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Speed Optimization with Emission Control Area Regulations

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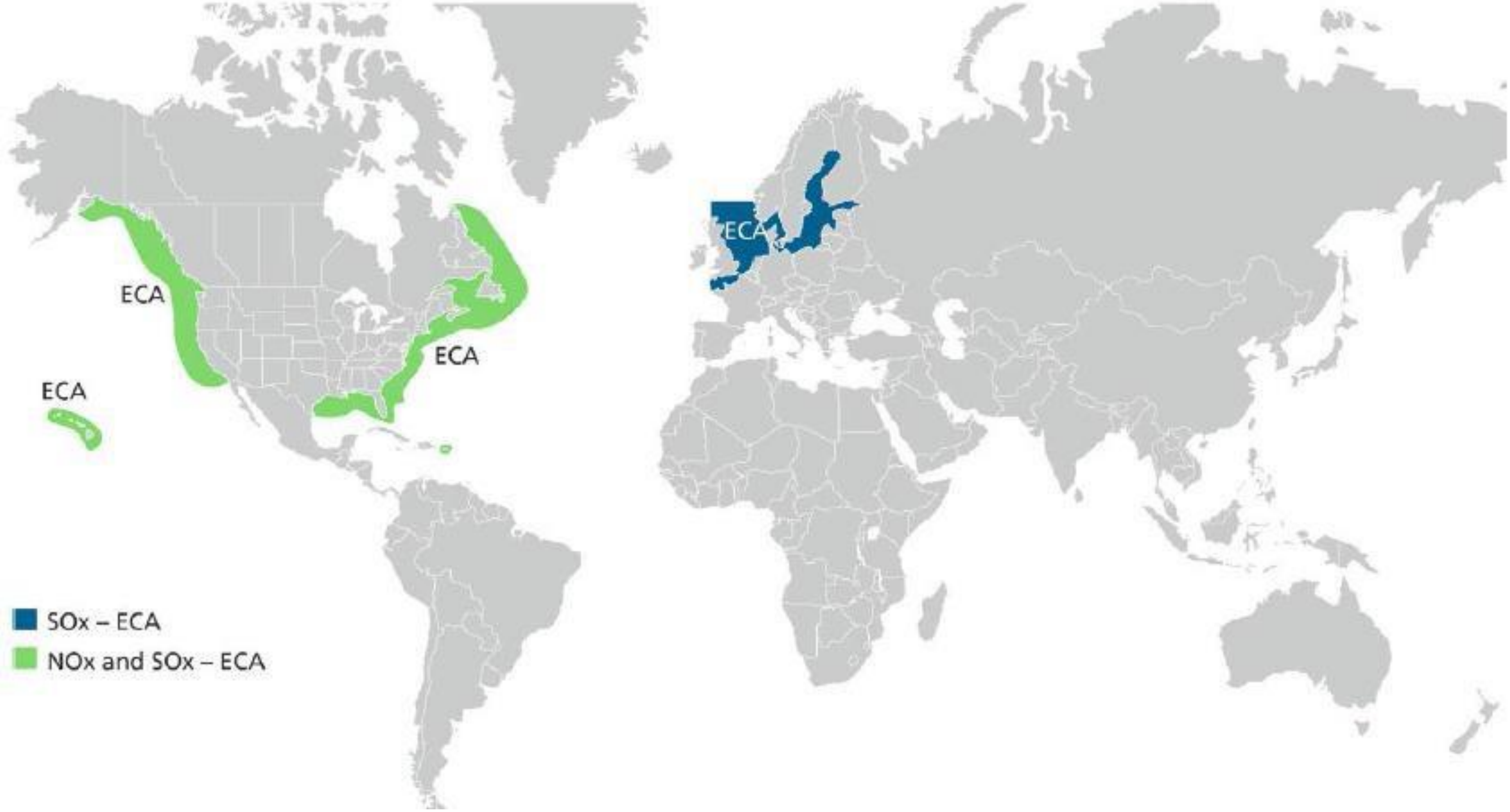
Outline

- Introduction to IMO, MARPOL & Emission Control Areas
- Speed optimization in shipping
- Problems and model
- Results
- Concluding remarks

