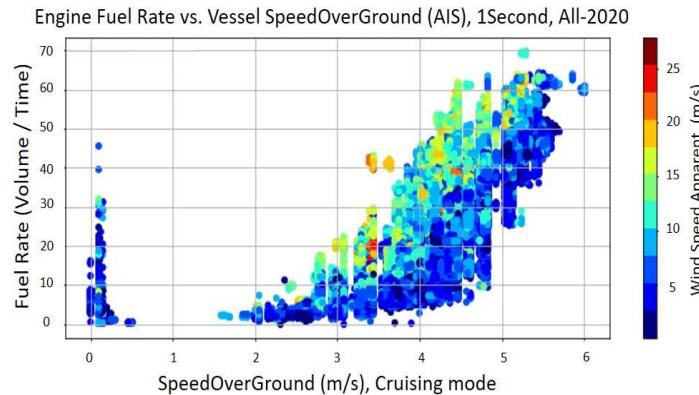
[3] Engine Volvo Penta tier13 A2022 8398." [Online]. Available: <https://www.volvpenta.com/about-us/news-page/2022/jun/imo-tier-iii-range-expands-with-new-d13-solutions/>



The vessel's data analytics

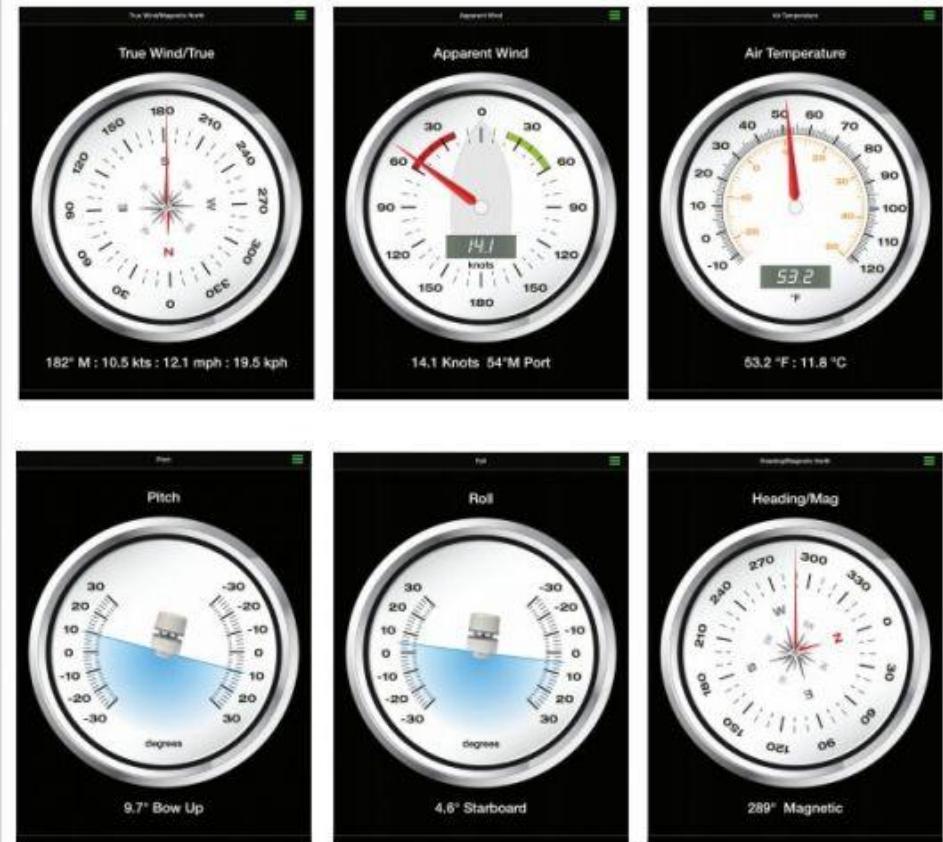


(a) Ship standard performance [4].



(b) Vessel Buro's Standard Performance Graph.

Some of Vessel's Motion and Environmental Data are Collected from an Instrument installed on the Vessel.



[5] <https://www.boatsnews.com/story/18720/the-weather-station-in-airmar-a-real-swiss-army-knife>

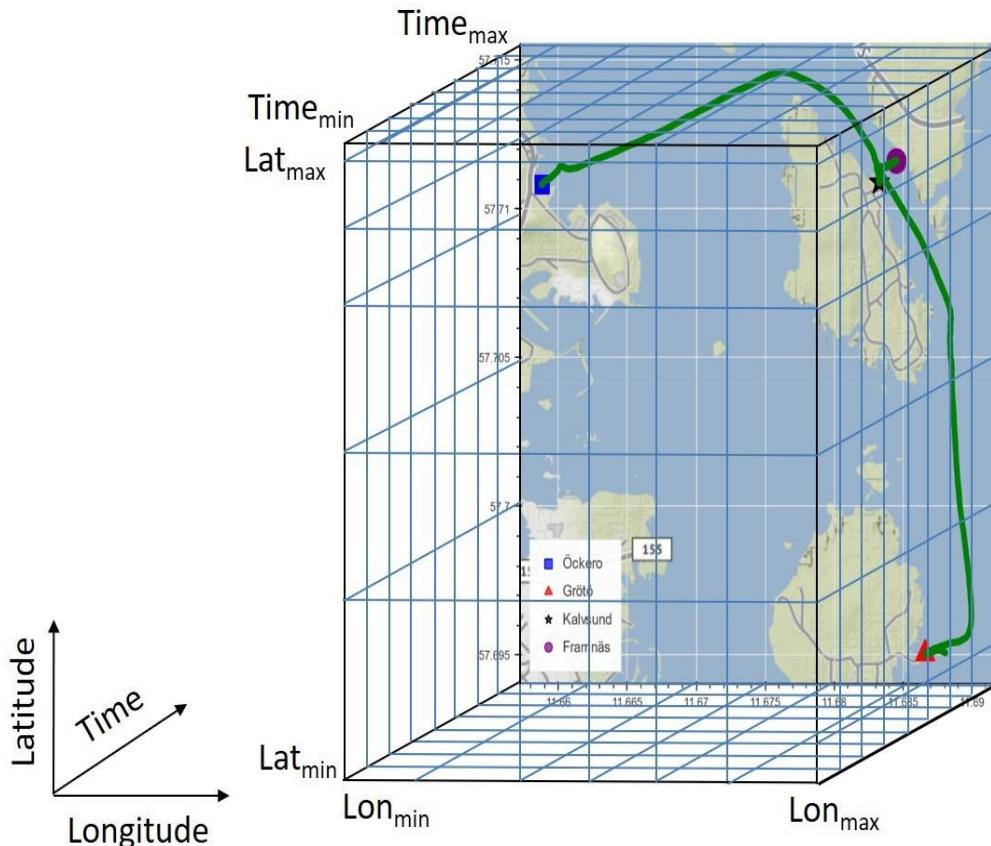
Trilinear Interpolation

A grid in which every point has three attributes:
Time, Latitude, and Longitude.

Time: 2019-11-26 to 2022-04-23

Space:
Longitude=11.68 (nearest)
Latitude=57.71 (nearest)

Data: Averaged values of available features of Onboard and Weather data from External Sources. [6-7]

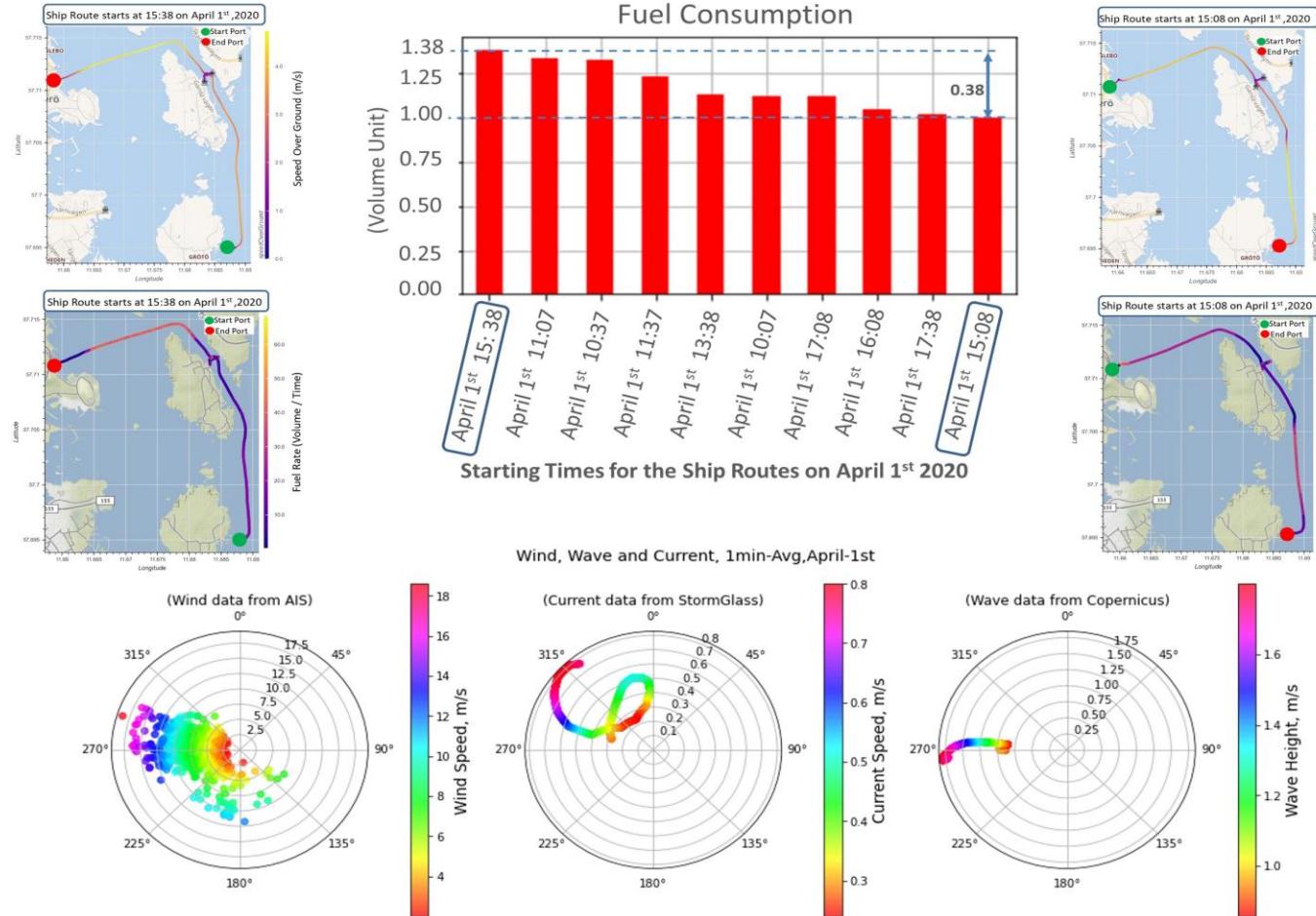


3-Dimension Linear Interpolation

[6] Copernicus Marine Service. [Online]. Available: <https://marine.copernicus.eu/>

[7] Stormglass API . [Online]. Available: <https://stormglass.io/>

What are the main factors that impact the vessel's fuel consumption for short-sea shipping?



The Vessel's Operational and Environmental Data on April 1st, 2020

What are the main factors that impact the vessel's fuel consumption for short-sea shipping?

Let's consider an illustrative case of a passenger ship with actual profiles of fuel consumption as illustrated in figure 1. This ship has main routes between a port on the South side and a port on the North side, on April 1st, 2020.

By associating the weather and voyage factors with this illustrative case, as the ship started her route at 15 : 38 and then at the last part of the route it changed her course direction toward west which is against the wind, current and wave directions, i.e., 270°(degree). Nevertheless, it could be obvious that the weather has impacted the ship's fuel consumption, the vessel's speed was also increased simultaneously when the vessel headed westward. Thus, at this combination of weather conditions and speed, the vessel's resistance has increased and hence the fuel consumption became higher by about 38% more than just the previous route that started at 15 : 08.

Therefore, different factors of the voyage status and their combinations with the weather conditions should all be considered to perform a rational reasoning for the vessel's fuel consumption.

```
In [9]: 1 dforig.shape
```

```
Out[9]: (36581527, 44) All Speeds
```

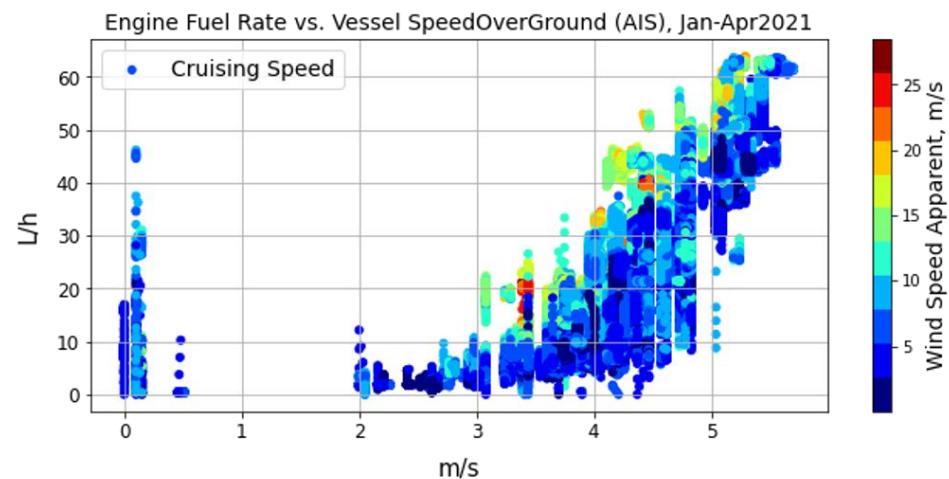
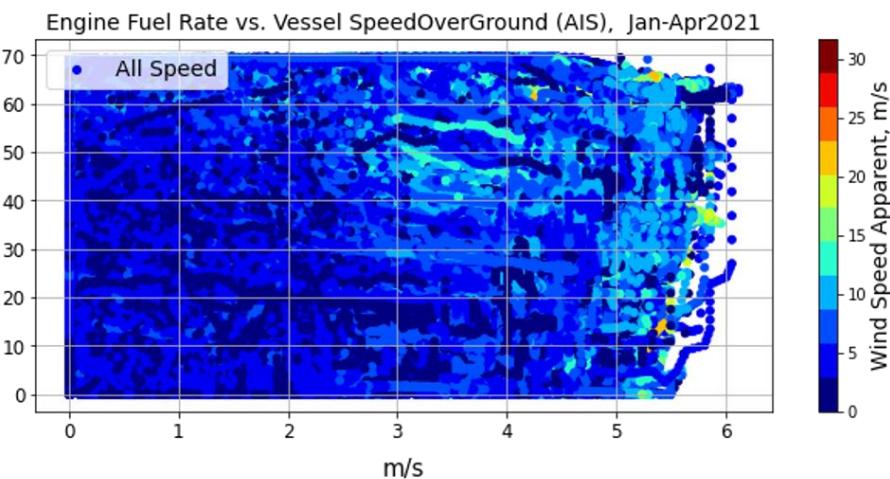
```
In [10]: 1 dforig.segmentState.unique()
```

```
Out[10]: array(['', 'cruising'], dtype=object)
```

