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CoolChainAssociation

CCA Annual General Meeting, Berlin **6 - 7 May 2010**

Carbon Footprint of Refrigerated Goods' Transportation

Comparison of Air, Land and Sea transport under Design Conditions and in Real Operation

Dr.-Ing. Yves Wild

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The solution is already there …

IPPING NEWS

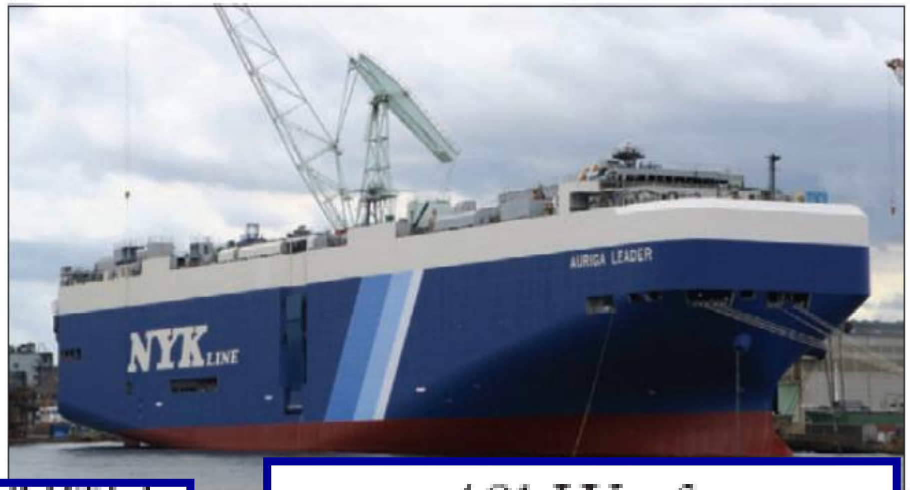
WorldCargo news

Solar powered car carrier makes maiden voyage

The AURIGA LEADER, the world's first cargo vessel to be partly powered using solar energy, made its maiden voyage from Japan to the US west coast Port of Long Beach earlier this month carrying a consignment of Prius cars and other Toyota vehicles.

Built at the Kobe Shipyard and launched in December last year, the ship is equipped with 328 solar panels, which can generate up to 40kW of energy. The solar array, installed at a cost of US$1.68M, provides a supplementary source of clean energy to the ship, helping to reduce the load on its auxiliary engines. The panels themselves also help to protect the vehicles from salt water, wind pressure and vibrations while at sea.

The car carrier is a joint project of Japanese operator Nippon Yusen Kaisha (NYK) and Nippon Oil Corp and is contracted exclusively to Toyota. The Japanese automaker will use the AURIGA LEADER, which can carry up to 6,200 ve-



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hip's p

tep towards meeting its

bon-dioxide emissions by 2010.

up to 0.2% of power

up to 40kW of energy

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- Introduction: CO_2 Emissions through Transportation Activities
  - Basics of the Conversion Fuel Consumption - CO_2 Emission
  - Transportation Activities as a Contributor to Global GHG Emissions
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CO_2 Emissions through Transportation Activities...

Fuel Combustion / CO_2 Emission: Stoichiometrical conversions

Carbon dioxide	
Chemical formula	CO_2
Molar mass of CO_2	44 g/mol

Combustion of pure coal	
Chemical formula	C
Molar mass	12 g/mol
CO_2 emission	3.667 kg CO_2/kg

Combustion of hydrocarbons	
Chemical formula	H-$(CH_2)_n$-H
Molar mass	14 g/mol
CO_2 emission	3.143 kg CO_2/kg