IMO & MARPOL

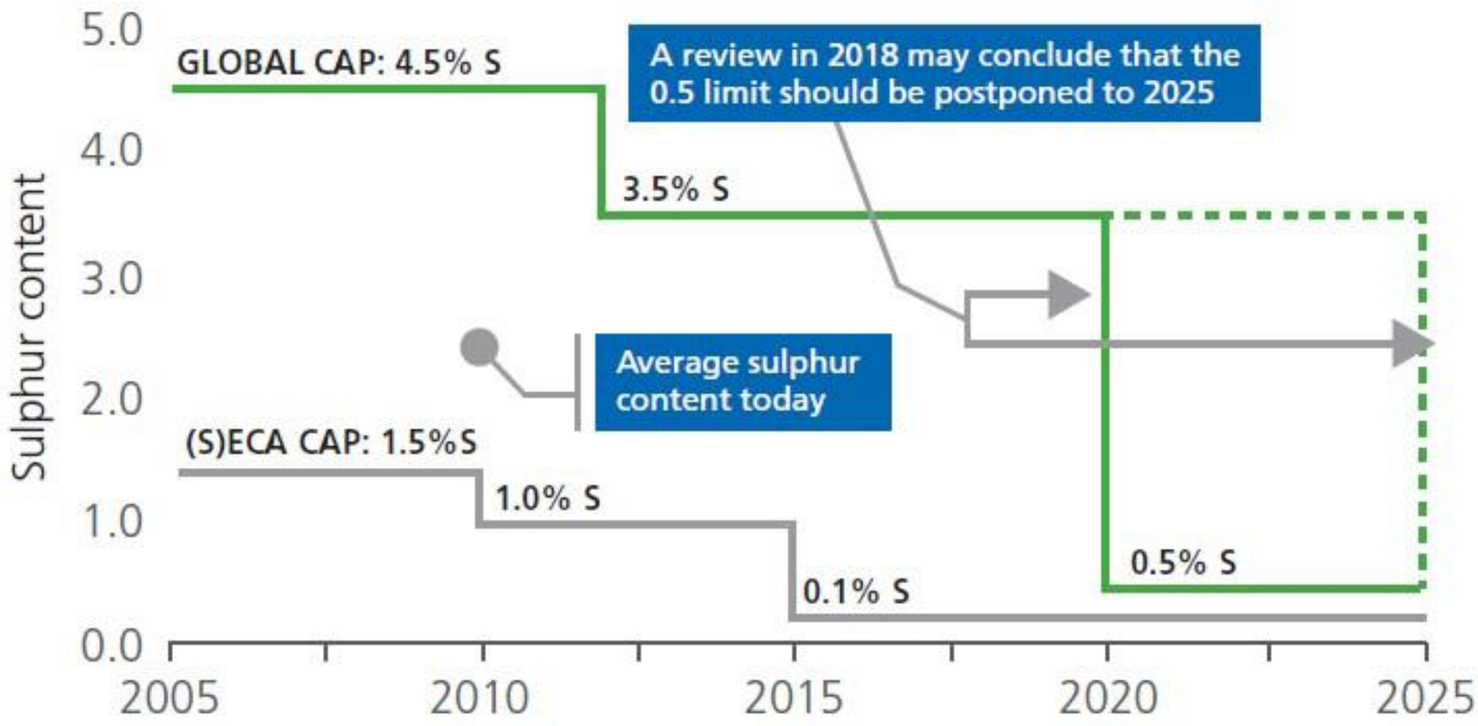
- The **International Maritime Organization (IMO)** is a specialized agency of the **United Nations**, responsible for the safety and security of shipping and the prevention of maritime pollution by ships.
  - International Convention for the Safety of Life at Sea (SOLAS)
  - International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW)
  - International Convention for the Prevention of Pollution from Ships (MARPOL)
- MARPOL contains six technical annexes
- Annex VI seeks to minimize airborne emissions from ships
  - In particular it introduces stricter regulations for emissions of SO_x, NO_x and PM

Emission Control Areas



Balland, 2013

Limits on sulphur content in fuel



Balland, 2013

ECA compliance options

- Fuel switching
  - Use different fuels when sailing inside and outside ECAs
  - Limit on sulphur content in fuel
  - High price difference between heavy fuel oil (HFO) and marine gasoline oil (MGO)
- Install scrubber
  - Clean exhausts gasses
  - No limit on sulphur content in fuel used
  - High installation costs, and unavailability period for vessels.
- LNG machinery system
  - LNG has very low sulphur content
  - Machinery systems demand space consuming infrastructure → Reduced cargo space
  - High capital investments

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Speed optimization in shipping

Speed optimization in shipping

- Speed optimization in shipping is an important topic
  - Fuel costs constitutes an important part of total operating costs
  - Lately fuel prices has increased and cargo rates has decreased → decreasing margins
  - Significant cost reductions by optimizing speed
    - Norstad et al. (2011) indicate that fuel cost savings can be as high as 40% compared to using a standard charter party speed