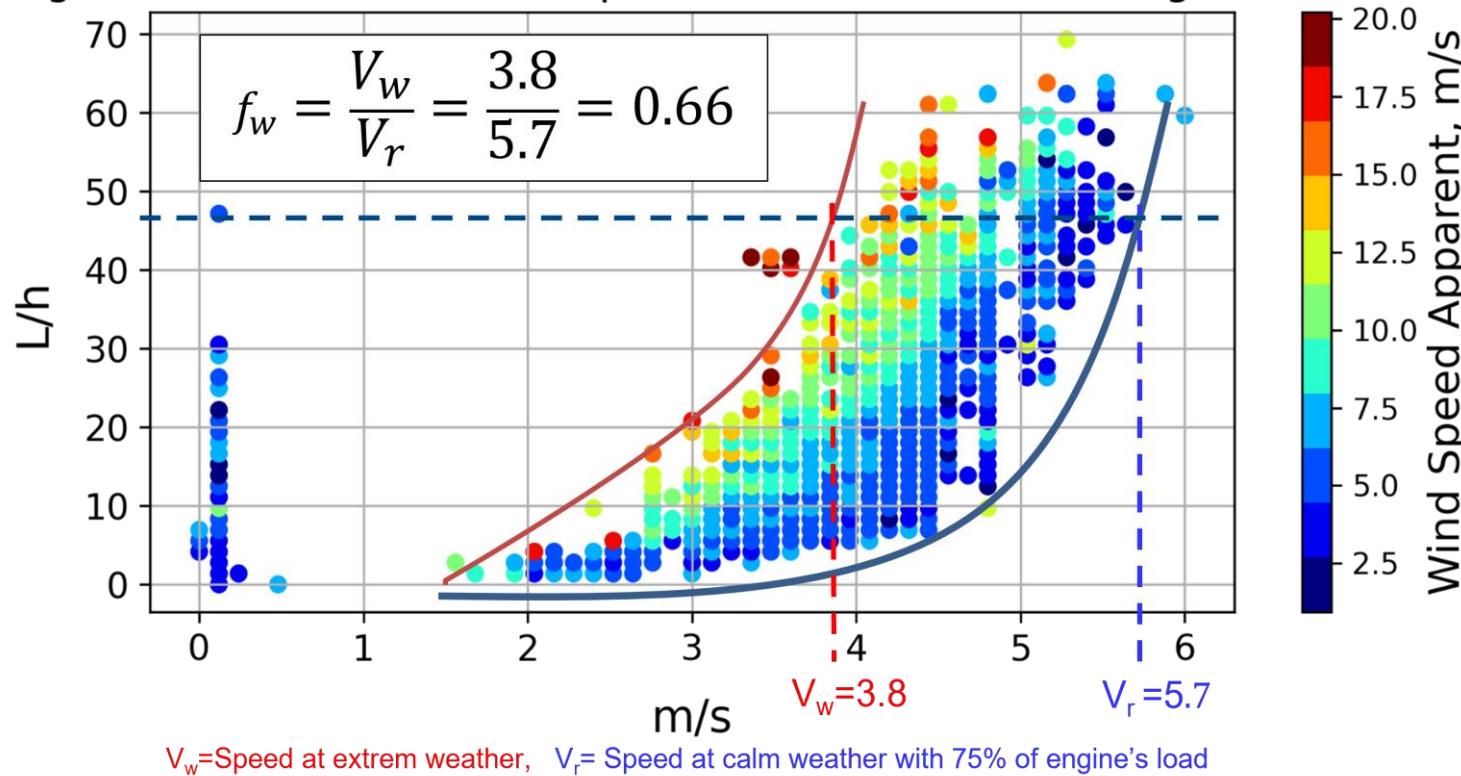
```
In [13]: 1 dforig[(dforig.segmentState=='cruising')].shape
```

```
Out[13]: (1681613, 44) Cruising Speed Only
```

Cruising mode in Buro's Data
 → 1681613 out of 36581527
 (i.e., 4.6% of data represent the
 cruising mode)



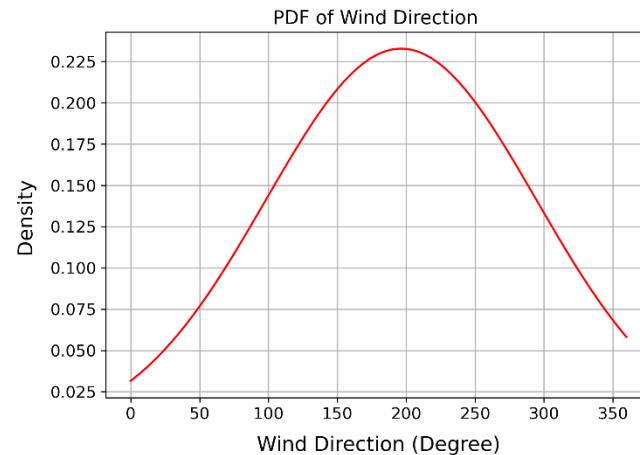
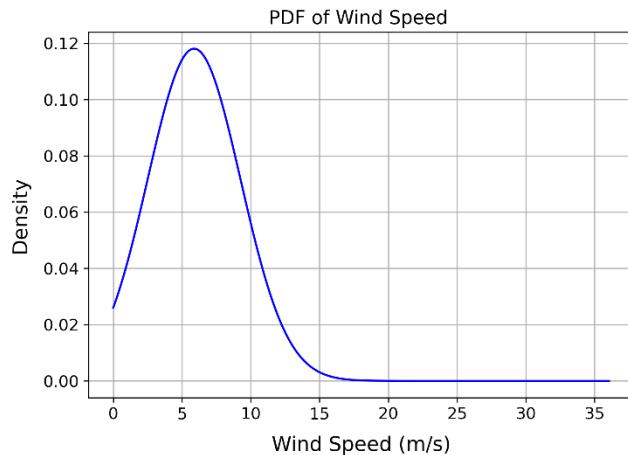
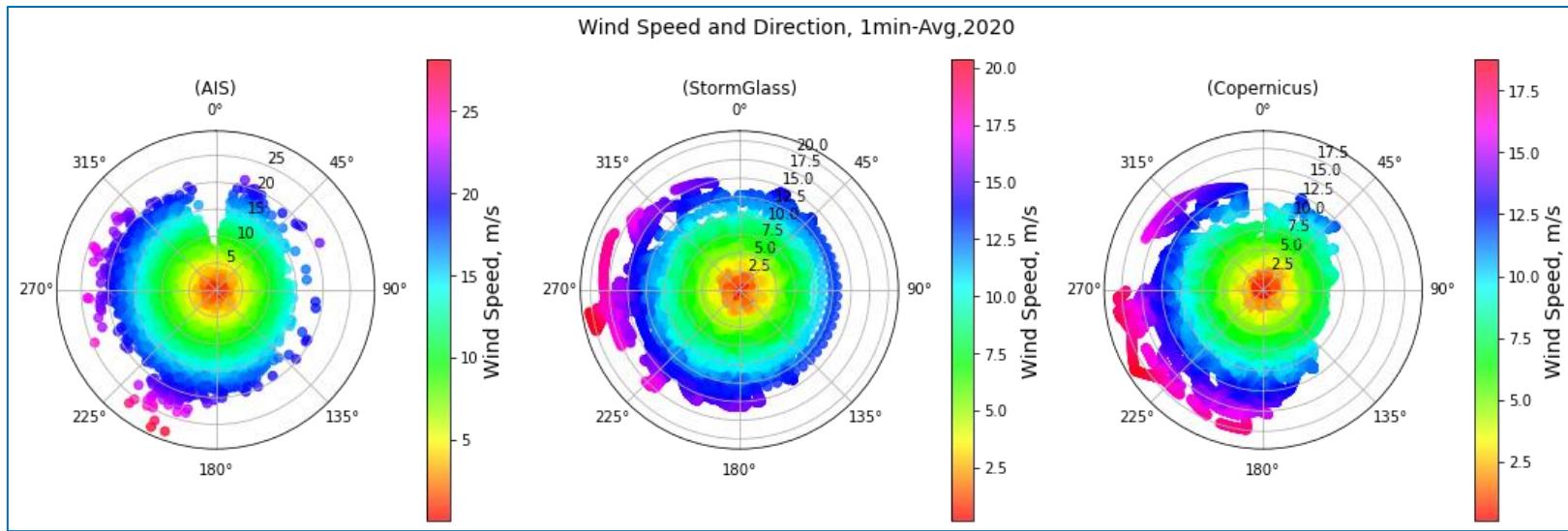
Engine Fuel Rate vs. Vessel SpeedOverGround , 1min-Avg, All-2020



The weather factor obtained from the vessel's standard performance graph

[8] Y. Kim, D. Hayden, D. Fathi, G. Hermanski, D. Hudson, P. d. Jong, K. Tanizawa, G. Thomas, and W. Chengshen, "Seakeeping committee final report and recommendations to the 27th ITTC," 2014.

Wind from Different Sources in the Entire 2020



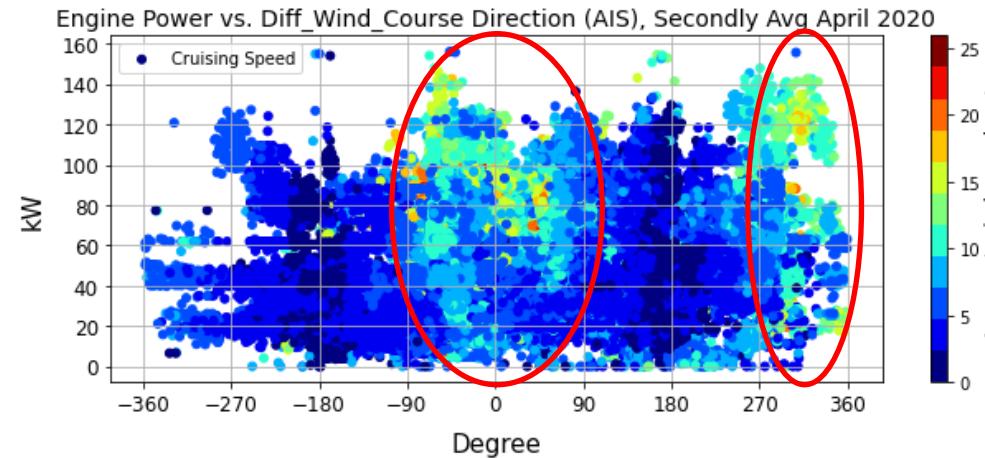
Probability Distribution of Wind Speed.

Spatial Analysis of the Vessel's Routes and Fuel Consumption

Head Wind

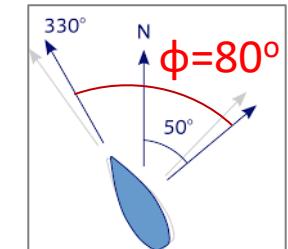
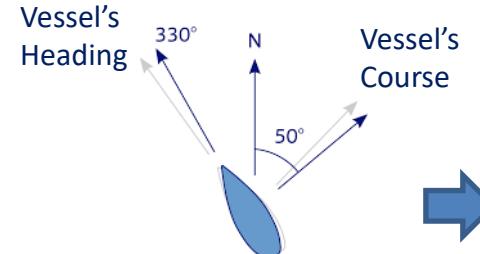


Tail Wind



$\text{Diff_Wind_Course} = \text{Wind Direction} - \text{Course Direction}$
Head winds are shown in the red oval shapes

Drift angle (ϕ) = Course direction – Heading direction



[9] Tsujimoto, M., & Orihara, H. (2019). Performance prediction of full-scale ship and analysis by means of on-board monitoring (Part 1 ship performance prediction in actual seas). *Journal of Marine Science and Technology*, 24(1), 16-33.

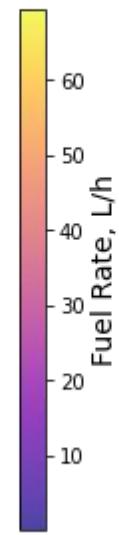
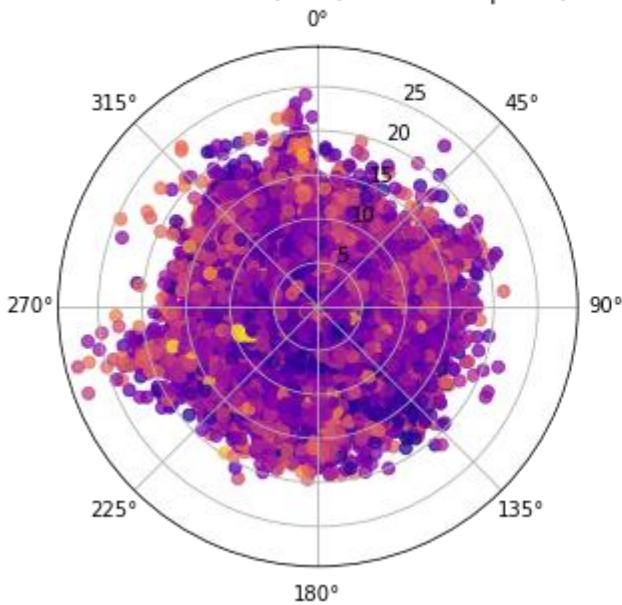
Spatial Analysis of the Vessel's Routes and Fuel Consumption

