Development of Hybrid Diesel - Electric Propulsion System for Ships

Reducing fuel consumption and emissions, optimizing propulsion, making greener shipping

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- World wide adopted methods for emission calculation
- Activity monitoring of vessels – Method of daily reports
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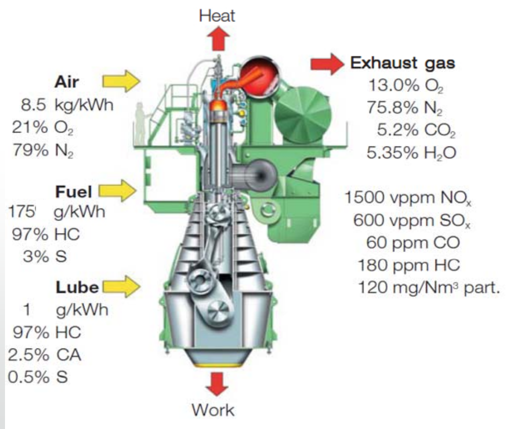
What is exhaust pollution from ships?

Typical exhaust pollution (production of smoke) due to transient engine loading in slow vessel speeds

Energy flow and emissions in 2-stroke:



World wide adopted methods for emission calculation

In relevant literature, 2 globally adopted methods are used:

- Top - Down method
  - Relies on world marine fuel sales
  - Wide spread of doubt due to unreliable statistics
- Bottom – Up or "Activity Based" method
  - More accurate method
  - Takes into account:
    - Ship movements
    - Ship characteristics
    - Corresponding fuel consumption figures
    - Emission factors

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Activity monitoring of vessels – Method of daily reports

Typical table containing information regarding the voyage, weather, main engine and auxiliary engine loading and propeller operation

Ship Speed:	***Knots***	14.84	14.46	14
Slip:	-	6.9P	2.4N	0.4N
Engine RPM:	***RPM***	114.8	116.8	115.3
Load of Engine:	***% MCR***	0.7530	0.8416	0.8233
Activity Time	***Hours***	9.5	24	24
	Wind	Abeam 4	Abeam 4	Ahead 5
Weather Type:	***condition***	Moderate	Moderate	Rough
	Current	abeam	abeam	Ahead
Distance Covered:	***sea miles***	140.98	347.04	336
Daily Consumption:	***tonnes***	14.5	41.6	40

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Activity monitoring of vessels – Method of daily reports

Typical table containing information regarding the voyage, weather, main engine and auxiliary engine loading and propeller operation

Auxiliary Engine	***Number in Op.***	2	3	2
Operational Time:	***hours***	4 + 9.5	24 + 11 +6	24 + 10
Total Output	***kW***	630	710	580
Fuel Type:	***HFO***			
Daily Consumption:	***tonnes***	3	3	3
Load Indicator	-	66	70	70
Fuel Admission Lever	-	64	68	68
T/C RPM	-	13200	13800	13600

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Data Editing and Statistical Analysis

- Interpolation using the shop test of each engine with the parameters:
  - Fuel Admission lever (rack position of injection pumps)
  - Load indicator (desired engine loading)
  - T/C Rotational speed
- Calculating the difference from the point of low emission and low consumption using the following equation:

$$Load_{extra_i} = x_i - 0.75$$

  - MAN B&W 7S50MC-C optimum point is at 75% of M.C.R.

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Data Editing and Statistical Analysis

- Calculation of extra energy required or not from optimum

$$Energy_{extra} = \sum_{i=1}^{n} Load_{extra_i} \cdot MCR \cdot time_i$$

- If the value is positive (+) more energy is required. Engine is more loaded for constant RPM
- If the value is negative (-) less energy is required. Ship's speed is increased