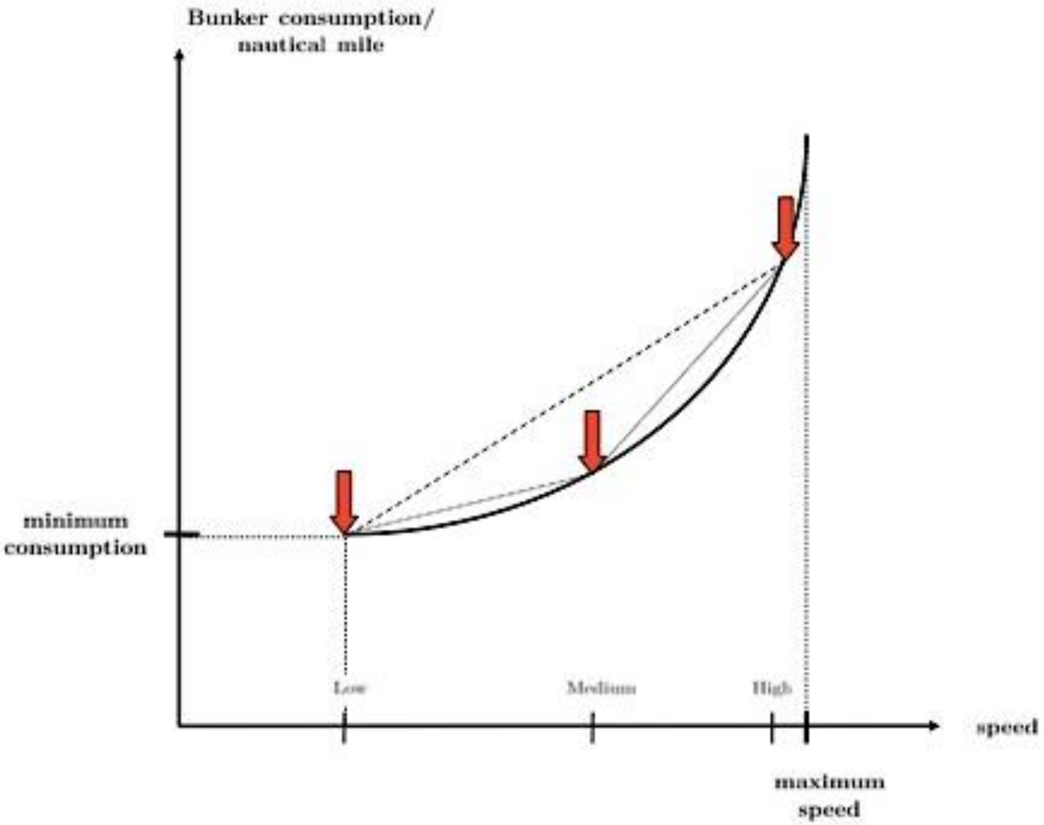
Speed optimization in shipping

- Fuel consumption is a non-linear function of speed

$$f = \left[F^{R,main} \cdot (\frac{v_i}{V_0})^3 + F^{R,aux}\right] \cdot s$$

(Doudnikoff and Lacoste, 2014)

- f is a convex function and may be linearized



(Andersson et al., 2014)

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Problem description

Problem description - Idea

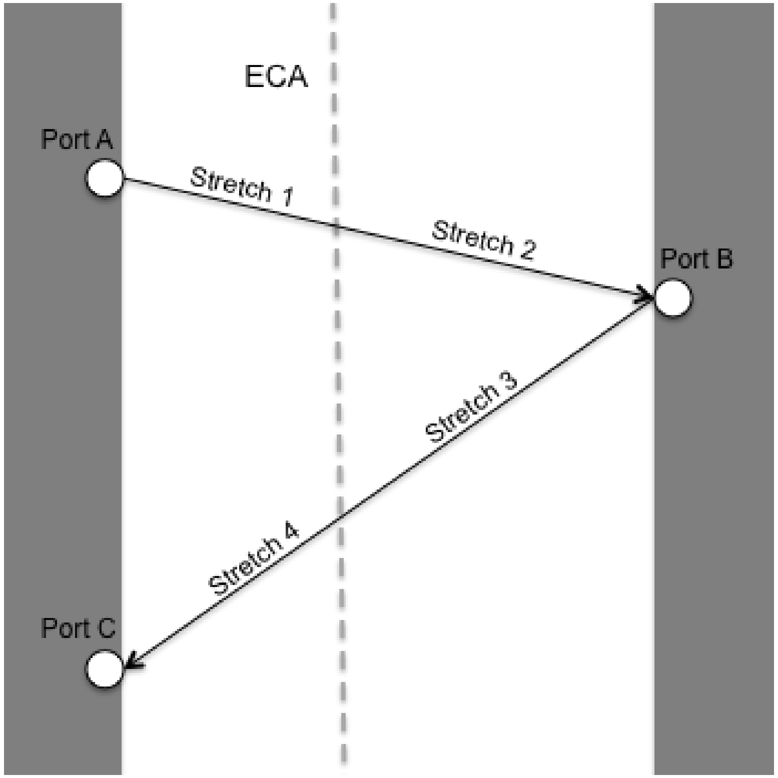
- ECA regulations will affect a shipping company's costs and it may take actions to reduce these costs that are counterproductive to the MARPOL Annex VI's goals.
  - When considering one fuel type, minimization of fuel cost and reduction of emissions are both results of minimizing the total fuel consumption
  - Introducing ECAs does not necessarily give the same environmental incentives to the shipping companies as minimizing the total fuel consumption is not equivalent to minimizing fuel costs.