Relevant for fuel consumption of ships and trucks

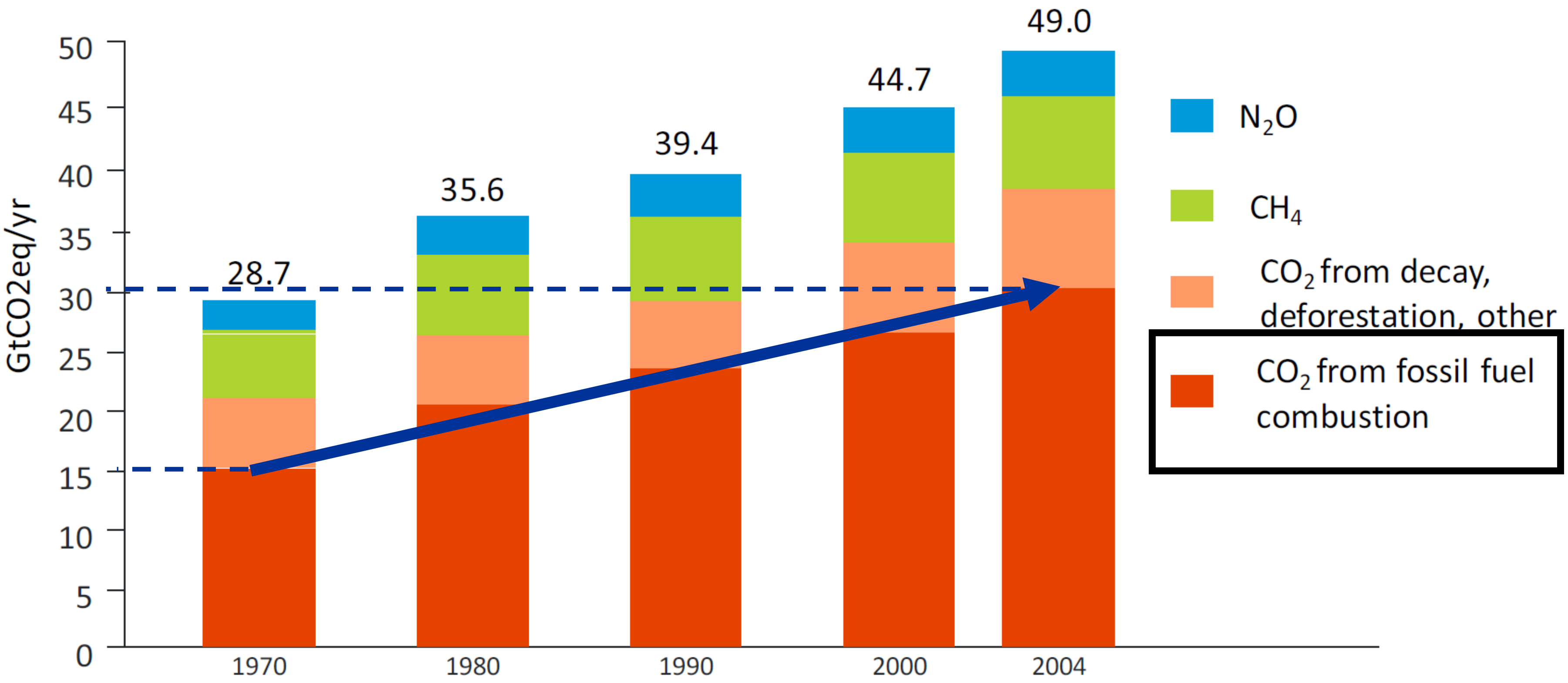
Combustion of kerosene (Jet A-1)	
Chemical formula	$C_{15}H_{32}$ *)
Molar mass	212 g/mol *)
CO_2 emission	3.113 kg CO_2/kg *)

Relevant for fuel consumption of aircrafts

Kerosene is a mixture of several Alkane series, Cycloalkanes and Aromatics, whereas the exact composition varies. Assuming that kerosene was pure $C_{15}H_{32}$ (pentadecane), the combustion of 1 mole kerosene leads to 15 moles CO_2.