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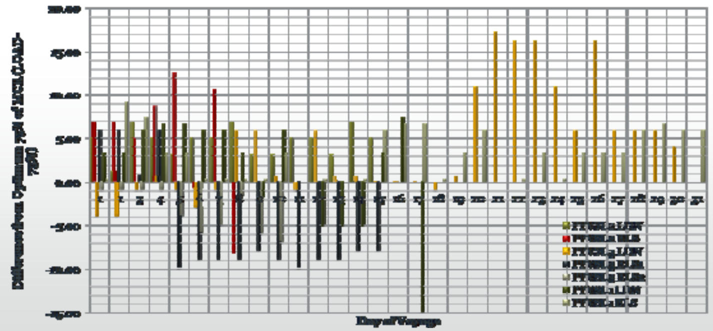
Engine loading difference from optimum

- 0.0 is considered to be the optimum point (75% for these engines)



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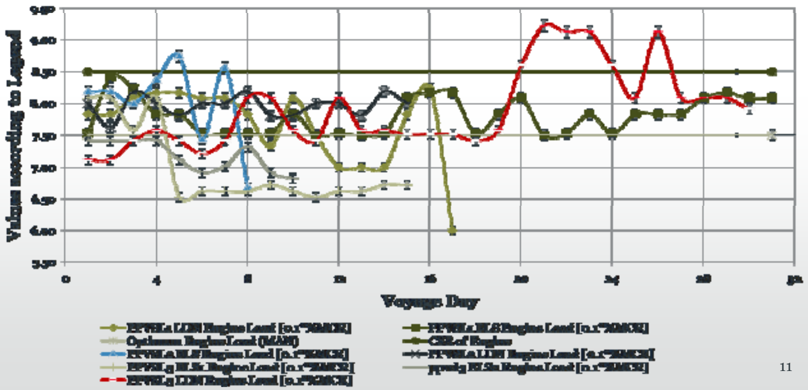
Engine loading variance during voyage

- Laden and Ballast condition



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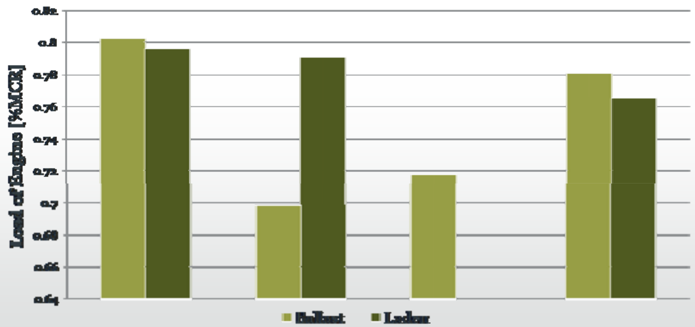
Analysis the previous chart shows (1/2):

- Mean values of engine loading during voyages



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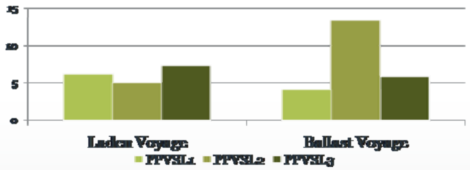
Analysis of the previous chart shows (2/2):

- Standard deviation (σ) from optimum



- As a result (for σ= 7%)
  - At least 75% of values will drop into the range of 61% - 89%
  - At least 89% of values will drop into the range of 51% - 96%
- As result, taking into account the following graphs, sizing of the storage medium can be performed

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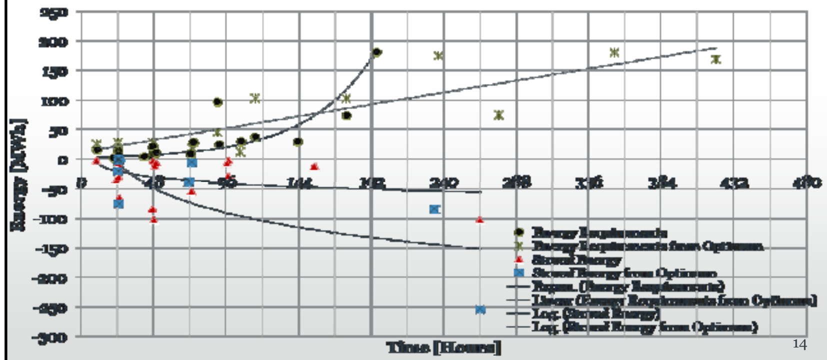
Extra or less energy requirements and regression application

- From optimum loading point and from voyage's mean point



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Hybrid Technology

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Why hybrid and All Electric Ship?