Problem description - Problems

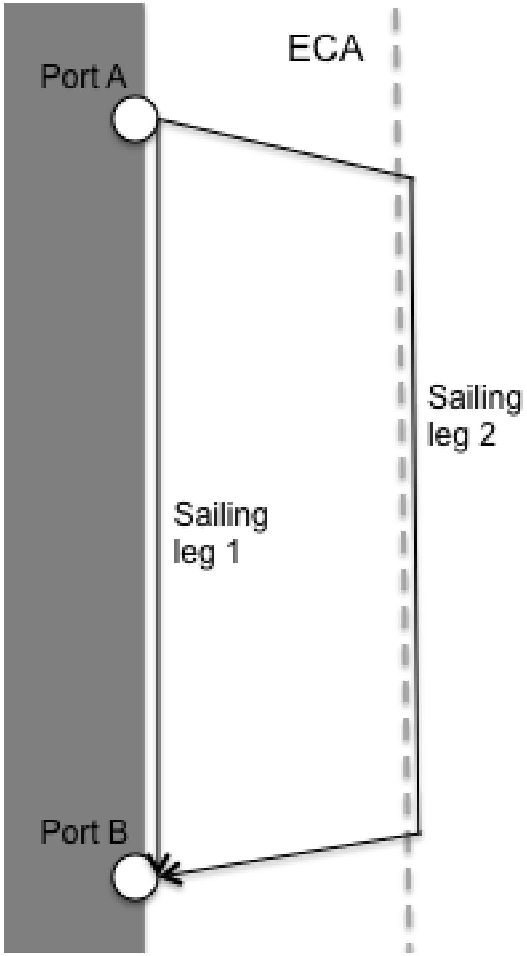
- Problems:
  - P1: Speed optimization with one leg option
  - P2: Speed optimization and alternative leg options

Problem	Sequence	Legs	Speed
P1	F	F	V
P2	F	V	V

Problem P1


ECA
Port A
Stretch 1
Stretch 2
Port B
Stretch 3
Stretch 4
Port C

Problem P2



Problem description - Model

Sets

B	Set of fuels
J	Set of sequenced legs, legs in J^b have stretch using fuel $b \in B$
R_j	Set of alternative sailing legs for each of the legs $j \in J$
V	Set of speed alternatives

Parameters

T_{jrv}^{ECA}	Sailing time within ECA along sailing leg alternative r on leg j with speed alternative v
T_{jrv}^{N}	Sailing time outside ECA along sailing leg alternative r on leg j with speed alternative v
T_j^{MIN}, T_j^{MAX}	Lower and upper time limit for starting leg j
F_{jrv}^{ECA}	Fuel consumption within ECA along sailing leg alternative r on leg j with speed alternative v
F_{jrv}^{N}	Fuel consumption outside ECA along sailing leg alternative r on leg j with speed alternative v
P_b	The price per ton of fuel type b

Decision variables

x_{jrv}^{ECA}	Weight of speed alternative v within ECA on leg j with alternative r
x_{jrv}^{N}	Weight of speed alternative v outside ECA on leg j with alternative r
t_j	Start time on leg j
z_{jr}	Binary variable, takes the value 1 if sailing leg alternative r is chosen for leg j, and 0 otherwise

Problem description - Model

Model

$$\min \sum_{b \in B} P_b \cdot \sum_{j \in J^b} \sum_{r \in R_j} \sum_{v \in V} F_{jrv} \cdot x_{jrv} \qquad (1)$$

$$t_j \geq t_{j-1} + \sum_{v \in V} \sum_{r \in R_j} (\mathrm{T}_{jrv}^{ECA} \cdot x_{jrv}^{ECA} + \mathrm{T}_{jrv}^{N} \cdot x_{jrv}^{N}) \qquad j \in J \qquad (2)$$

$$\sum_{v \in V} x_{jrv}^{ECA} = z_{jr} \qquad j \in J, r \in R_j \qquad (3)$$

$$\sum_{v \in V} x_{jrv}^{N} = z_{jr} \qquad j \in J, r \in R_j \qquad (4)$$

$$\sum_{r \in R_j} z_{jr} = 1 \qquad j \in J \qquad (5)$$

$$T_j^{MIN} \leq t_j \leq T_j^{MAX} \qquad j \in J \qquad (6)$$

$$z_{jr} \in \{0,1\} \qquad j \in J, r \in R_j \qquad (7)$$

$$x_{jrv}^{ECA}, x_{jrv}^{N} \geq 0 \qquad j \in J, r \in R_j, v \in V \qquad (8)$$

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Computational study

Computational study - Cases

Problem	Case	Route
P1	C1.1	Gothenburg – Le Havre – Santander – Livorno
	C1.2	San Francisco – Hueneme – Honolulu
P2	C2.1	Bremerhaven – Antwerp – Halifax – Brunswick
	C2.2	Yokohama – Prince Rupert – Long Beach – Lazaro Cardenas
	C2.3a	Kristiansand – Santander
	C2.3b	Flekkefjord – Santander
	C2.3c	Stavanger – Santander
	C2.3d	Bergen – Santander
	C2.3e	Florø – Santander
	C2.4a	Singapore – Southampton
	C2.4b	Cilcap – Southampton
	C2.4c	Dampier – Southampton