Circles=Wind Speed

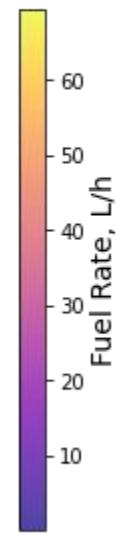
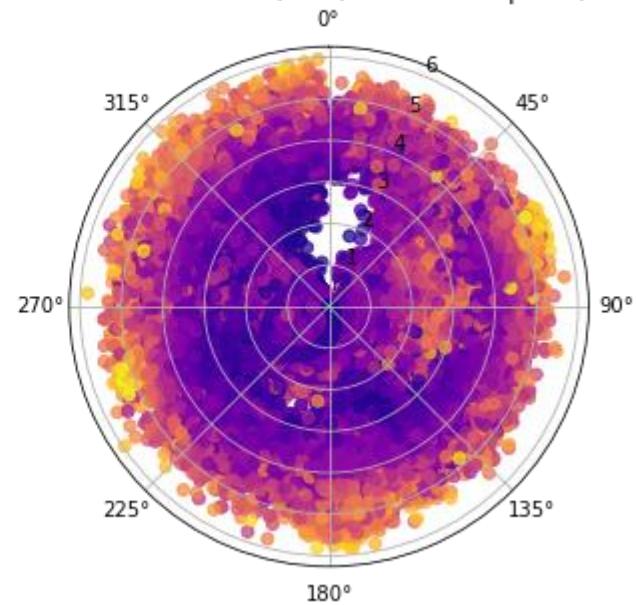
Wind, Wave and Current, 1min-Avg, All 2020

Circles=Vessel Speed

Vessel Course Direction (Dots) and Wind Speed (Circles)



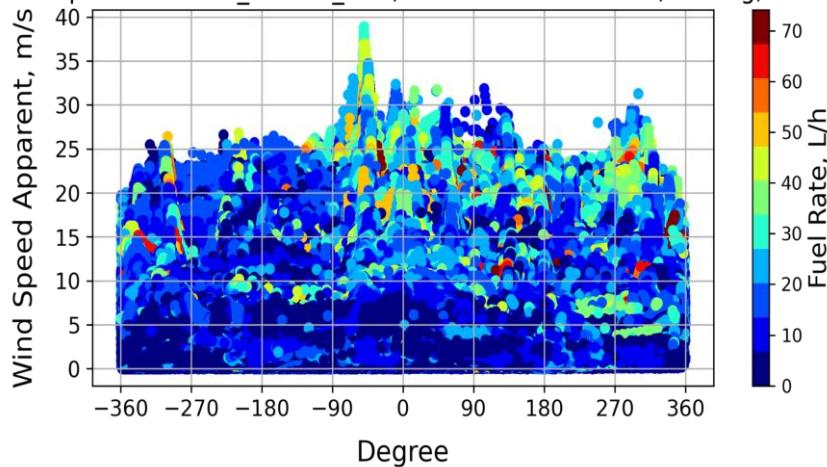
Vessel Course Direction (Dots) and Vessel Speed (Circles)



Polar graph for the Vessel's Course with wind and vessel speed and fuel rate

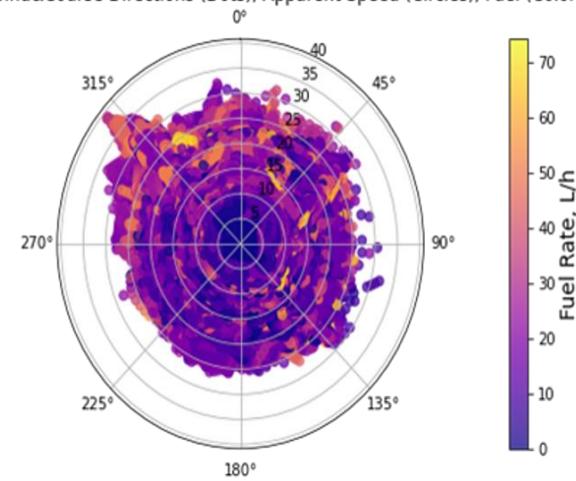
Spatial Analysis of the Vessel's Routes and Fuel Consumption

Apparent Speed vs. Wind_Course_Diff., with Fuel as Colorbar, 1S-Avg, All-2020



(a) Color-bar Plot of the Speed Apparent vs. Differences of Wind and Vessel's Directions with Fuel Rate

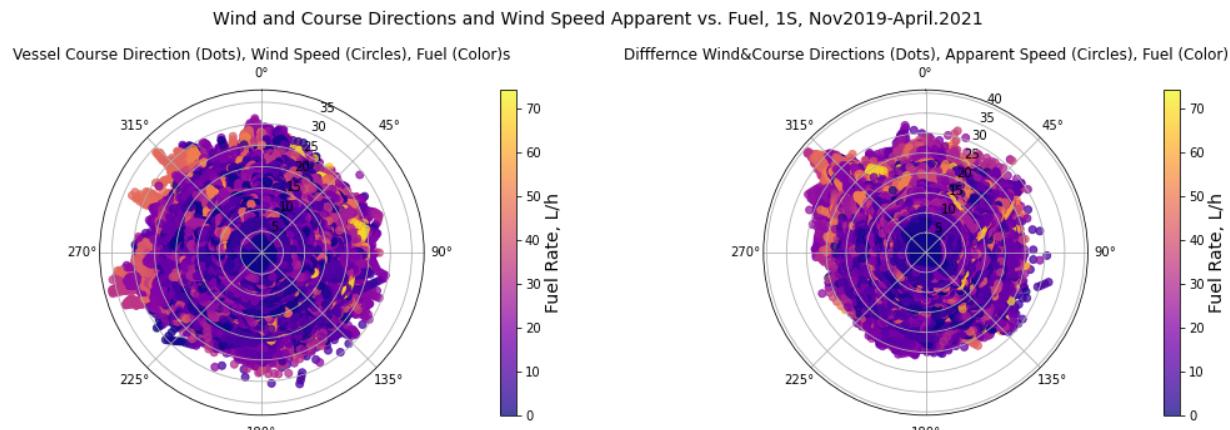
Difference Wind&Course Directions (Dots), Apparent Speed (Circles), Fuel (Color)



(b) Polar Plot of Differences of Wind and Vessel's Directions with Fuel Rate

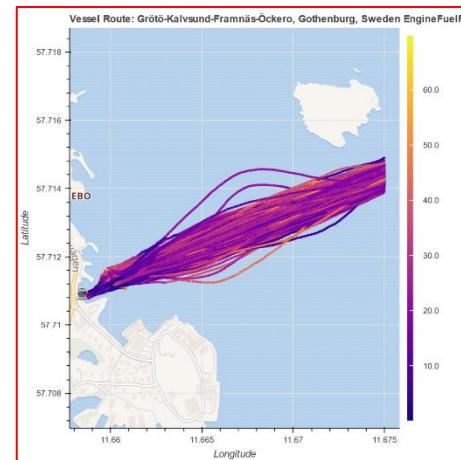
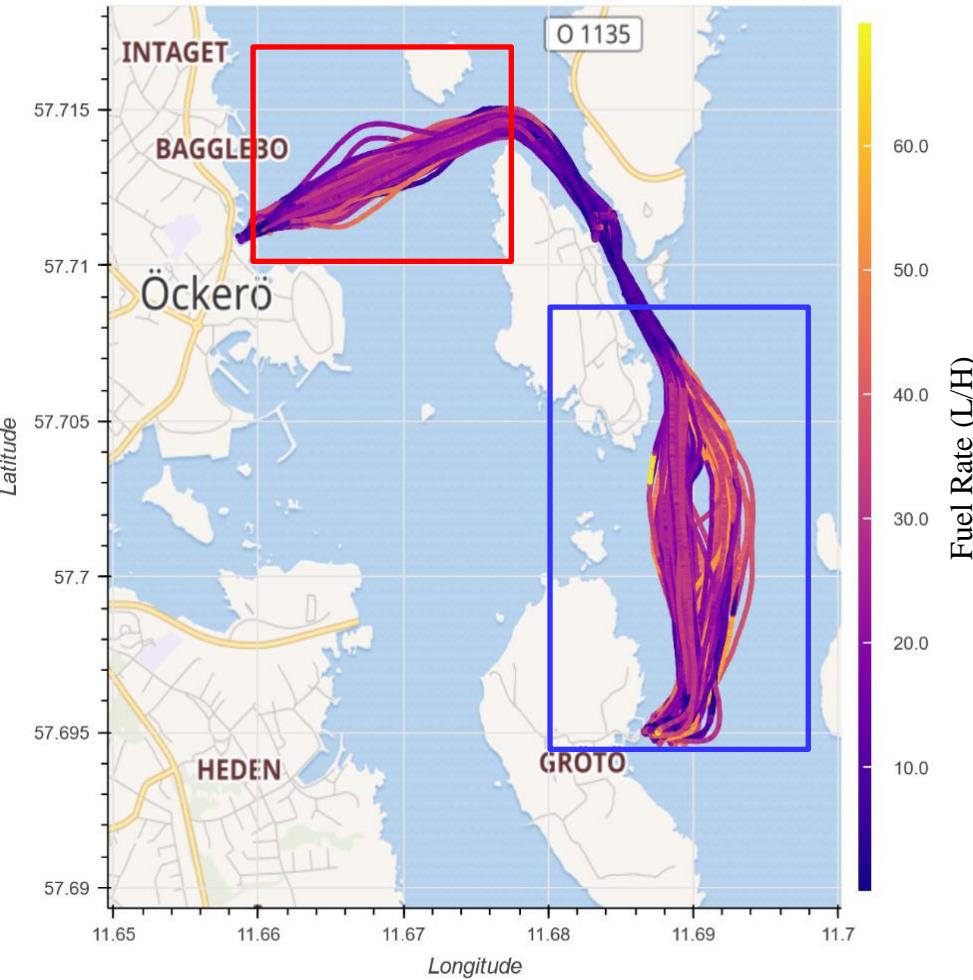
Spatial Analysis of the Vessel's Routes and Fuel Consumption

Diff_WindCourse Intervals	count	fuel avg	sog avg	Sp_app avg	Diff_wncr avg	Wind_sp avg	Wind_dr avg	Course avg
(0, 90]	8147300	15.42	2.21	7.40	45.06	5.76	219.91	174.86
(90, 180]	7478087	15.23	2.27	4.99	131.87	5.66	253.69	121.83
(180, 270]	2573125	16.70	1.75	4.86	218.78	5.57	286.16	67.38
(270, 360]	940072	18.55	1.86	7.20	298.07	6.05	322.35	24.28
[0, -90)	8452311	15.79	2.22	8.05	-41.39	6.27	188.71	230.10
[-90, -180)	4080962	13.65	1.78	5.03	-135.41	5.45	130.83	266.23
[-180, -270)	3430024	13.69	2.36	5.07	-219.81	5.97	79.45	299.26
[-270, -360)	1479646	15.22	2.58	8.35	-300.98	6.74	35.80	336.78

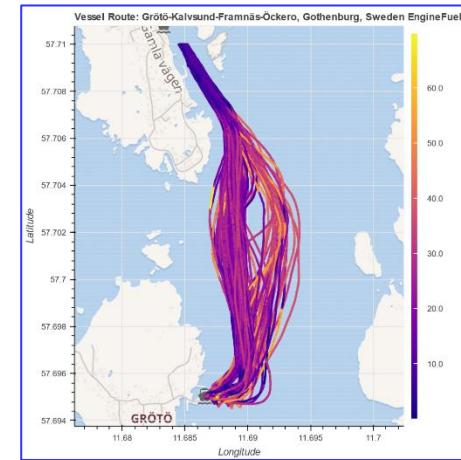


Spatial Analysis of the Vessel's Routes and Fuel Consumption

Vessel Route: Grötö-Kalvsund-Framnäs-Öckerö, Gothenburg, Sweden EngineFuelRa



Northwest section of routes, March-April 2020



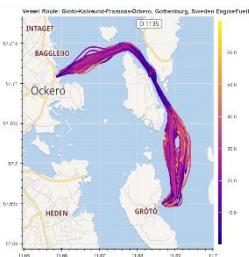
Southeast section of routes, March-April 2020

Spatial Analysis of the Vessel's Routes and Fuel Consumption

Total Route

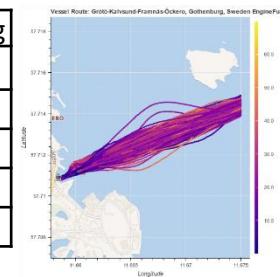
	fuel	time	distance	SOG_avg	SpApp_avg	Diff_cswd_avg	Wind_sp_avg
Total Avg	6.84	21.02	3.88	3.00	8.06	3.14	6.96
Top100 Avg	5.56	20.29	3.80	3.06	7.58	27.16	6.60
Top50 Avg	4.94	20.24	3.78	3.08	7.54	45.59	6.73
Bottom100 Avg	8.24	21.60	3.97	2.97	8.52	-24.38	7.30
Bottom50 Avg	9.13	21.57	3.99	2.99	8.53	-34.53	7.18

Routes from South to North



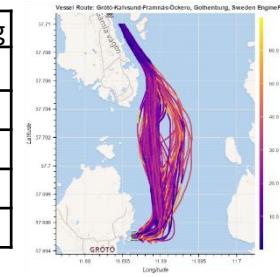
Northwest Segment

	fuel	time	distance	SOG_avg	SpApp_avg	Diff_cswd_avg	Wind_sp_avg
Total Avg	2.21	6.16	1.25	3.24	8.90	-3.62	7.14
Top100 Avg	1.78	5.93	1.22	3.24	8.88	19.69	7.21
Top50 Avg	1.56	6.02	1.21	3.21	8.97	32.41	7.38
Bottom100 Avg	2.68	6.38	1.29	3.27	8.85	-28.61	6.94
Bottom50 Avg	2.96	6.41	1.31	3.32	8.37	-37.35	6.41



Southeast Segment

	fuel	time	distance	SOG_avg	SpApp_avg	Diff_cswd_avg	Wind_sp_avg
Total Avg	2.18	5.59	1.27	3.99	8.60	-33.91	7.92
Top100 Avg	1.70	5.51	1.25	3.98	7.73	-3.49	7.16
Top50 Avg	1.48	5.53	1.25	3.95	7.57	20.45	7.32
Bottom100 Avg	2.71	5.66	1.29	4.00	9.40	-67.44	8.66
Bottom50 Avg	3.05	5.53	1.28	4.09	9.59	-76.35	8.60

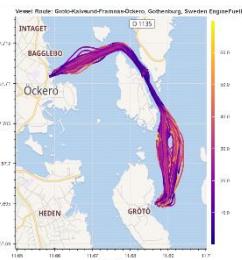


Spatial Analysis of the Vessel's Routes and Fuel Consumption

Total Route

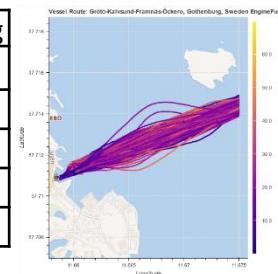
	fuel	time	distance	SOG_avg	SpApp_avg	Diff_cswd_avg	Wind_sp_avg
Total Avg	6.00	20.30	3.77	3.11	6.63	-63.30	6.03
Top100 Avg	4.75	19.87	3.74	3.16	5.72	-67.48	5.37
Top50 Avg	4.28	19.59	3.73	3.21	5.36	-78.94	5.12
Bottom100 Avg	7.24	20.78	3.80	3.05	7.58	-60.54	6.81
Bottom50 Avg	7.90	20.94	3.80	3.05	8.32	-50.38	7.30