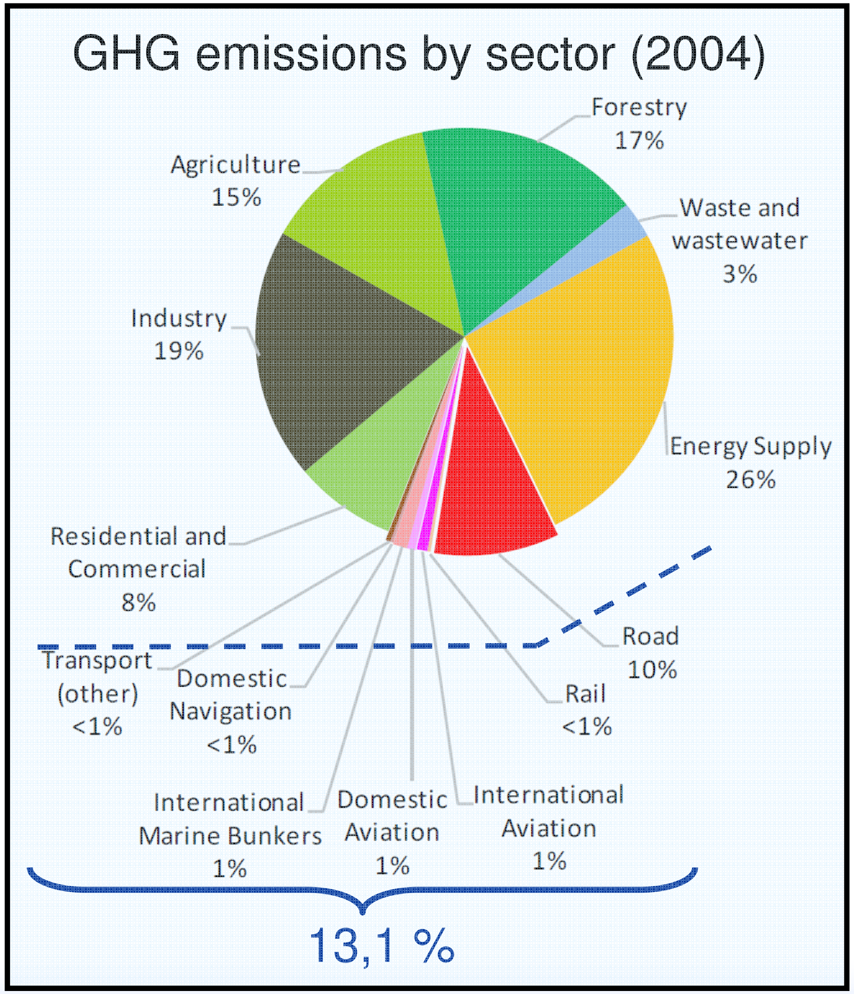
Combustion of methane (natural gas)	
Chemical formula	CH_4
Molar mass	16 g/mol
CO_2 emission	2.750 kg CO_2/kg

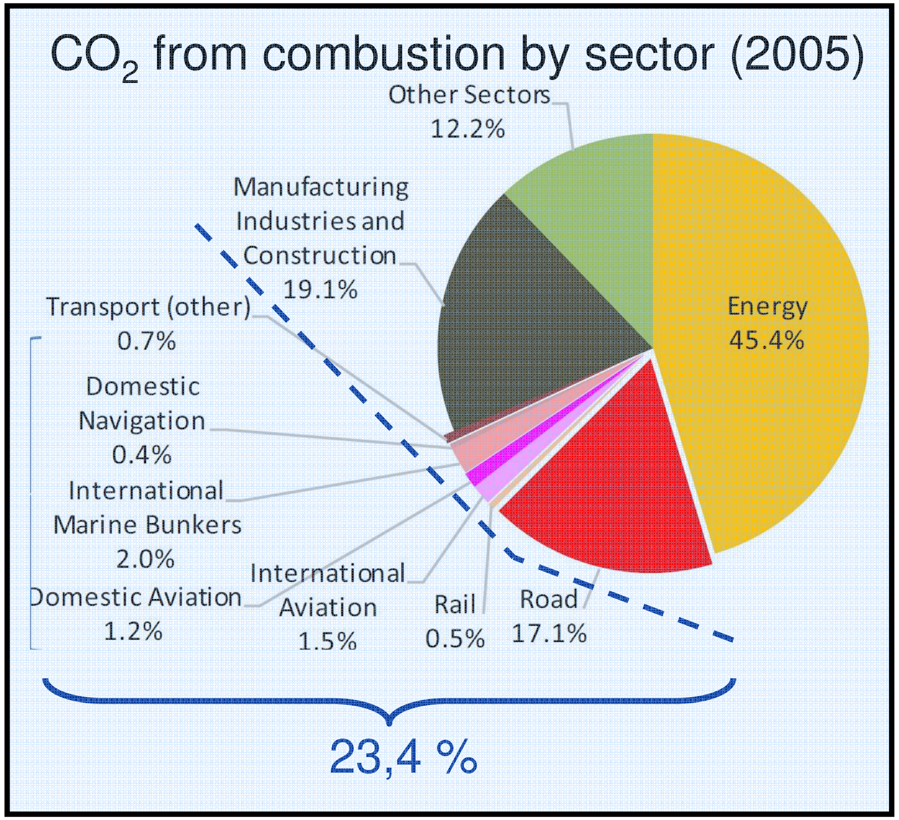
CO_2 Emission from Combustion has doubled since 1970



Source: Greenhouse Gas Reduction Strategies in the Transportation Sector: Preliminary Report, © OECD/ITF, 2008

Transportation Activities as a Contributor to Global Emissions





Source: Greenhouse Gas Reduction Strategies in the Transportation Sector: Preliminary Report, © OECD/ITF, 2008