Computational study - assumptions

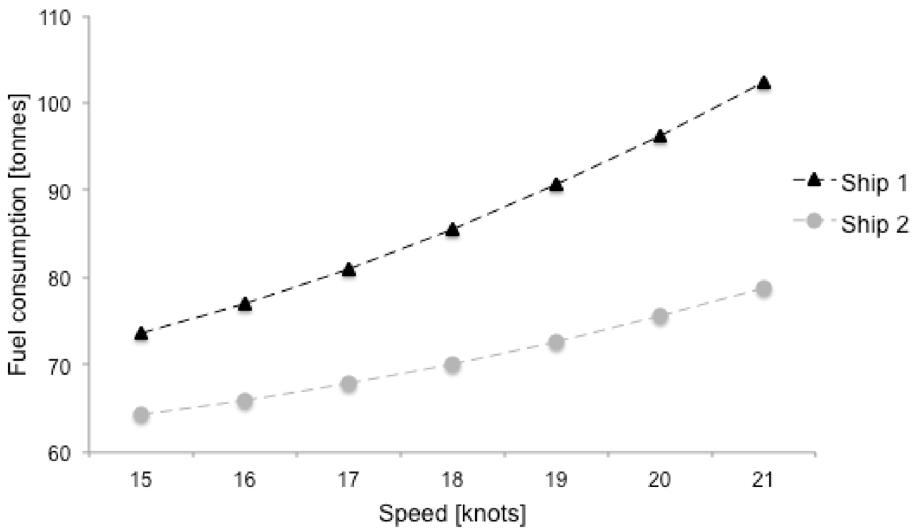
- Fixed fuel price – based on average prices in Rotterdam, Holland and Houston, USA

Scenario name	ECA	Non-ECA
No ECA scenario	590	590
Standard scenario	920	590

- Additional price scenarios investigated to evaluate impact of future prices

Computational study - assumptions

- Fuel consumption



Computational study - assumptions

- Generation of time windows
  - Based on randomly sampled sailing speed between ports
    - Sailing speed sampled from the range [17,19] knots
  - Time windows generated for each port j :
    - $\hat{t}$ is the width of the time window in days
    - T_j is the visit time given the sampled speed
    - $[T_j - \hat{t}, T_j + \hat{t}]$
  - Different instances are created for each price scenario

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Results

Case C1.1

Leg	ECA	Non-ECA	Total
Gothenburg – Le Havre	680	0	680
Le Havre – Santander	210	345	555
Santander – Livorno	0	1,738	1,738
Total distance	890	2,083	2,973

- $\hat{t} \in \{0.25, 0.5, 0.75, 1\}$

Case C1.1

Speed and consumption

Scenario	Average speed			Average fuel consumption			
	ECA	Non-ECA	Ratio	ECA	Non-ECA	Total	Increase
C1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C1.1_1200	15.12	16.82	11.19%	131.8	335.4	467.2	0.53%

Plan sailing and speed as no ECAs exists, then impose the cost of different fuel types

Fuel costs

Scenario	Optimised fuel costs			Benchmark fuel costs			Saving
	ECA	Non-ECA	Total	ECA	Non-ECA	Total	
C1.1_920	122,816	196,119	318,935	127,173	192,637	319,811	876
C1.1_960	127,913	196,356	324,269	132,703	192,637	325,340	1,071
C1.1_1020	134,611	197,637	332,248	140,997	192,637	333,634	1,386
C1.1_1200	158,120	197,895	356,015	165,878	192,637	358,516	2,501

Case C1.1

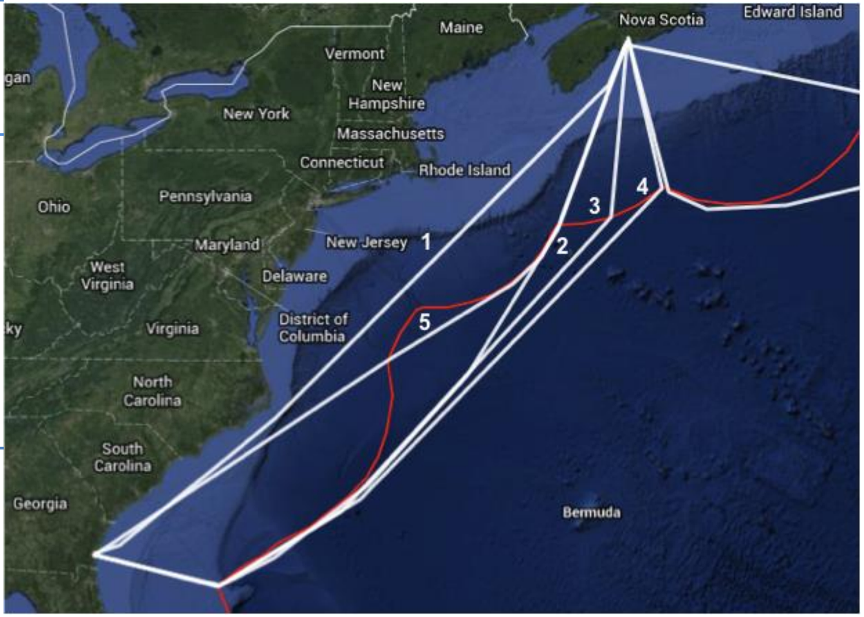
Emissions

Scenario	CO_2 emissions Tonnes	CO_2 emissions Increase	SO_x emissions Kilograms	SO_x emissions Decrease
C1.1_590	1 473.2	-	251.0	-
C1.1_920	1 476.9	0.25%	182.2	-27.41%
C1.1_960	1 477.4	0.28%	182.4	-27.33%
C1.1_1020	1 480.2	0.48%	183.5	-26.87%
C1.1_1200	1 481.0	0.53%	183.5	-26.87%