Routes from North to South



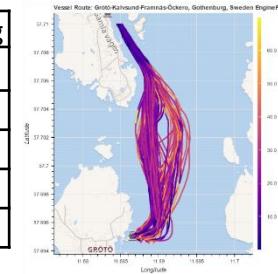
Northwest Segment

	fuel	time	distance	SOG_avg	SpApp_avg	Diff_cswd_avg	Wind_sp_avg
Total Avg	1.88	5.09	1.21	4.12	5.64	-128.15	6.21
Top100 Avg	1.54	5.13	1.19	4.01	5.89	-119.84	6.03
Top50 Avg	1.42	5.23	1.19	3.95	5.81	-120.72	5.81
Bottom100 Avg	2.18	5.03	1.22	4.22	5.36	-138.44	6.43
Bottom50 Avg	2.32	4.95	1.22	4.29	5.54	-130.08	6.36



Southeast Segment

	fuel	time	distance	SOG_avg	SpApp_avg	Diff_cswd_avg	Wind_sp_avg
Total Avg	1.69	5.96	1.19	3.64	8.40	-25.93	6.85
Top100 Avg	1.19	5.81	1.18	3.68	6.51	-32.10	5.61
Top50 Avg	1.07	5.71	1.19	3.74	5.77	-46.78	5.05
Bottom100 Avg	2.21	6.12	1.18	3.60	10.38	-20.89	8.25
Bottom50 Avg	2.49	6.24	1.17	3.53	11.49	-9.53	9.17



Correlation of Engine's Fuel Rate with Weather factors

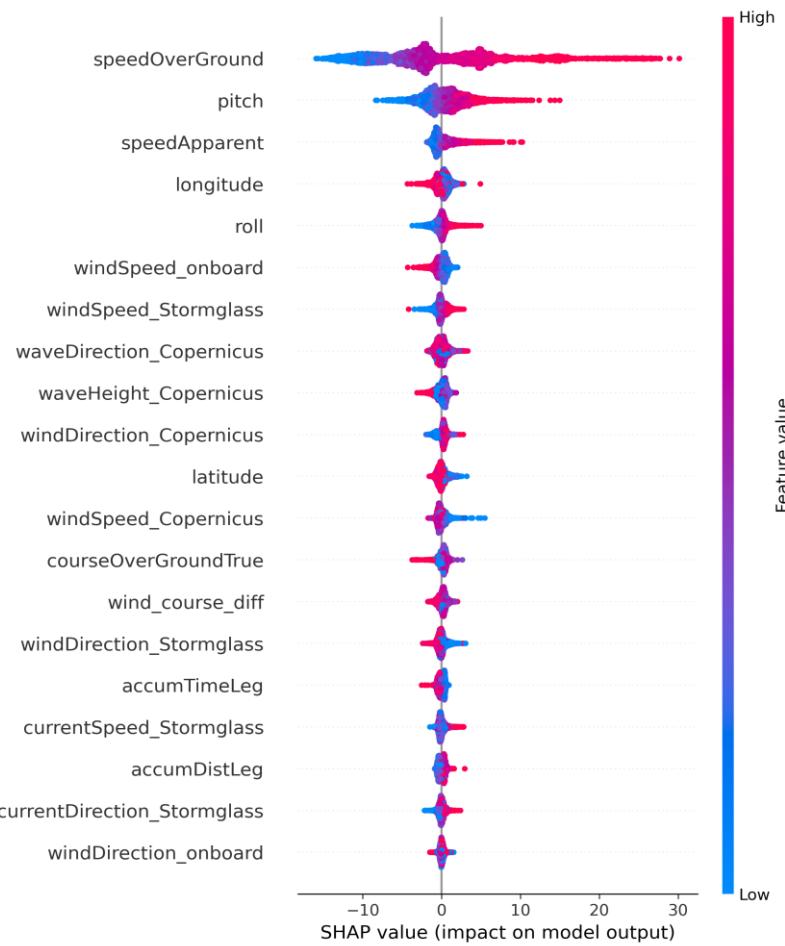
Correlation 1 Min	Speed_sog_ais	wind_sog_ais	wind_cds	wind_sg	wind_dr_sog_ais	wind_dr_cds	wind_dr_sg	wind_app_ais	wind_app_cds	wind_app_sg	current_sp_sg	current_Dr_sg	wave_ht_cds	wave_dr_cds	wavedrg_cff_cds	roll_ais	pitch_ais	engine_fuelrate_ais
Speed_sog_Ais	1.0000	0.1780	0.0175	-0.0099	-0.0200	0.1071	0.0902	0.6076	0.0859	0.0575	-0.0632	0.0024	0.0134	0.1060	0.0134	0.0129	0.4497	0.4986
wind_sog_ais	0.1780	1.0000	0.6009	0.5602	0.0518	0.0495	0.0556	0.8897	0.5537	0.5364	0.2956	0.1175	0.6021	-0.0379	0.5905	0.0869	0.2051	0.2468
wind_cds	0.0175	0.6009	1.0000	0.8699	0.1349	0.1686	0.1776	0.4858	0.9566	0.8432	0.4392	0.2979	0.9627	0.0550	0.9599	0.0349	0.0857	0.1064
wind_sg	-0.0099	0.5602	0.8699	1.0000	0.1359	0.1119	0.1322	0.4513	0.8283	0.9595	0.4683	0.2423	0.8690	0.0371	0.8588	0.0491	0.0584	0.1100
wind_dr_sog_ais	-0.0200	0.0518	0.1349	0.1359	1.0000	0.6837	0.5944	0.0326	0.1212	0.1196	-0.0616	0.2091	0.1581	0.6151	0.1274	0.0145	-0.0182	0.0051
wind_dr_cds	0.1071	0.0495	0.1686	0.1119	0.6837	1.0000	0.7230	0.0459	0.1675	0.1088	-0.0163	0.3189	0.1949	0.6905	0.1624	0.0224	0.0072	0.0454
wind_dr_sg	0.0902	0.0556	0.1776	0.1322	0.5944	0.7230	1.0000	0.0498	0.1724	0.1228	0.0114	0.3050	0.1946	0.6109	0.1677	0.0235	0.0063	0.0300
wind_app_ais	0.6076	0.8897	0.4858	0.4513	0.0326	0.0459	0.0498	1.0000	0.4898	0.4727	0.2320	0.0963	0.4856	-0.0250	0.4773	0.0761	0.3742	0.4306
wind_app_cds	0.0859	0.5537	0.9566	0.8283	0.1212	0.1675	0.1724	0.4898	1.0000	0.8759	0.4131	0.2938	0.9206	0.0512	0.9177	0.0660	0.1294	0.1542
wind_app_sg	0.0575	0.5364	0.8432	0.9595	0.1196	0.1088	0.1228	0.4727	0.8759	1.0000	0.4451	0.2377	0.8409	0.0299	0.8306	0.0787	0.1060	0.1545
current_sp_sg	-0.0632	0.2956	0.4392	0.4683	-0.0616	-0.0163	0.0114	0.2320	0.4131	0.4451	1.0000	0.1660	0.4584	-0.0799	0.4453	0.0090	0.0177	0.0475
current_dr_sg	0.0024	0.1175	0.2979	0.2423	0.2091	0.3189	0.3050	0.0963	0.2938	0.2377	0.1660	1.0000	0.3072	0.2364	0.2813	0.0119	0.0001	0.0443
wave_ht_cds	0.0134	0.6021	0.9627	0.8690	0.1581	0.1949	0.1946	0.4856	0.9206	0.8409	0.4584	0.3072	1.0000	0.0822	0.9642	0.0213	0.0780	0.1062
wave_dr_cds	0.1060	-0.0379	0.0550	0.0371	0.6151	0.6905	0.6109	-0.0250	0.0512	0.0299	-0.0799	0.2364	0.0822	1.0000	0.0604	0.0317	-0.0122	0.0167
wavedrg_cff_cds	0.0134	0.5905	0.9599	0.8588	0.1274	0.1624	0.1677	0.4773	0.9177	0.8306	0.4453	0.2813	0.9642	0.0604	1.0000	0.0265	0.0771	0.1097
roll_ais	0.0129	0.0869	0.0349	0.0491	0.0145	0.0224	0.0235	0.0761	0.0660	0.0787	0.0090	0.0119	0.0213	0.0317	0.0265	1.0000	-0.0690	0.0839
pitch_ais	0.4497	0.2051	0.0857	0.0584	-0.0182	0.0072	0.0063	0.3742	0.1294	0.1060	0.0177	0.0001	0.0780	-0.0122	0.0771	-0.0690	1.0000	0.6003
engine_fuelrate_ais	0.4986	0.2468	0.1064	0.1100	0.0051	0.0454	0.0300	0.4306	0.1542	0.1545	0.0475	0.0443	0.1062	0.0167	0.1097	0.0839	0.6003	1.0000

*(AIS): Onboard Data, (CDS): Copernicus Weather data, (SG): Storm Glass Weather Data

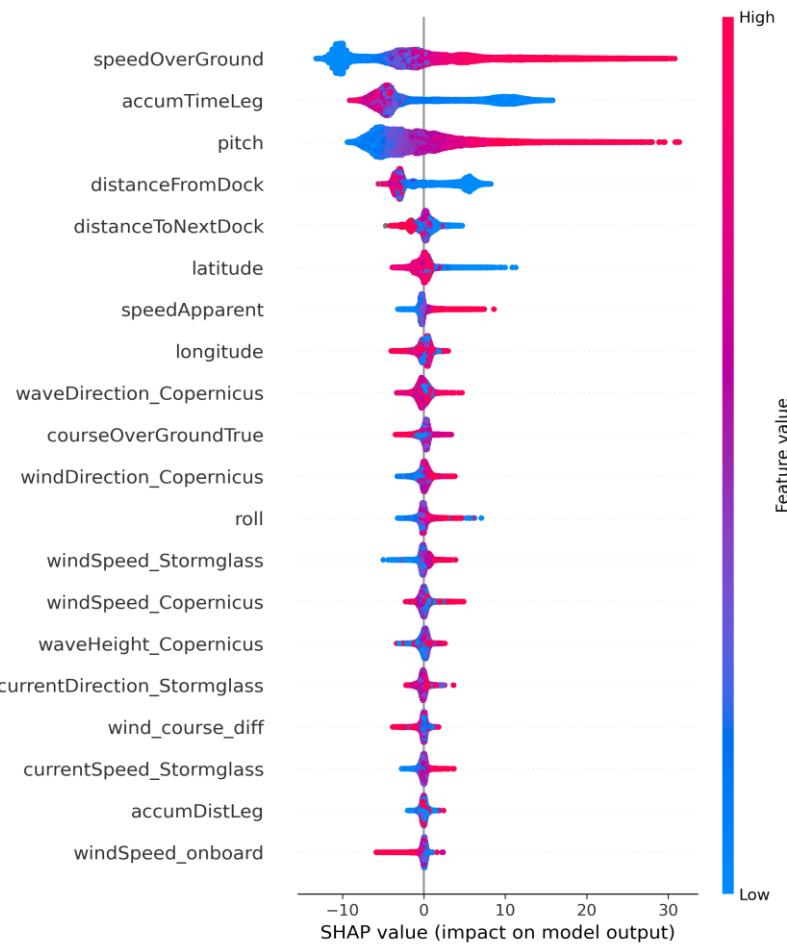
All 2020

1-Minute

All Speeds



(a) Shapley values for the available features

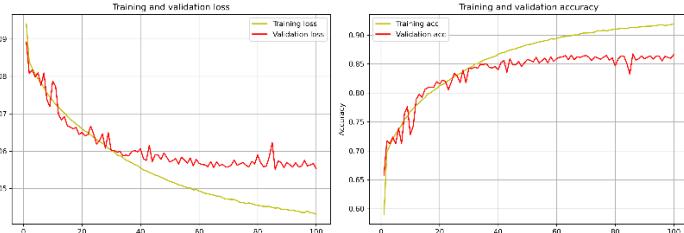


(b) Shapley values for the available features with cruising-mode speeds with all speeds

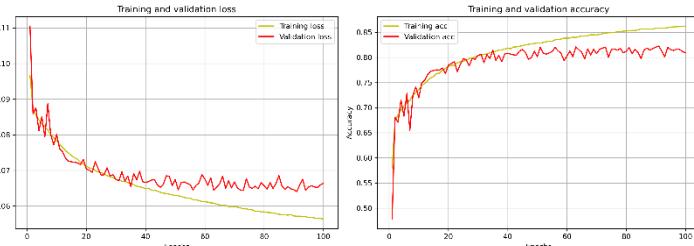
[10] S. M. Lundberg and S.-I. Lee, "A unified approach to interpreting model predictions," Advances in neural information processing systems, vol. 30, 2017.