Emission measurement parameters: Concern of different stakeholders

Parameter	**g CO_2 / t·km** (specific emission)	**g CO_2 / kg Cargo** (specific emission)	**t CO_2 (e.g. per year)** (total emission)
Description	Carbon emission which occurs during transportation of one ton of cargo for one kilometer distance	Carbon emission which occurs during transportation of one kg of cargo for the whole voyage	Total Carbon emission which occurs during one voyage or during all voyages of one ship/plane/truck/train or fleet (at a certain time span)
Interested parties	• **Transportation process owner** (fuel consumption) • **Producer of ships / trucks / aircrafts** (benchmarking)	• **Final consumers** with environmental awareness • **Retailers** etc.	• **Governments / Authorities** • All stakeholders dealing with **Carbon trading**

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Environmental Indexing: Example IMO Indices (Sea Transportation)…

Energy Efficiency Design Index (EEDI) for new vessels

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}{*}\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

Emissions main engine

Emissions auxiliary engines

Theoretical transportation activity
(Capacity * Reference speed)

Coefficients / Factors
(for ship-specific design elements, e.g. heat recovery systems)

Formula as per definition of IMO Marine Environmental Protection Committee (MEPC), 59th meeting (2009), outlined in the „Report on the […] second Intersessional Meeting of the Working Group on GHG Emissions from Ships" (MEPC 59/4/2)

→ Calculation based on **theoretical** reference conditions
→ **Cargo refrigeration not considered** herein

Energy Efficiency Operational Indicator (EEOI) for existing ships

$$Index = \frac{(\sum_i FC \times C_{Carbon})_{Fuel\ type1} + (\sum_i FC \times C_{Carbon})_{Fuel\ type2} + (\sum_i FC \times C_{Carbon})_{Fuel\ type3} + \ldots}{\sum_i m_{cargo,i} \times D_i}$$

Index i: Number of voyages

Numerator: Actual emissions
(Sum of fuel consumptions * spec. CO_2 emissions)

Denominator: Actual transport activity
(Sum of cargo masses * covered distance)

Formula as per definition of IMO Marine Environmental Protection Committee (MEPC), 59th meeting (2009), outlined in the „Energy Efficiency Operational Indicator (EEOI), Report of the correspondence group […]" (MEPC 59/4/15)

→ Reasonable: Summing-up **real consumptions**
→ **Cargo refrigeration is not explicitly named**, but is included in the analysis of overall consumptions
→ Problem: **Missing commitment** for benchmarking

IMO-Indices: Pros and Cons

	EEDI (based on design parameters)	EEOI (operation of existing ships)
Pros	+ Comparable + New ships can be classified + Incentive for designing measures to increase the efficiency of energy + Agreement on final formula definition is likely	+ Very **meaningful**, since it is based on an analysis of empirical (actual) data + **Considering all energy consumer on board** (e.g. refrigeration system) + Influence of operational data is considered
Contras	- Not aplicable for existing ships, thus **not adequate for Status Quo analysis** - Index is based on **theoretical design data only** - Optimizing efficiency by improving **ship's operation** (e.g. actual speed) **not considered** - **Cargo refrigeration not considered** - Finds low acceptance at ship yards	- **Confidential data**: Reservations against publication - Needs provision of big amounts of data and execution of a complex analysis

→ **EEDI** is **not adequate** for analysing actual CO_2 emissions

→ **EEOI** calculation approach is reasonable, but **won't be enforceable** as a common standard

Different calculation approaches for CO_2 emission analysis

EEDI: **Nominal** consumption analysis		EEOI: **Actual** consumption analysis
• Theoretical approach	↔	• Analysis of real consumptions
• Calculation for a reference voyage	↔	• Calculation for realized voyages
• Many influences are not considered	↔	• All operational influences are considered
• Results dependent on assumptions: • Specific emissions for engines • Distance / speed for reference voyage • Full reference capacity	↔	• Results not dependent on assumptions: • Overall consumption includes all types of power demand • Impacts of real ship operation (speed, cargo data etc.) are considered

→ Results for the same ship (and voyage) **may vary widely**, dependent on the chosen calculation approach

→ Important for comparisons: **Which method was applied**?