No ECAs – use HFO in all areas

Case C2.1

Leg	Leg option	Distance		
		ECA	Non-ECA	Total
Bremerhaven – Antwerp	1	306	0	306
Antwerp – Halifax	1	772	2,101	2,873
Halifax – Brunswick	1	1,186	0	1,186
	2	514	831	1,345
	3	476	890	1,366
	4	445	987	1,432
	5	879	352	1,231



- $\hat{t} \in \{0.5,\ 1, 1.5, 2, 2.5\}$

Case C2.1

Choice of leg option

Situation	Leg	Chosen leg option	Distance ECA	Distance Non-ECA	Distance Total	Speed ECA	Speed Non-ECA
C2.1_920_TW_0.5	3	5	879	352	1,231	16.0	17.4
	Total		**1,957**	**2,453**	**4,410**		
C2.1_920_TW_1	3	5	879	352	1,231	16.0	17.0
	Total		**1,957**	**2,453**	**4,410**		
C2.1_920_TW_1.5	3	5	879	352	1,231	15.0	16.0
	Total		**1,957**	**2,453**	**4,410**		
C2.1_920_TW_2	3	2	514	831	1,345	15.0	15.0
	Total		**1,592**	**2,932**	**4,524**		
C2.1_920_TW_2.5	3	3	476	890	1,366	15.0	15.0
	Total		**1,554**	**2,991**	**4,545**		

Case C2.1

Speed and consumption

	Average speed			Average distances			
Scenario	ECA	Non-ECA	Ratio	ECA	Non-ECA	Total	Ratio
C2.1_590	15.7	15.7	0.00%	2,264	2,101	4,365	-7.20%
C2.1_760	15.6	15.8	1.85%	2,080	2,312	4,392	11.17%
C2.1_900	15.3	16.3	6.62%	1,811	2,645	4,456	46.03%
C2.1_920	15.3	16.3	6.62%	1,803	2,656	4,460	47.30%
C2.1_970	15.4	16.4	6.59%	1,657	2,848	4,505	71.84%
C2.1_1020	15.2	16.6	9.50%	1,584	2,944	4,528	85.80%
C2.1_1200	15.2	16.7	9.63%	1,577	2,956	4,532	87.44%
C2.1_2000	15.0	17.2	14.75%	1,504	3,115	4,619	107.05%

Case C2.1

Fuel costs

Scenario	Optimised fuel costs ECA	Optimised fuel costs Non-ECA	Optimised fuel costs Total	Benchmark fuel costs ECA	Benchmark fuel costs Non-ECA	Benchmark fuel costs Total	Saving
C2.1_760	239,421	208,549	**447,970**	261,507	188,480	**449,988**	**2,018**
C2.1_900	243,344	244,018	**487,362**	309,679	188,480	**498,160**	**10,797**
C2.1_920	247,723	245,043	**492,766**	316,561	188,480	**505,042**	**12,276**
C2.1_970	241,332	264,590	**505,922**	333,766	188,480	**522,246**	**16,324**
C2.1_1020	240,097	277,954	**518,051**	350,970	188,480	**539,450**	**21,400**
C2.1_1200	281,124	279,248	**560,373**	412,906	188,480	**601,386**	**41,014**
C2.1_2000	442,876	302,596	**745,472**	688,176	188,480	**876,657**	**131,185**