All Speeds

All Variable, 22inputs



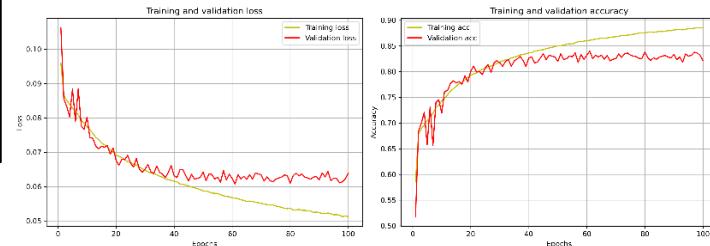
11inputs Wind from Copernicus



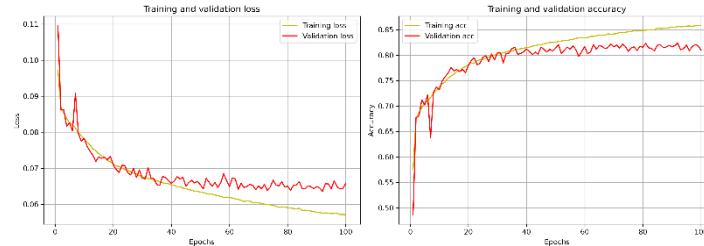
Plots of ANN Training and searching optimal ANN's parameters and inputs

Predictive Analytics

11inputs Wind from Onboard

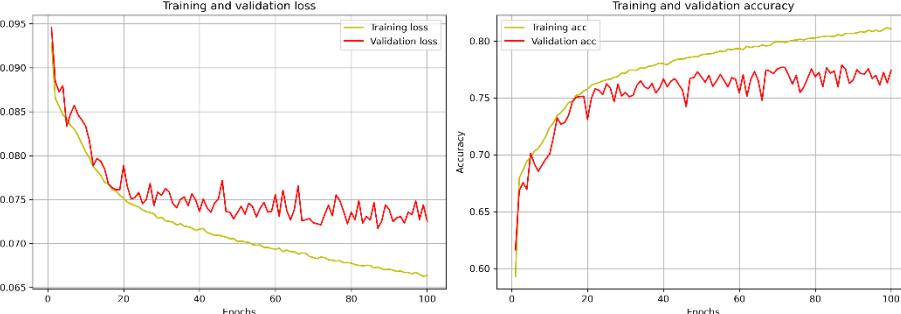


11inputs Wind from Sormglass

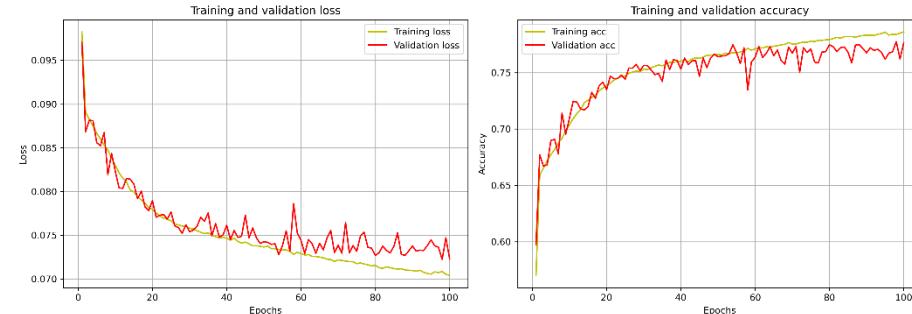


Without Wind-related or any weather-related variables

AllVars, Excluding weather related variables, 10inputs

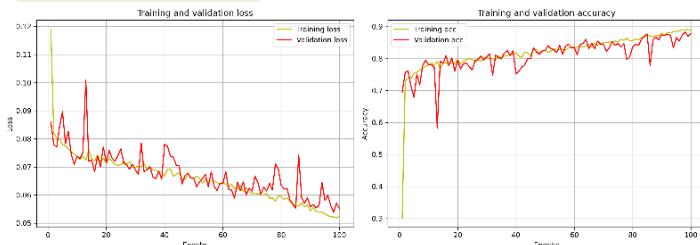


11inputs, Excluding wind-related variables, 7inputs



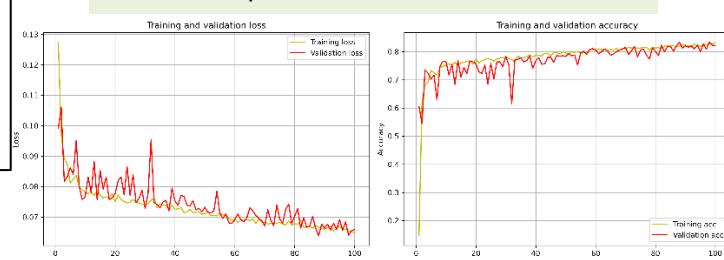
Cruising Speed Only → (i.e., 4.6% of All-Speeds data are used for these results)

AllVars, 22inputs

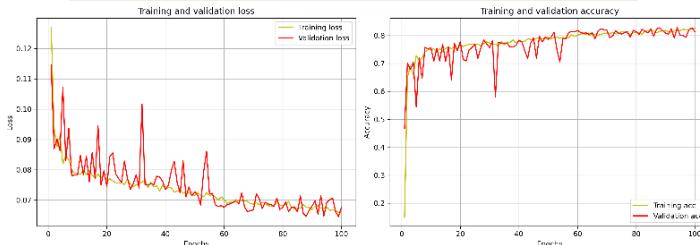


Plots of ANN Training and searching optimal ANN's parameters and inputs

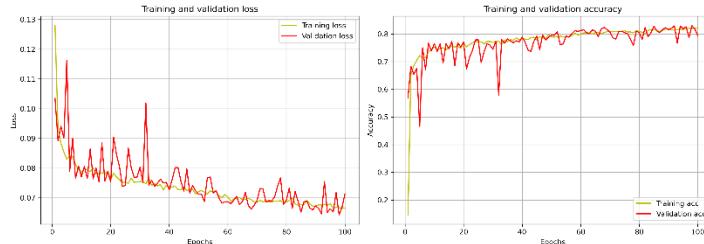
11inputs Wind from Onboard



11inputs Wind from Copernicus

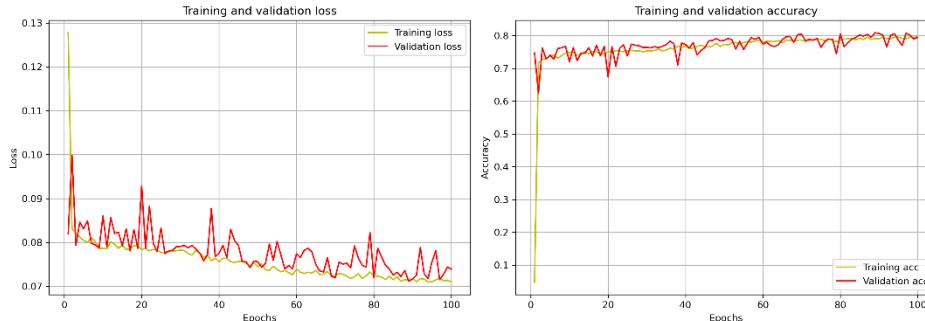


11inputs Wind from Sormglass

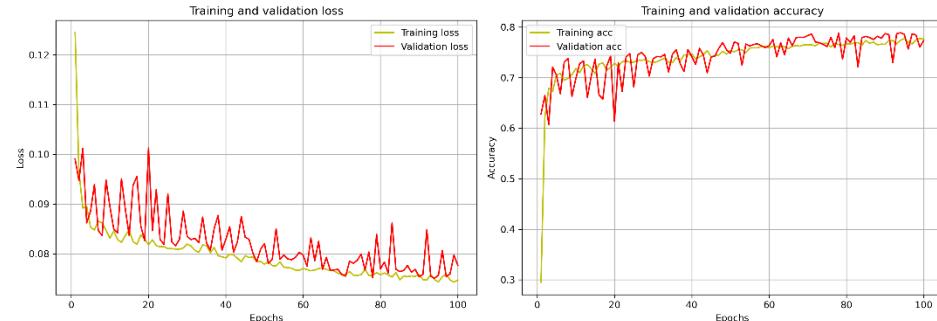


Without Wind-related or any weather-related variables

AllVars, Excluding weather related variables, 10inputs



11inputs, Excluding wind-related variables, 7inputs

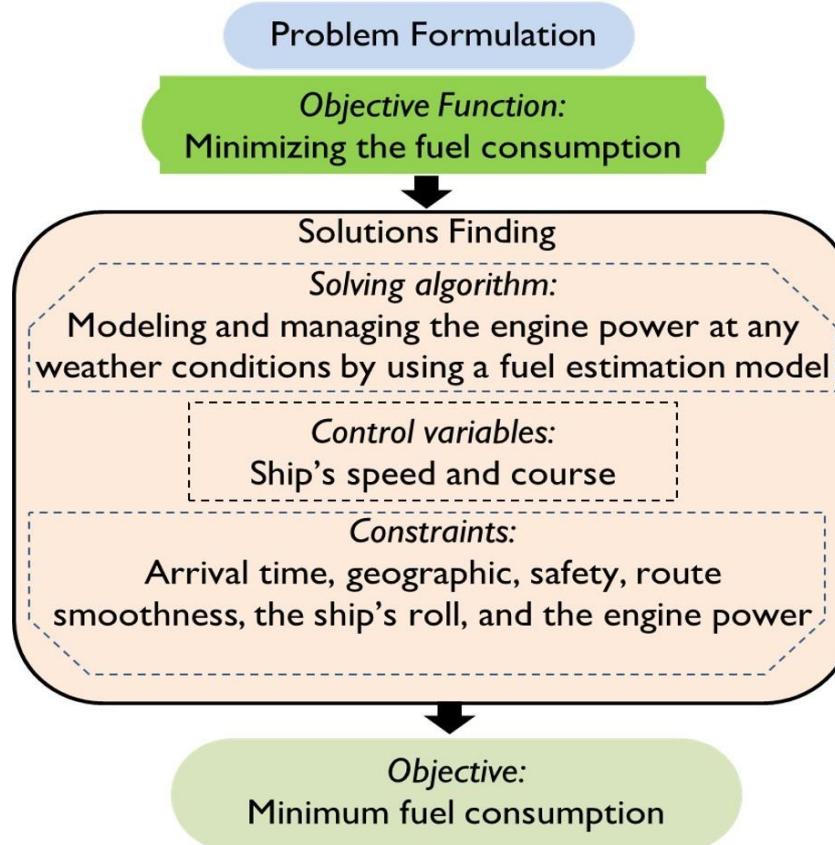


Results of ANN regression, where fuel-rate is the ANN output, and ANN input with different cases, for both cruising-mode speeds and all speeds

Index	No.# ANN Inputs	All Speeds			Cruising-Mode Speeds		
		RMSE	R2	MAE	RMSE	R2	MAE
Using onboard wind for weather conditions	11	0.0643	0.8298	0.0476	0.0663	0.8304	0.0515
Using wind-Copernicus for weather conditions	11	0.0669	0.8156	0.0496	0.0679	0.8218	0.0539
Using wind-Stormglass for weather conditions	11	0.0664	0.8188	0.0490	0.0715	0.8024	0.0563
Excluding wind-related variables	7	0.0728	0.7853	0.0534	0.0781	0.7788	0.0587
All available variables	22	0.0557	0.8722	0.0411	0.0557	0.8799	0.0417
Excluding weather-related from all available variables	10	0.0732	0.7829	0.0532	0.0743	0.8002	0.0566
ANN info.: Model=Sequential, Layers=10, #Neurons=100, Activation=relu, Optimizer=adam, Loss=rmse, Epochs=100							

Index	No.# of Inputs	Inputs of ANN
Inputs including wind-related variables	11	speedOverGround, courseOverGroundTrue, windSpeedOverGround, directionTrue, distanceFromDock, accumDistLeg, accumTimeLeg, distanceToNextDock, speedApparent, pitch, wind_course_diff
Inputs excluding wind-related variables	7	speedOverGround, courseOverGroundTrue, distanceFromDock, accumDistLeg, accumTimeLeg, distanceToNextDock, pitch
Inputs of all available variables	22	speedOverGround, courseOverGroundTrue, distanceFromDock, accumDistLeg, accumTimeLeg, distanceToNextDock, speedApparent, pitch, wind_course_diff, roll, latitude, longitude, windSpeed_onboard, windDirection_onboard, currentSpeed_Stormglass, currentDirection_Stormglass, windSpeed_Stormglass, windDirection_Stormglass, windSpeed_Copernicus, windDirection_Copernicus, waveHeight_Copernicus, waveDirection_Copernicus
Excluding weather-related variables	10	speedOverGround, courseOverGroundTrue, distanceFromDock, distanceToNextDock, accumDistLeg, accumTimeLeg, pitch, roll, latitude, longitude

Minimization of the Vessel's Fuel Consumption



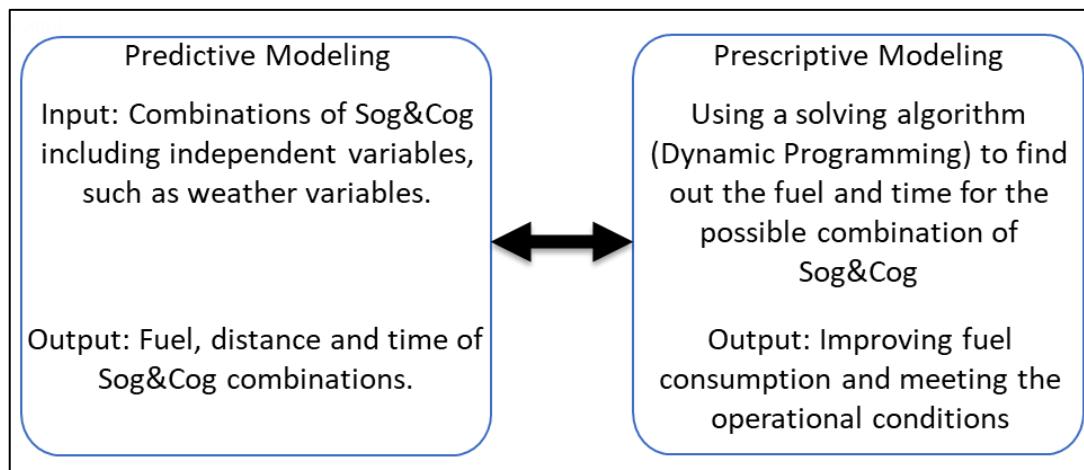
- [11] Zis, T. P., Psaraftis, H. N., & Ding, L. (2020). Ship weather routing: A taxonomy and survey. *Ocean Engineering*
- [12] Fan, A., Yang, J., Yang, L., Wu, D., & Vladimir, N. (2022). A review of ship fuel consumption models, *Ocean Engineering*,
- [13] Wang, K., Wang, J., Huang, L., Yuan, Y., Wu, G., Xing, H., & Jiang, X. (2022). A comprehensive review on the prediction of ship energy consumption and pollution gas emissions. *Ocean Engineering*.
- [14] Moradi, M. H., Brutsche, M., Wenig, M., Wagner, U., & Koch, T. (2022). Marine route optimization using reinforcement learning approach to reduce fuel consumption and consequently minimize CO₂ emissions. *Ocean Engineering*.

Minimization of the Vessel's Fuel Consumption

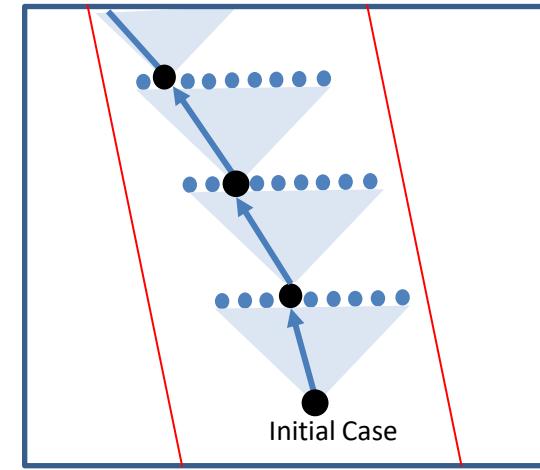
Control Variables → Vessel's SpeedOverGround (Sog), and Vessels Course direction (Cog).

Sog & Cog are changed from the initial case (i.e., measured onboard data). The perturbation are up, down, fixed states for each of Sog and Cog, and within the specified operational limits.