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Example: Calculation differences of IMO indices at a reefer ship study

EEDI: **Nominal** consumption analysis		EEOI: **Actual** consumption analysis
• Assumption: Ship is always fully laden (100% cargo capacity is used)	⟷	• Northbound: Parts of cargo are loaded in one of three loading ports only: < 100% cargo capacity is used
• No consideration of emissions during nearly empty backhaul voyages	⟷	• Southbound: Ships are mainly empty but fuel consumption is registered (<< 100% cargo capacity is used)
• No consideration of power demand for refrigeration[1]	⟷	• Fuel consumption due to power demand of refrigeration is included
• No consideration of emissions during harbour times	⟷	• Emissions during harbour times are included
• Consumption of engines is calculated as per their reference/design operation	⟷	• Real consumption of engines (non-optimal operation) is considered

→ **EEOI** results may be up to **300-400% higher than EEDI figures**

Methodologies of CO_2 Emission Calculation…

Main fuel consumers of transport

Ships:

- Main engine propulsion (pure “transport”)
- Base Load, e.g.:
  - Navigation, On-board electronics
  - Provisions refrigeration machine, galley
  - Air conditioning
  - Crew‘s electrical power consumption

Base Load mainly powered by separate auxiliary engines

Aircrafts:

- Turbines of Jet engine (pure “transport”)
- Base Load, e.g.:
  - Hydraulic and pneumatic systems
  - Navigation
  - Air conditioning
  - Other electrical power consumptions

⬇

Base Load powered by jet engine turbine or by separate auxiliary power unit (APU)

Trucks:

- Engine (pure “transport”)
- Base Load, e.g.:
  - On-board electronics
  - Air conditioning

⬇

Base Load directly powered by engine

→ Consumption is varying dependent on ship / aircraft / truck **size, speed, distance** and **cargo mass**

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Additional fuel consumers during reefer cargo transportation

Reefer ships:

- Power consumption for refrigeration system
- Cooling water and refrigerant pumps
- Recirculation fans
- CA system (if any)

Container ships and trucks:

- Power consumption of reefer containers includes refrigeration system + heat removal (cargo hold ventilation, cooling water pumps etc.)

Aircrafts:

- Cargo Refrigeration (if there is any) is powered by turbines
- Related fuel consumption is included in main kerosene consumption

→ Consumption is dependent on **refrigeration system**, **type** and total **mass of cargo** as well as **climatic conditions**

Nominal consumption – Assumtions taken at a study for reefer ships

Assumptions:

- Power demand of one reefer container: 6.6 kW / FEU
- Specific power demand of reefer cargo holds: 150 W / t cargo
- Distance for reference voyage: 5,000 nm
- Reference speed: 20 kn
- Consumption at different speeds calculated as per the „Third power law“
- Base Load: Estimated according to the ship size

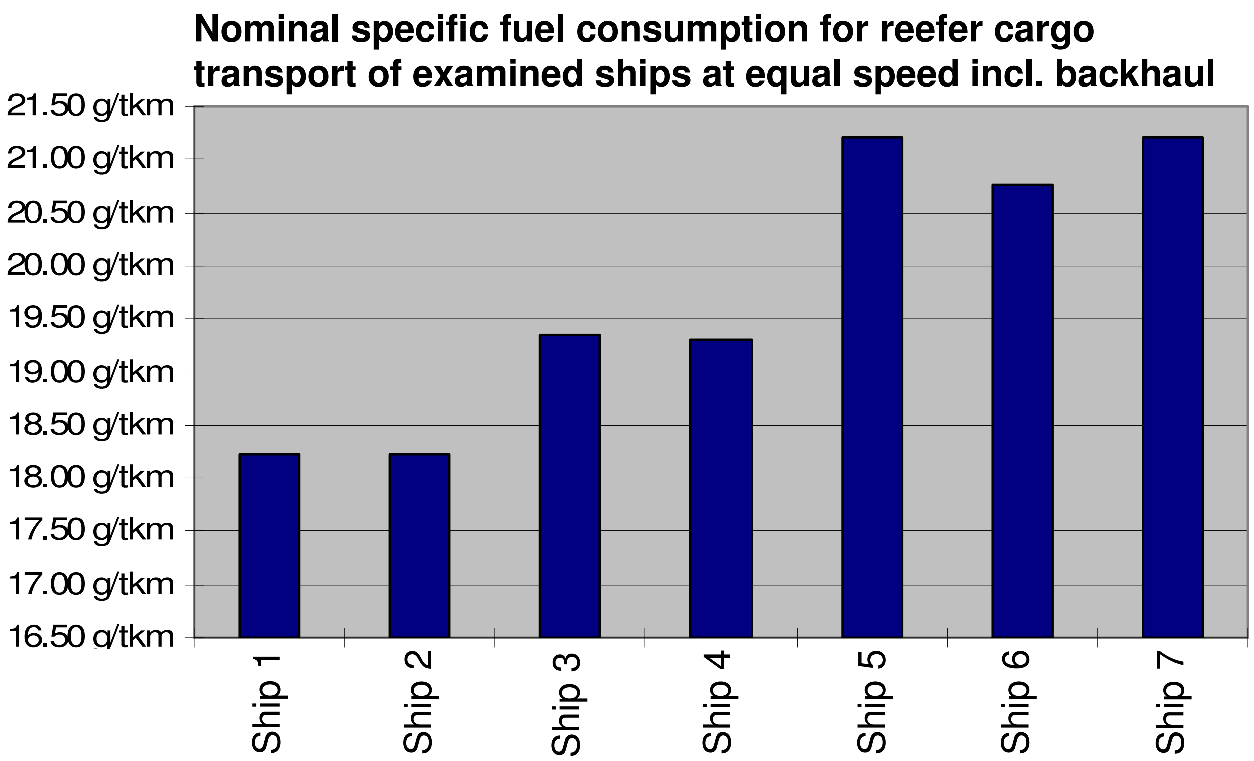
Not considered:

- Harbour times
- Cooling down of reefer cargo
- Unloaded voyages (backhaul); assumption: ships are always fully laden

→ **Many assumptions needed**

→ Some **real circumstances cannot be considered** in the calculation

Nominal consumption – Results of a study for reefer ships



→ **Average related CO_2 emission is 62.1 g/tkm**

→ Based on **many assumptions; many issues no considered all**

Actual consumption – Calculation basics (same study for reefer ships)

Calculation details:

- Analysis of empirical consumption data
- Actual consumptions, cargo loads and distances covered were taken

Considered issues:

- Partly loaded voyages (backhaul)
- Cargo cooling down during transportation
- GHG emissions due to refrigerant leakages at ports

→ Considering **all energy consumption** needed for cargo transport

→ Considering **all cargo which is transported**

Actual consumption – Sample analysis sheet for a ship´s voyage

Total cargo (From \ To)	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7
Port 1		1,534.5 t					
Port 2			1,534.5 t				
Port 3				1,242.0 t			
Port 4					1,514.0 t		
Port 5	5,574.9 t						1,120.0 t
Port 6					3,713.1 t		
Port 7						2,165.3 t	

Actual cargo data

Distances (From \ To)	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7
Port 1		1,150 km	1,952 km	3,925 km	6,064 km	6,501 km	7,568 km
Port 2	1,150 km		809 km	2,782 km	4,921 km	5,358 km	6,423 km
Port 3	1,952 km	809 km		2,054 km	4,182 km	4,632 km	5,692 km
Port 4	3,925 km	2,782 km	2,054 km		2,160 km	2,610 km	3,680 km
Port 5	6,064 km	4,921 km	4,182 km	2,160 km		480 km	1,537 km
Port 6	6,501 km	5,358 km	4,632 km	2,610 km	480 km		1,135 km
Port 7	7,568 km	6,423 km	5,692 km	3,680 km	1,537 km	1,135 km	

Actual distances

Transport (From \ To)	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7	Total Southbound
Port 1		1,765,022 tkm	0 tkm	0 tkm	0 tkm	0 tkm	0 tkm	
Port 2	0 tkm		1,242,053 tkm	0 tkm	0 tkm	0 tkm	0 tkm	
Port 3	0 tkm	0 tkm		2,551,202 tkm	0 tkm	0 tkm	0 tkm	
Port 4	0 tkm	0 tkm	0 tkm		3,269,761 tkm	0 tkm	0 tkm	**10,549,857 tkm**
Port 5	33,806,816 tkm	0 tkm	0 tkm	0 tkm		0 tkm	1,721,820 tkm	
Port 6	0 tkm	0 tkm	0 tkm	0 tkm	1,781,268 tkm		0 tkm	
Port 7	0 tkm	0 tkm	0 tkm	0 tkm	0 tkm	2,458,454 tkm		
Total Northbound	**38,046,538 tkm**							**48,596,396 tkm**

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Actual consumption – Results (same study for reefer ships)