Case C2.1

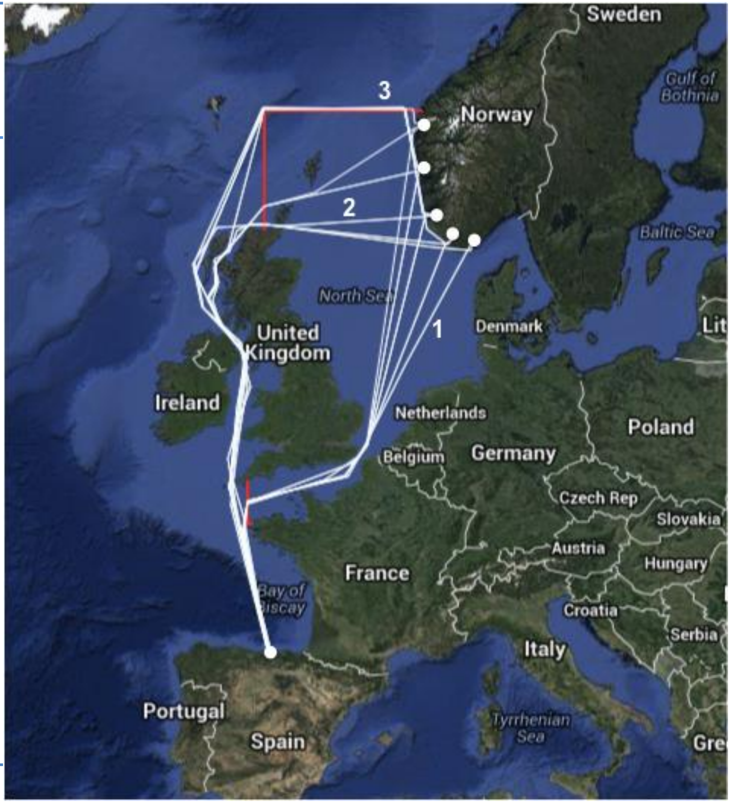
Comparison of Model P1 and P2

Decisions	Fuel consumption			Fuel costs		
	ECA	Non-ECA	Total	USD	Difference	Saving
Benchmark	344.1	319.5	663.5	505,042	-	-
P1 Optimised	337.4	327.5	664.9	503,653	-0.27%	1,389
P2 Optimised	269.3	415.3	684.6	492,766	**-2.43%**	**12,276**

Decisions	CO_2 emissions		SO_X emissions			
	Total	Difference	ECA	Non-ECA	Total	Difference
Benchmark	2,103	-	68.8	172.5	241.3	-
P1 Optimised	2,107	0.21%	67.5	176.9	244.3	1.25%
P2 Optimised	2,170	**3.17%**	53.9	224.3	278.1	**15.25%**

Case C2.3

Case	Leg	Leg option	ECA	Distance Non-ECA	Total
2.3a	Kristiansand – Santander	1	761	360	1,121
		2	395	1,025	1,420
2.3b	Flekkefjord – Santander	1	760	361	1,121
		2	340	1,030	1,370
		3	275	1,400	1,675
2.3c	Stavanger – Santander	1	790	362	1,152
		2	310	1,065	1,375
		3	230	1,430	1,660
2.3d	Bergen – Santander	1	872	365	1,237
		2	277	1,020	1,297
		3	120	1,420	1,540
2.3e	Florø – Santander	1	927	365	1,292
		2	307	1,022	1,329
		3	34	1,425	1,459



- $\hat{t} \in \{0.25, 0.5,\ 0.75, 1,\ 1.25, 1.5\}$

Case C2.3

Speed and consumption

Scenario	Average speed			Average distances			
	ECA	Non-ECA	Ratio	ECA	Non-ECA	Total	Difference
C2.3c_590	15.44	15.44	0.00%	783	363	1,146	-
C2.3c_920	15.27	15.84	3.64%	625	597	1,222	6.66%
C2.3d_590	15.49	15.49	0.00%	872	365	1,237	-
C2.3d_920	15.36	15.96	3.79%	277	1,020	1,297	4.85%
C2.3e_590	15.52	15.52	0.00%	927	365	1,292	-
C2.3e_920	15.28	15.86	3.73%	216	1,156	1,372	6.22%

Scenario	Average fuel consumption					
	ECA	Difference	Non-ECA	Difference	Total	Difference
C2.3c_590	117.8	-	54.6	-	172.4	-
C2.3c_920	93.6	-20.51%	90.3	65.40%	183.9	6.70%
C2.3d_590	131.5	-	55.0	-	186.5	-
C2.3d_920	41.5	-68.43%	157.8	186.62%	199.3	6.83%
C2.3e_590	140.0	-	55.1	-	195.1	-
C2.3e_920	32.4	-76.84%	177.0	221.11%	209.4	7.33%

Case C2.3

Comparison to benchmark

Scenario	Optimised fuel costs			Benchmark fuel costs			Saving
	ECA	Non-ECA	Total	ECA	Non-ECA	Total	
C2.3c_920	86,120	53,279	139,399	108,343	32,211	140,555	1,156
C2.3d_920	38,195	92,073	131,267	120,970	32,473	153,442	22,175
C2.3e_920	29,826	104,416	134,242	128,777	32,517	161,295	27,052

Scenario	CO_2 emissions		SO_X emissions	
	Tonnes	Difference	Kilograms	Difference
C2.3c_590	546.4	-	93.1	-
C2.3c_920	583.0	6.70%	50.6	-45.60%
C2.3d_590	591.3	-	100.7	-
C2.3d_920	631.7	6.83%	86.0	-14.60%
C2.3e_590	618.4	-	105.3	-
C2.3e_920	663.8	7.33%	96.2	-8.67%