The Sog&Cog are changed simultaneously. So, there are $3^2=9$ combinations of possible Sog&Cog scenarios. When scenarios Sog&Cog are developed, their fuel consumption and time duration are calculated by using the predictive models of fuel and time. Thus, some of these Sog&Cog scenarios might be better than the initial case in terms of fuel and time.

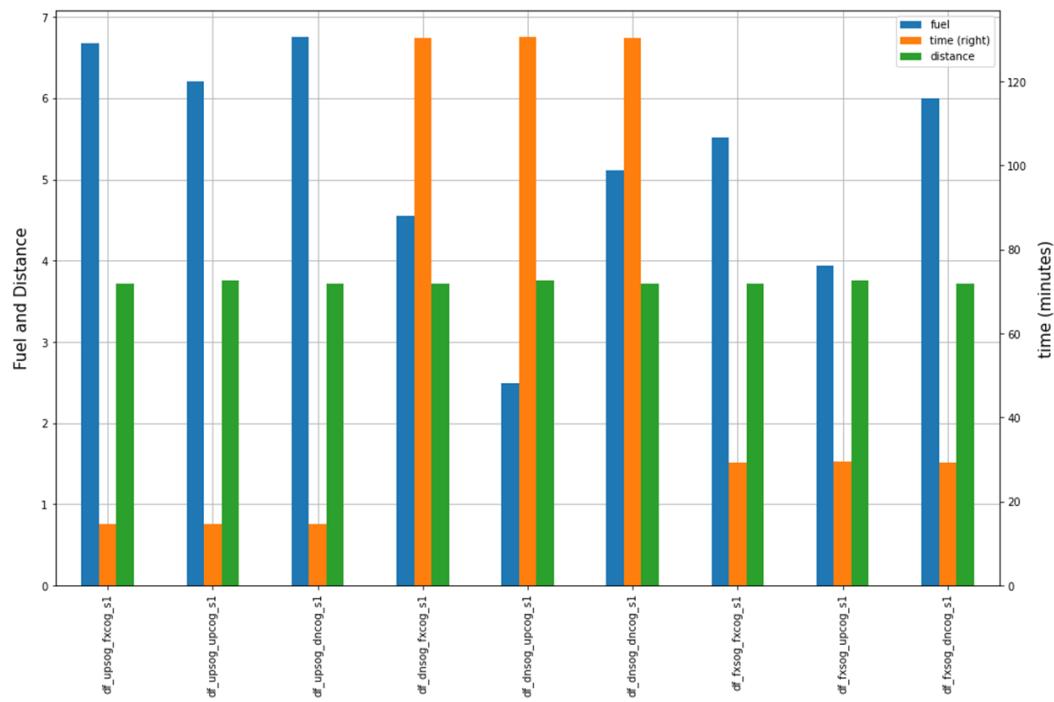


Workflow for the Sog&Cog combinations for improving fuel consumption



The possible motion outcomes of vessel's Sog&Cog combinations

Minimization of the Vessel's Fuel Consumption



Fuel, time and distance histograms of 9 scenarios of combinations of (Sog&Cog)

Dynamic Programming

Searching for the Best Combination of speedOverGround and CourseOverGround for Every Step on the Route

Time_i = distance/speed

If (Time_i = Time_fx_i)
Adjust Sog_i & Cog_i, Repeat

Fuel consumption

Time Constraint

If (Time > ETA)

Sog= sog_fx
Cog= cog_fx

Fuel Consumption

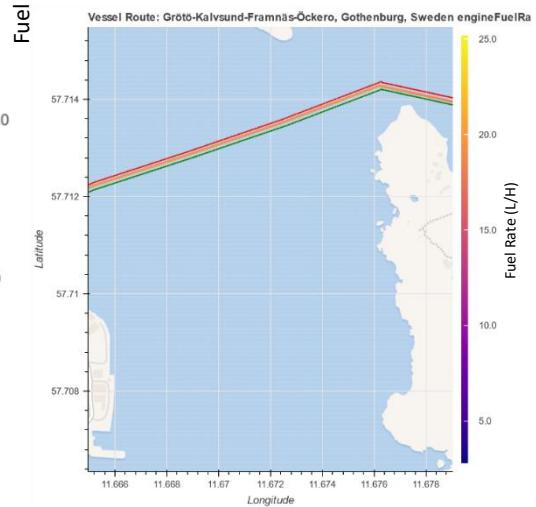
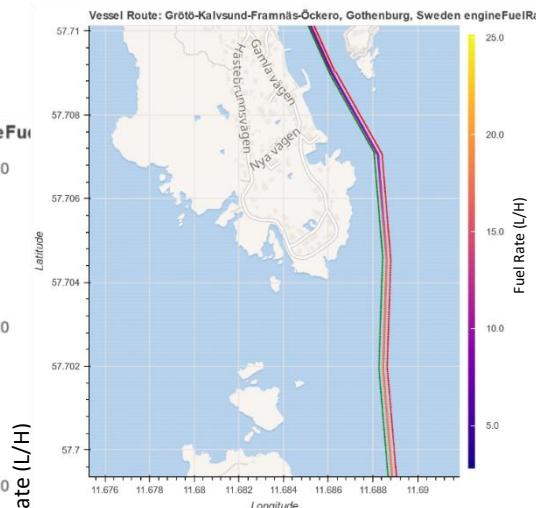
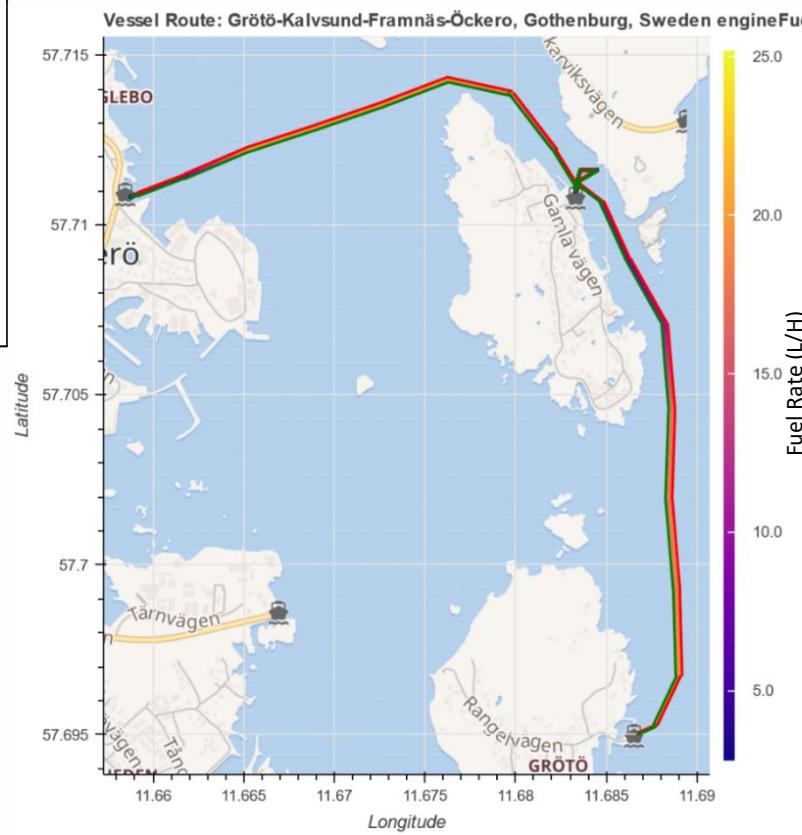
Minimization of the Vessel's Fuel Consumption

Inputs (Standard deviation)

speedOverGround (Sog) 1.814429
 courseOverGroundTrue (Cog) 79.069031
 windSpeedOverGround 1.886672
 directionTrue 12.712350
 distanceFromDock 262.871839
 accumDistLeg 655.590683
 accumTimeLeg 148.352875
 distanceToNextDock 589.982764
 speedApparent 2.967198
 pitch 0.003220
 wind_course_diff 80.518787

Sog: Vessel's SpeedOverGround,
 Cog: Vessel's Course direction

Vessel's Route from South to North, [2020-04-05 20:38]

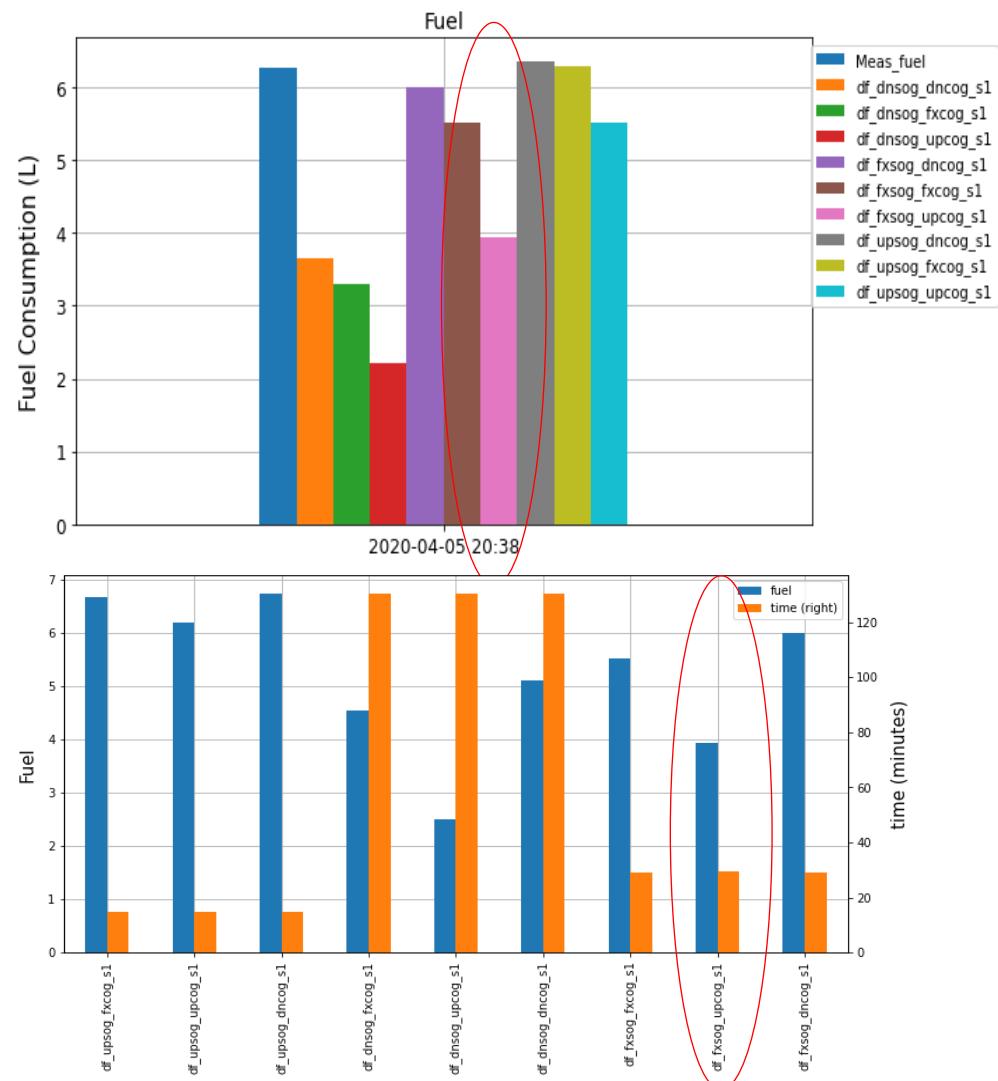
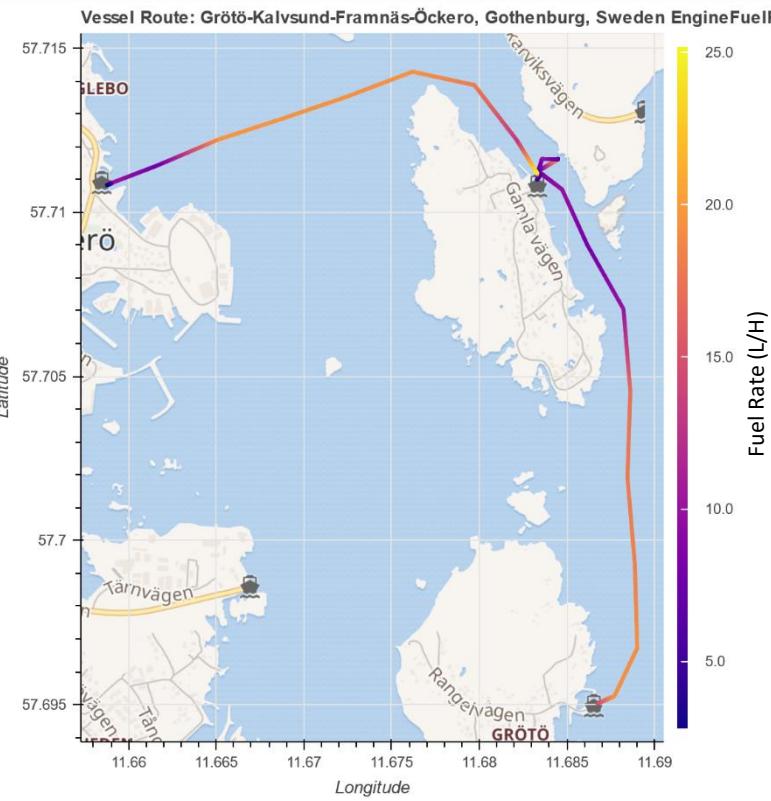


What happened if...