- Uncouples propeller and Diesel engine
- Better energy flow and management (electricity)
- Exploits better the thermal efficiency of the engine(s)
- Electric motors adapt RPM→ optimization in selection of propeller
- Exploits greener means of energy, like solar
- Load levelling → transient load removal
- Application in low steaming by switching off generator sets
- Stored energy can achieve locally zero emission ships

Battery Selection, Energy: 40MWh

- Key Features:
  - Weight and capacity
  - Discharging rate
  - Cost

Energy density and required added weight per battery type (Linden, 2000)

Type	Wh/kg	Cost [$/kg]	Req. tons
Lead Acid	35	3.15	1142.9
Vanadium - Bromine	50	15	800.0
Silver Cadmium	70	-	571.4
Zinc - Bromine	70	-	571.4
Sodium/nickel chloride	115	12.65	347.8
Lithium Ion	150	90	266.7

Battery Selection, Energy: 40MWh

- Sodium Nickel Chloride (Zebra®) Battery
  - Already developed by Rolls Royce
  - High energy density per available kWh
  - Lightweight compared to Lead Acid (~40% of weight)
  - Good discharging rate profile
  - Low maintenance cost
  - Tested in marine environment
  - Lower Cost than (VBr-RFB) → Potential to drop more

Diesel Generator Selection

- 3 scenarios of proposed sizing (before optimization algorithms)
  - 6 Identical generators
  - 2 generators to cover the 60% of MCR, 4 more to reach 100% of MCR
  - Scenario 1 but the output reduced until 90%
- Reminder that:
  - Engines operate at 85% of MCR optimum point
  - Generator efficiency 95%- 97%
  - → Increase in overall MCR of Diesel Generators

Fuel Savings

- If the system was in placed, judging from consumption reports from voyages, the potential fuel savings are the following:

Fuel Savings per Voyage

Vessel	Fuel Savings	Energy NET
PPVSL1	99 tonnes	82.2 MWh
PPVSL2	70 tonnes	180.4 MWh
PPVSL3	294 tonnes	133.2 MWh
Vessel	**Charging Fuel**	**Final F. Savings**
PPVSL1	0.86 tonnes/Day	5.0 tonnes/Day
PPVSL2	2.00 tonnes/Day	2.3 tonnes/Day
PPVSL3	0.76 tonnes/Day	8.7 tonnes/Day

Emission Reduction:

- Related only to fuel oil consumption:
- Potential to decrease more with optimum operation

Emission reduction per day

Vessel	Pollutant	Savings [tonnes/Day]
PPVSL1	CO_2	15.76
	NO_x	0.43
	SO_x	0.30
PPVSL2	CO_2	7.42
	NO_x	0.20
	SO_x	0.14
PPVSL3	CO_2	27.6
	NO_x	0.76
	SO_x	0.40

Economic feasibility

- Internal Rate of Return of Investment as criterion
- 40% direct payment, 60% bank loan
- 8% fixed bank interest
- 10% increase in fuel price per year

$$\sum_{j=0}^{n} \frac{FS_j}{(1+IRR)^j} = Cost_{hybrid} + \sum_{j=1}^{n} \frac{C_j}{(1+IRR)^j}$$

Internal Rate of Return of each scenario

Storage	Scenario	IRR
ZEBRA®	2	20.7%
Vanadium	2	4.3%
Vanadium	3	4.4%

Conclusions and Discussion

Conclusions

- Hybrid is economically feasible
- Lower temperatures inside the cylinder drop more NOx
- ZEBRA® battery is a potential solution along with redox flow cell batteries
- Local zero emissions is possible to achieve
- Increase in overall efficiency ~ 15%
- Improved selection of propellers
- Improved design of stern hull form, flow optimization, better trim

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Future planned work

- Simulation and optimization algorithms
- Diesel Generator sets → Scenarios of number and type
- Expansion to the whole fleet of Bulkers
- Selection of Electric Motors
- Alternatives for electric charging
- Sustainable “green technology”
- Investigation of Hybrid Nuclear propulsion

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