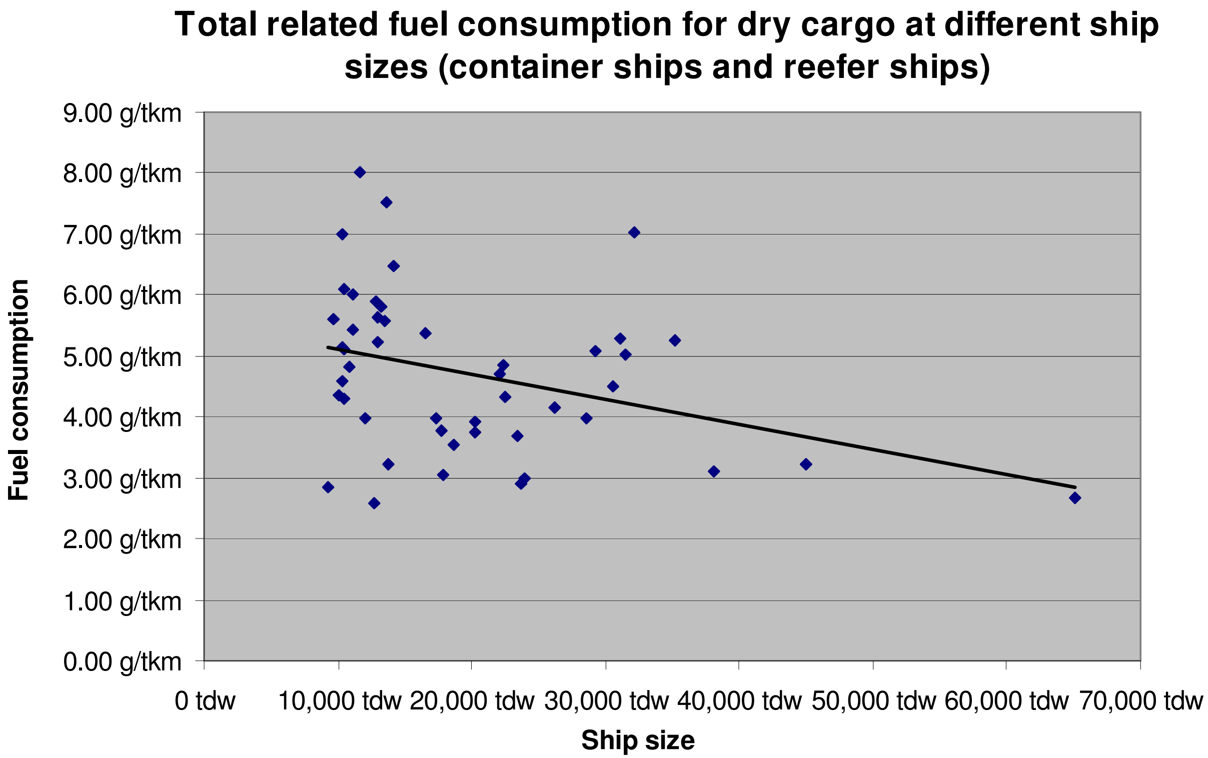
	Vessel name	Ship 1	Ship 2	Ship 3	Ship 4	TOTAL / Average
	No. of analyzed voyages	**6**	**9**	**1**	**10**	**26**
Transport	Northbound	201,498,218 tkm	256,543,742 tkm	27,441,175 tkm	312,150,462 tkm	797,633,596 tkm
	Southbound	51,746,137 tkm	15,669,621 tkm	1,292,002 tkm	23,810,404 tkm	92,518,163 tkm
	Total	**253,244,354 tkm**	**272,213,362 tkm**	**28,733,177 tkm**	**335,960,866 tkm**	**890,151,760 tkm**
	Duration	**168.79 days**	**258.60 days**	**29.92 days**	**282.92 days**	**740.22 days**
Fuel consumption	Low sulfur fuel (LSF)	0.00 t	0.00 t	0.00 t	0.00 t	0.00 t
	Diesel Oil (DO)	21.11 t	70.68 t	3.10 t	23.60 t	118.49 t
	Fuel Oil (FO)	4,915.81 t	6,299.91 t	706.05 t	7,703.18 t	19,624.95 t
	Cylinder Oil ME (CO)	33.25 t	44.59 t	4.96 t	54.09 t	136.90 t
	Total	**4,970.17 t** 29.45 t/day	**6,415.18 t** 24.81 t/day	**714.11 t** 23.87 t/day	**7,780.87 t** 27.50 t/day	**19,880.33 t** 26.86 t/day
	Specific fuel consumption NB only	24.7 g/tkm	25.0 g/tkm	26.0 g/tkm	24.9 g/tkm	24.9 g/tkm
	Specific fuel consumption SB+NB	**19.6 g/tkm**	**23.6 g/tkm**	**24.9 g/tkm**	**23.2 g/tkm**	**22.3 g/tkm**
	Total Carbon emission	**15,621.2 t**	**20,162.9 t**	**2,244.5 t**	**24,455.3 t**	**62,483.9 t**
	Specific Carbon emission NB only	77.5 g/tkm	78.6 g/tkm	81.8 g/tkm	78.3 g/tkm	78.3 g/tkm
	Specific Carbon emmission SB+NB	**61.7 g/tkm**	**74.1 g/tkm**	**78.1 g/tkm**	**72.8 g/tkm**	**70.2 g/tkm**