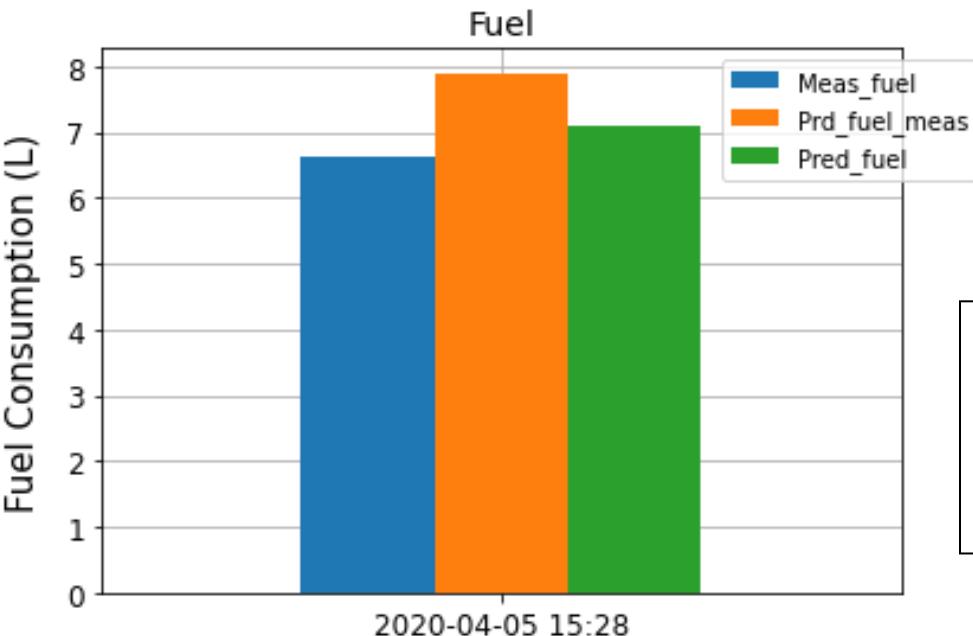
- Changing 1 std of Sog&Cog
- Changing $\frac{1}{2}$ std of Sog&Cog
- Changing $\frac{1}{4}$ std of Sog&Cog,
- Changing $\frac{1}{8}$ std of Sog&Cog,

Minimization of the Vessel's Fuel Consumption

Vessel's Rotue from South to North
[2020-04-05 20:38]



Minimization of the Vessel's Fuel Consumption



improve of pred fuel -6.74 %
improve of pred fuel 10.13 %

Mea_rt: Fuel is measured from Onboard data.
Prd_meas_rt: Fuel is predicted by using ANN with onboard data (22 inputs).
Prd_rt: Fuel is predicted by using ANN with onboard measured data, but SOG & COG are predicted values from another ANN model.

Minimization of the Vessel's Fuel Consumption

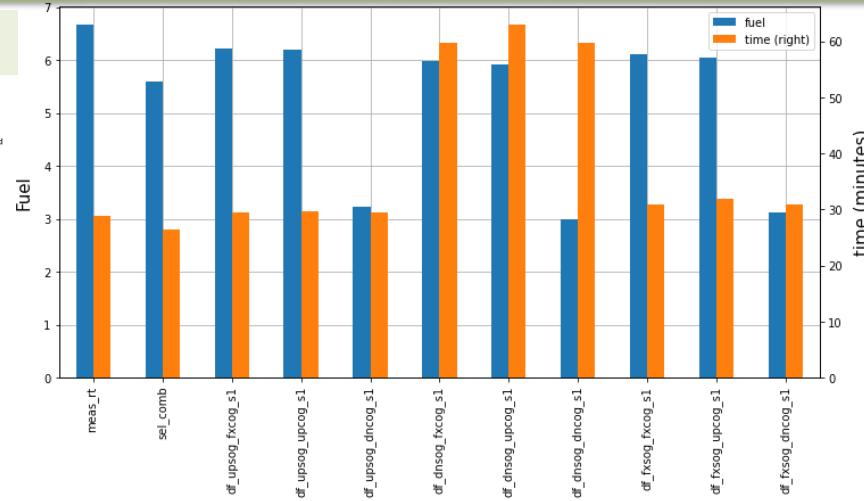
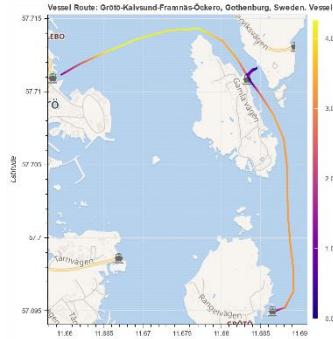
From North to South

Change=1/8 std of Sog&Cog, Route ➔ [2020-04-05 15:10]

	Meas_rt	sel_comb	df_upsog_fxcog_s1	df_upsog_upcog_s1	df_upsog_dncog_s1	df_dnsog_fxcog_s1	df_dnsog_upcog_s1	df_dnsog_dncog_s1	df_fxsof_fxcog_s1	df_fxsof_upcog_s1	df_fxsof_dncog_s1
fuel	6.68	5.59	6.22	6.19	3.23	5.97	5.91	3.00	6.10	6.05	3.11
time	28.92	26.46	29.38	29.75	29.38	59.70	63.06	59.70	30.90	31.82	30.90
distance	4.02	3.81	3.79	3.82	3.79	3.79	3.82	3.79	3.79	3.82	3.79
improve over other routes	16.22	0.00	10.11	9.61	-73.38	6.34	5.41	-86.64	8.28	7.56	-79.69

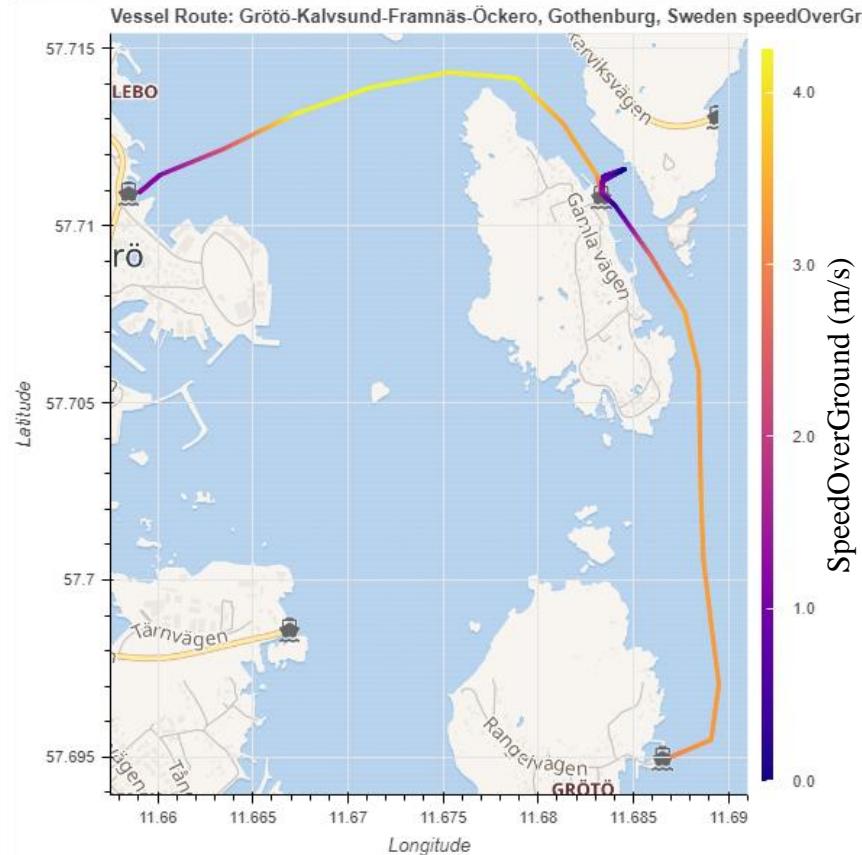
Sog: Vessel's SpeedOverGround, Cog: Vessel's Course direction

```
Counter({'df_upsog_dncog_s1': 6,
'df_upsog_upcog_s1': 2,
'df_fxsof_upcog_s1': 10,
'df_fxsof_fxcog_s1': 11})
```

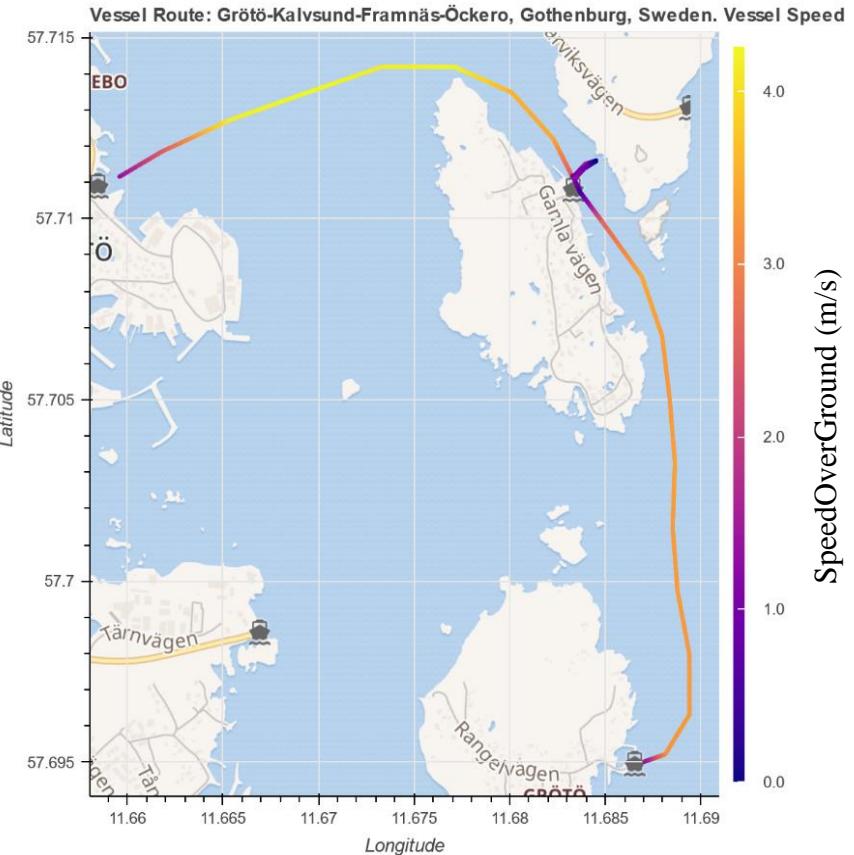


Minimization of the Vessel's Fuel Consumption

Initial Route, Route → [2020-04-05 15:10],
Vessel's Speed is shown by the color bar.



Change=1/8 std of Sog&Cog, Route → [2020-04-05 15:10],
Vessel's Speed is shown by the color bar.



Minimization of the Vessel's Fuel Consumption

From South to North

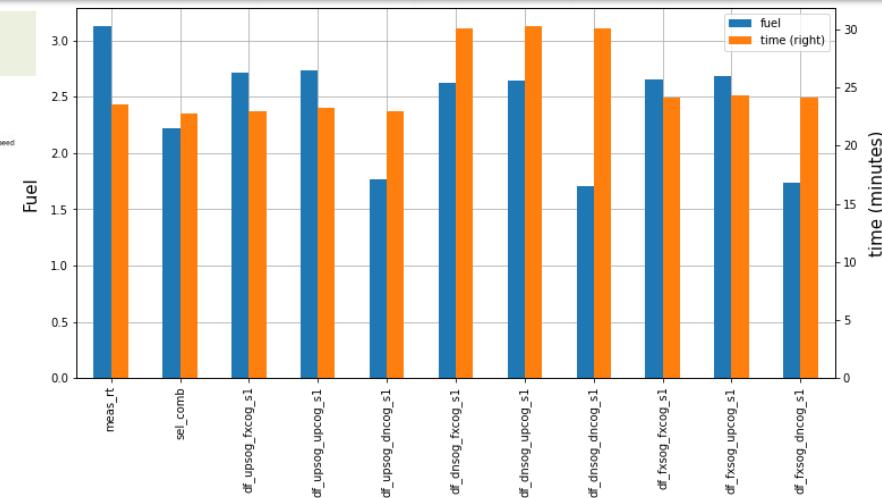
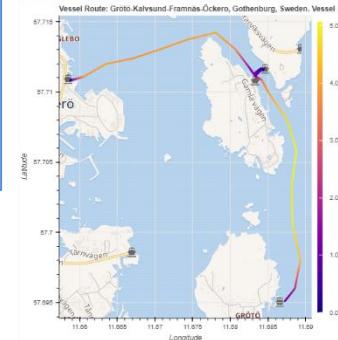
Change=1/8 std of Sog&Cog, Route ➔ [2020-04-05 20:38]

	Meas_rt	sel_comb	df_upsog_fxco	df_upsog_upcog_s1	df_upsog_dncog_s1	df_dnsog_fxco	df_dnsog_upcog_s1	df_dnsog_dncog_s1	df_fxso	df_fxso	df_fxso
fuel	6.27	4.11	4.57	4.61	2.97	4.55	4.57	2.93	4.55	4.59	2.95
time	23.54	23.41	22.98	23.22	22.98	30.08	30.32	30.08	24.11	24.37	24.11
distance	3.87	3.78	3.71	3.78	3.71	3.71	3.78	3.71	3.71	3.78	3.71
improve over other routes	34.33	0.00	9.93	10.67	-38.49	9.47	9.97	-40.37	9.66	10.28	-39.66

Sog: Vessel's SpeedOverGround, Cog: Vessel's Course direction

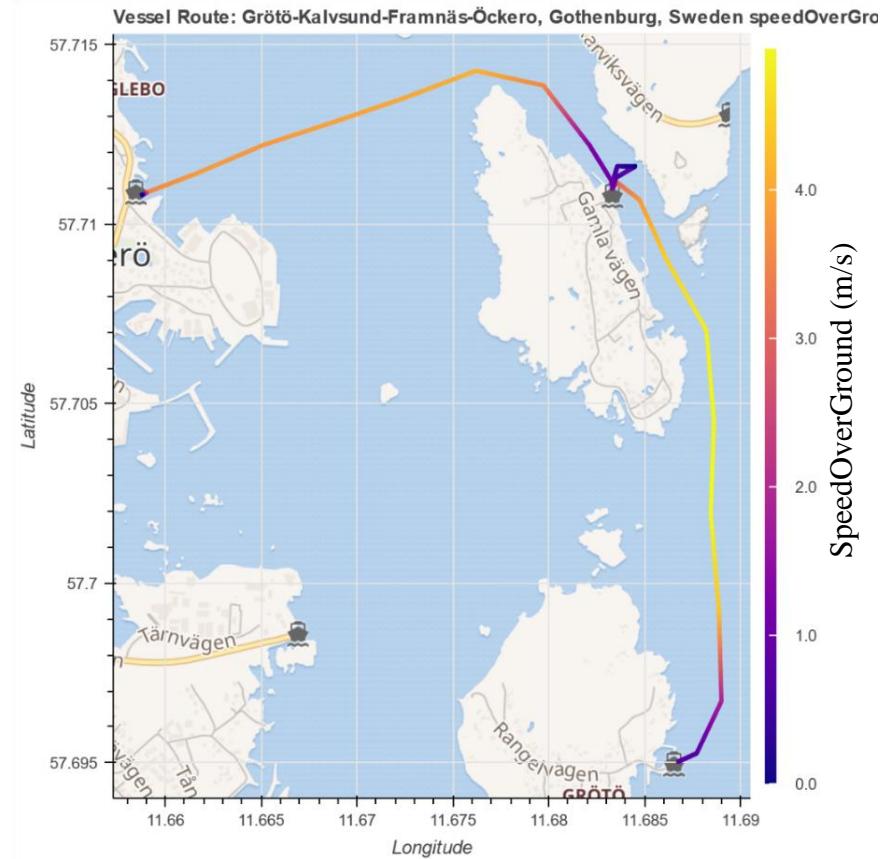
```
Counter({'df_upsog_dncog_s1': 8,
'df_upsog_upcog_s1': 4,
'df_fxso_upcog_s1': 5,
'df_fxso_fxco_s1