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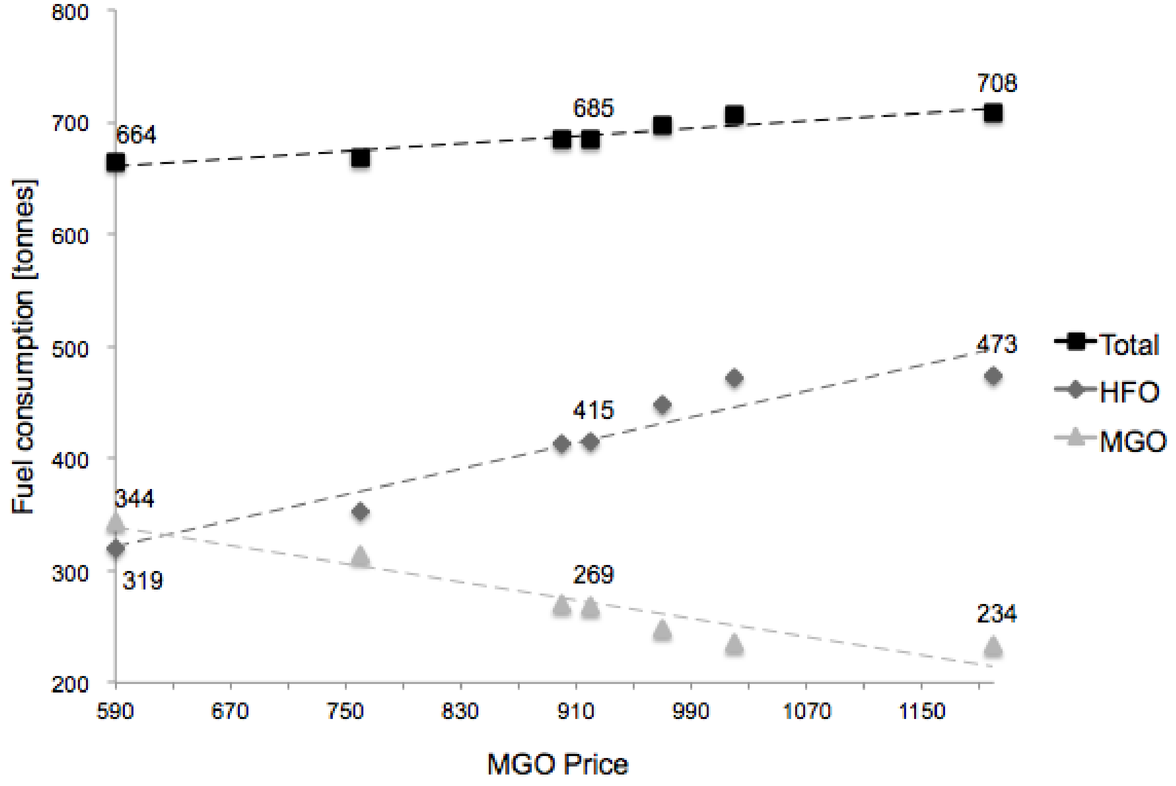
Concluding remarks

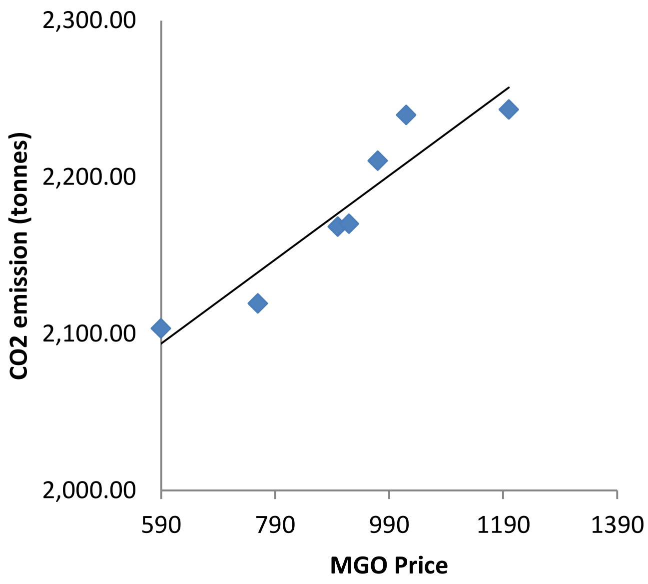
Concluding remarks

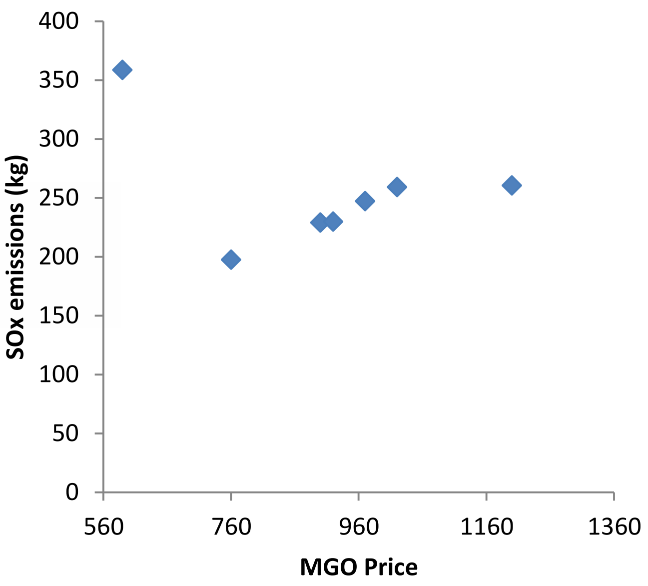
Fuel consumption as a function of MGO price



Concluding remarks

Global emissions as a function of MGO price





Concluding remarks

- Our computational study shows that in order to reduce cost, shipping companies may
  - increase speed outside ECAs
  - sail around the ECAs.
  - or both
- **This leads to higher total CO_2 emissions**

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Thank you.
Questions?

Maritime Routing and Speed Optimization with Emission Control Area Regulations

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