```

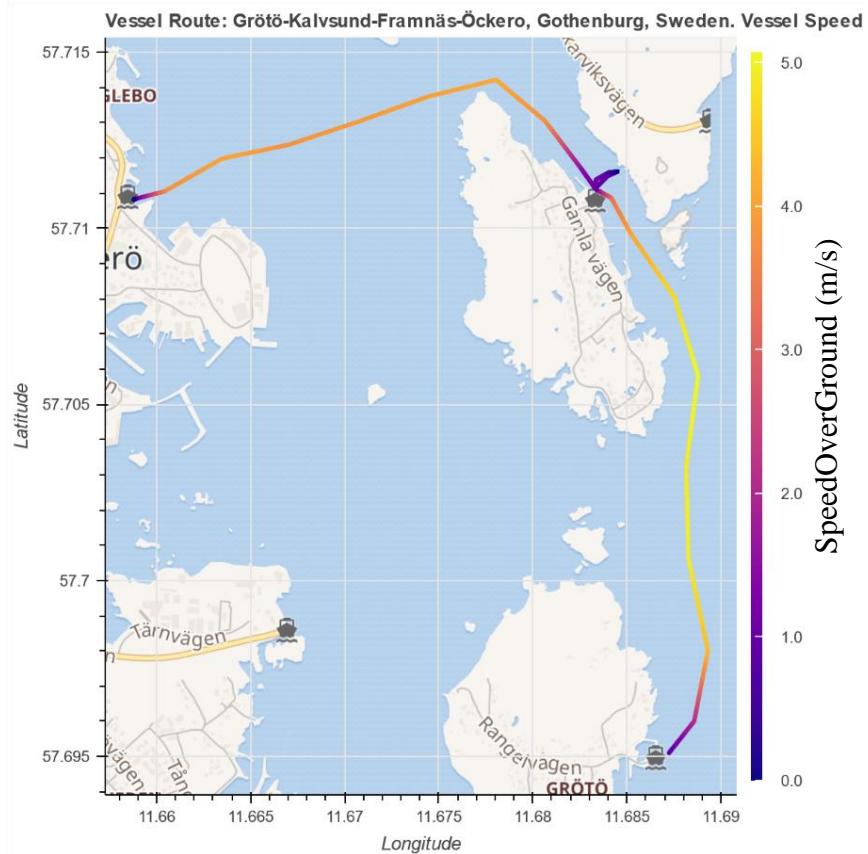


Minimization of the Vessel's Fuel Consumption

Initial Route, Route → [2020-04-05 20:38],
Vessel's Speed is shown by the color bar.

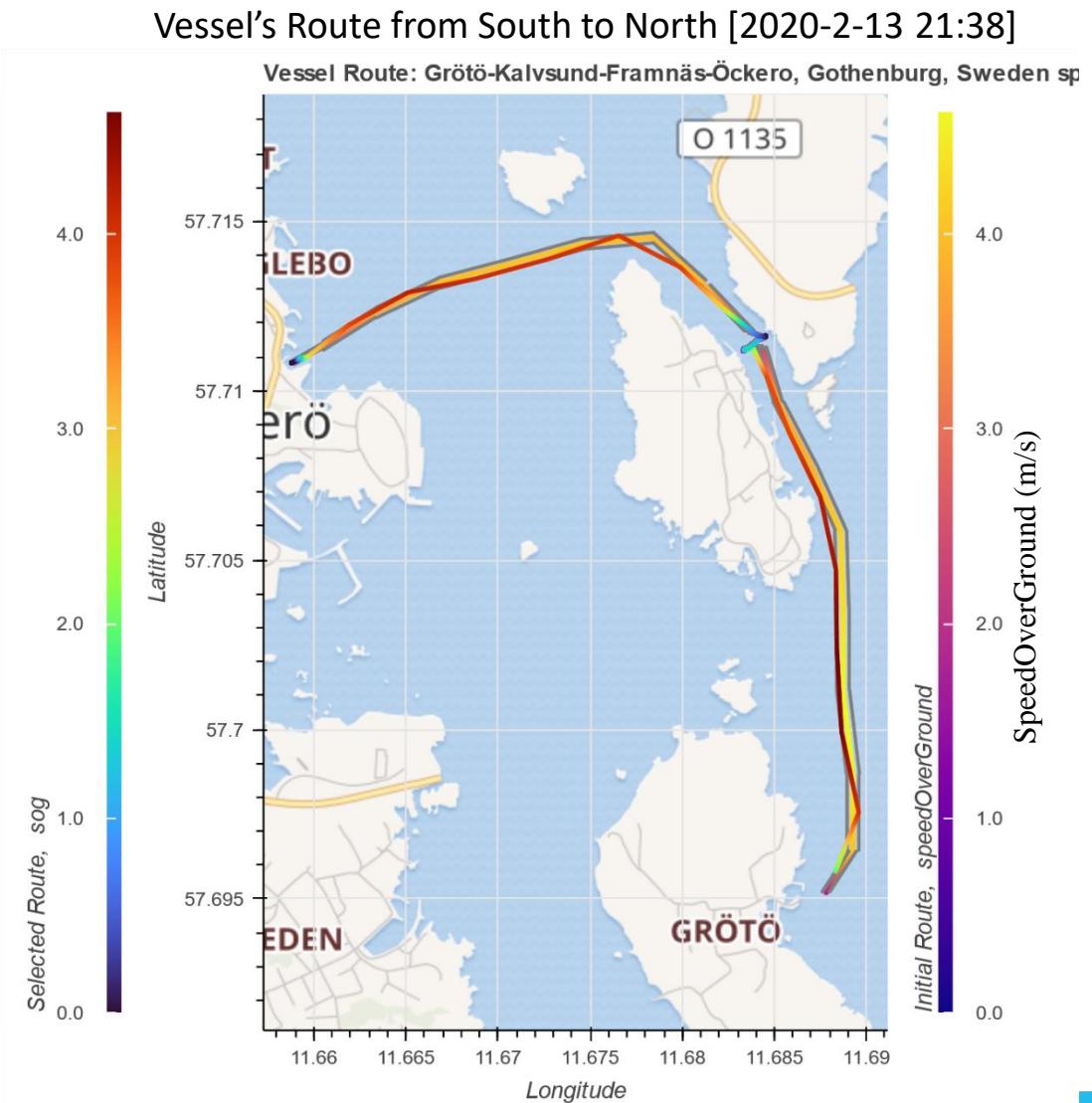


Change=1/8 std of Sog&Cog, Route → [2020-04-05 20:38],
Vessel's Speed is shown by the color bar.



Minimization of the Vessel's Fuel Consumption

Illustration of a selected route
with its boundary region



Minimization of the Vessel's Fuel Consumption

Statistics of a selected route

	meas_rt	sel_comb	df_upsog_fxcog_s1	df_upsog_upcog_s1	df_upsog_dncog_s1	df_dnsog_fxcog_s1	df_dnsog_upcog_s1	df_dnsog_dncog_s1	df_fxsof_xcog_s1	df_fxsof_upcog_s1	df_fxsof_dncog_s1
fuel	4.5639	2.2264	2.4341	2.4789	2.3028	2.2713	2.3101	2.1441	2.3556	2.3975	2.2263
time	18.5998	15.5468	23.7333	23.6300	23.7333	18.5383	27.7897	18.5383	22.2609	21.6821	22.2609
distance	3.7622	3.5055	3.6441	3.7062	3.6441	3.6441	3.7062	3.6441	3.6441	3.7062	3.6441
Time_ExPorts	21.0000	21.0000	21.0000	21.0000	21.0000	21.0000	21.0000	21.0000	21.0000	21.0000	21.0000
sel_comb_count	0.0000	0.0000	0.0000	2.0000	3.0000	0.0000	1.0000	0.0000	24.0000	3.0000	0.0000

Meas_rt: Routes' statistics when Fuel is measured from Onboard data.

Prd_meas_rt: Routes' statistics when Fuel and distance are predicted by using ANN with onboard measured data (22 inputs).

Prd_rt: Routes' statistics when Fuel and distance is predicted by using ANN with onboard measured data, but SOG & COG are predicted values from another ANN model.

Minimization of the Vessel's Fuel Consumption

Total Statistics of Sensitivity Analysis of (Sog & Cog) for Routes from North to South

RT_id	start_time	end_time	fuel_sel	fuel_meas	fuel_fx	time_sel	time_meas	time_fx	distance_sel	distance_meas	distance_fx	improve_sel	improve_meas	improve_fx
143	2020-02-19 22:11:00	2020-02-19 22:34:00	2.3657	3.0178	2.6672	18.8317	21.0381	23.9200	3.3211	3.7192	3.5356	0.0000	21.6078	11.3054
31	2020-01-22 05:06:00	2020-01-22 05:31:00	3.7696	3.7181	5.2756	17.0355	18.6093	21.2551	3.3442	3.7049	3.5059	0.0000	-1.3875	28.5459
123	2020-02-16 21:11:00	2020-02-16 21:35:00	2.8343	3.4675	3.3617	16.1820	19.9938	19.5353	3.2890	3.7120	3.5328	0.0000	18.2598	15.6890
184	2020-05-29 22:11:00	2020-05-29 22:33:00	4.1333	4.2796	4.8425	14.2427	17.4424	16.4177	3.2139	3.6781	3.4451	0.0000	3.4191	14.6460
212	2020-06-10 08:11:00	2020-06-10 08:34:00	5.4400	4.3844	6.4316	16.2690	18.3556	19.2042	3.2772	3.6732	3.4662	0.0000	-24.0747	15.4186
14	2020-01-19 07:08:00	2020-01-19 07:29:00	3.1671	3.1904	3.8309	16.2468	20.7106	21.3537	3.3763	3.7549	3.5260	0.0000	0.7287	17.3271
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
10	2020-01-17 15:11:00	2020-01-17 15:37:00	7.8794	10.3812	9.0079	15.4895	18.9403	24.1521	3.4404	3.8067	3.6956	0.0000	24.1001	12.5289
117	2020-02-16 12:41:00	2020-02-16 13:06:00	6.8629	9.7184	7.7958	15.2729	21.0180	18.8517	3.3380	3.8699	3.5816	0.0000	29.3826	11.9675
57	2020-01-27 08:11:00	2020-01-27 08:37:00	5.7046	9.8132	6.7773	18.1873	22.0188	21.4736	3.4116	3.9110	3.7027	0.0000	41.8683	15.8275
116	2020-02-16 09:41:00	2020-02-16 10:06:00	5.3939	10.2446	5.7864	16.4409	20.3245	19.0468	3.3327	3.7562	3.4854	0.0000	47.3494	6.7840
56	2020-01-27 07:06:00	2020-01-27 07:34:00	7.4641	9.4711	8.4850	17.7502	23.9923	25.1409	3.4652	4.0089	3.7662	0.0000	21.1912	12.0327
148	2020-02-20 21:10:00	2020-02-20 21:39:00	6.5094	9.3528	7.1502	21.5869	28.2192	26.2300	3.6063	4.0546	3.8491	0.0000	30.4013	8.9614
													16.12 %	13.75 %

Total Statistics of Sensitivity Analysis of (Sog & Cog) for Routes from South to North

RT_id	start_time	end_time	fuel_sel	fuel_meas	fuel_fx	time_sel	time_meas	time_fx	distance_sel	distance_meas	distance_fx	improve_sel	improve_meas	improve_fx
234	2020-06-10 05:35:00	2020-06-10 06:05:00	2.7955	4.1054	3.1979	17.2024	19.4429	21.3220	3.4763	3.7439	3.6763	0.0000	31.9062	12.5823
151	2020-02-16 21:37:00	2020-02-16 22:10:00	1.5846	3.3537	1.8222	19.8252	22.5507	24.1039	3.5088	3.7625	3.7302	0.0000	52.7497	13.0381
71	2020-01-27 05:36:00	2020-01-27 06:06:00	3.0560	4.2572	3.7147	16.7147	19.9605	20.7067	3.4509	3.7429	3.6382	0.0000	28.2158	17.7334
79	2020-01-28 05:36:00	2020-01-28 06:05:00	1.5589	4.2842	1.8038	16.7806	18.9221	27.4204	3.4901	3.7030	3.5871	0.0000	63.6114	13.5759
167	2020-02-19 22:36:00	2020-02-19 23:09:00	2.9528	3.4310	3.4602	21.5017	22.4353	22.4004	3.7140	3.7145	3.6695	0.0000	13.9391	14.6654
65	2020-01-25 23:38:00	2020-01-26 00:08:00	2.5304	4.4599	2.6914	17.1776	20.5034	19.1324	3.3215	3.7312	3.4824	0.0000	43.2633	5.9805
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
17	2020-01-18 20:38:00	2020-01-18 21:11:00	6.1411	10.4796	7.0235	16.9058	22.9298	23.5898	3.4892	4.0932	3.9056	0.0000	41.4001	12.5634
36	2020-01-21 16:38:00	2020-01-21 17:11:00	8.1226	10.9472	8.6461	16.1319	22.3516	26.1851	3.6631	4.0934	3.9259	0.0000	25.8020	6.0544
43	2020-01-22 13:38:00	2020-01-22 14:11:00	7.8802	11.0638	9.1681	16.9732	19.7541	33.4771	3.6957	3.8975	3.8403	0.0000	28.7753	14.0482
118	2020-02-06 11:39:00	2020-02-06 12:06:00	6.7428	11.3370	7.8373	15.1999	21.6332	29.3259	3.3967	3.9552	3.7397	0.0000	40.5242	13.9663
44	2020-01-22 15:38:00	2020-01-22 16:11:00	7.8820	11.4362	8.7765	17.2251	21.7469	22.1487	3.5578	4.0984	3.8958	0.0000	31.0784	10.1918
41	2020-01-22 06:35:00	2020-01-22 07:05:00	11.0770	11.7608	12.8244	18.6095	22.7132	35.1997	3.8947	4.3538	3.9740	0.0000	5.8142	13.6259
													31.31%	12.28 %

_meas : Routes' statistics when Fuel is measured form Onboard data.

_fx : Routes' statistics when Fuel and distance are predicted by using ANN with onboard measured data (22 inputs).

_sel : Routes' statistics when Fuel and distance is predicted by using ANN with onboard measured data, but SOG & COG are predicted values from another ANN model.

Thanks for your listening
Any Qs?

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