→ **Average CO_2 emission is 70.2 g/tkm**

→ Calculation based on analysis of real figures leads to **different results** than calculation based on nominal approach

Comparison of Different Transportation Modes…

Fuel Consumption of Sea Transport



Calculation basis:

- *Empirical study about reefer ship data*
- *Consumption at design conditions (theoretical approach)*
- *No Consideration of refrigeration*

→ **Fuel consumption** ranges from **3-9 g/tkm**
→ **BUT:** Calculation based on **theoretical approach** at **design conditions**
→ Analysis of **real data** has shown **higher values**
→ **No consideration of refrigeration**

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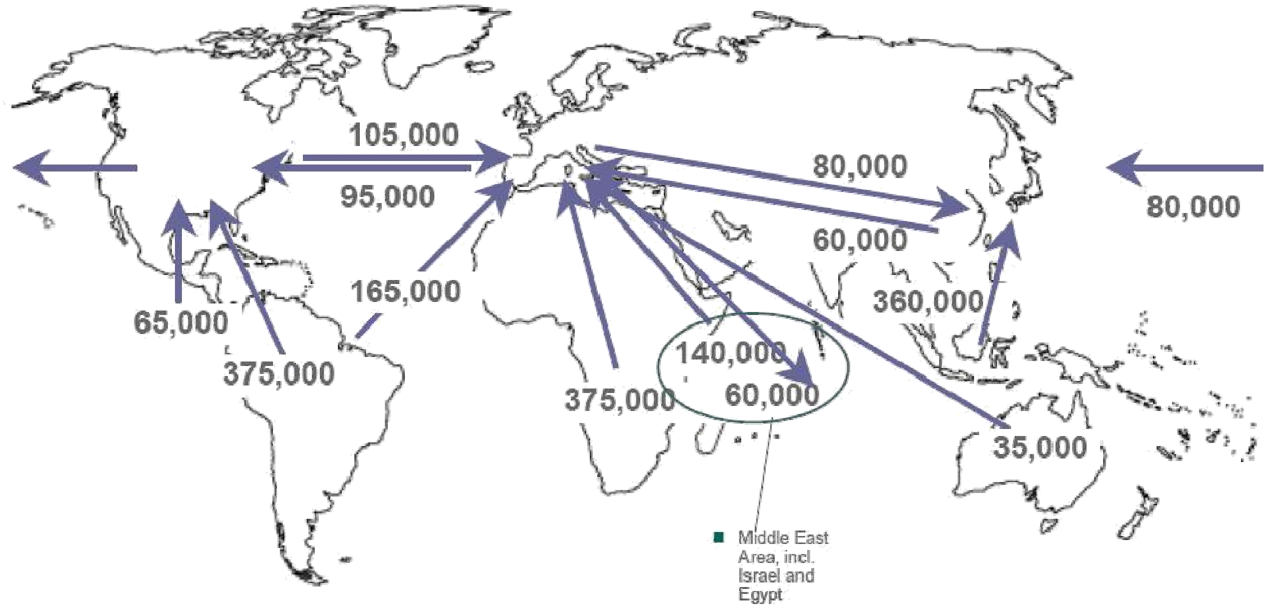
Worldwide Air Transport

→ Perishable products are **mainly transported intercontinentally** from South to North

→ Main routes are: Latin america to North america, North america to Asia/Pacific, Europe to Asia/Pacific

Estimated total air cargo of perishable products in 2005:

2 mio. t



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Fuel Consumption of Air Transport

Calculation basis:

- *Consumption at design conditions (theoretical approach)*
- *No Consideration of refrigeration*

Type	Payload [t]	Speed [km/h]	Range [km]	Fuel mass [t]	Total mass [t]	Spec. fuel consumption [g/tkm]
Boeing B777	104	895	9.000	181	347	193,4
Boeing B747	120		5.200	83	384	133,0

→ **Fuel consumption** ranges from **130-200 g/tkm**
→ **BUT:** Calculation based on **theoretical approach** at **design conditions**
→ An analysis of **real data** might lead to **higher values (?)**
→ **No consideration of refrigeration**

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Fuel Consumption of Road Transport (Trucks)

Calculation basis:

- *Consumption at design conditions (theoretical approach)*
- *No Consideration of refrigeration*

Emission standard	CO_2 [g/tkm]	NO_x [mg/tkm]	CH_x [mg/tkm]	Particles [mg/tkm]
EURO 1	72	673	59	21
EURO 2	69	746	39	10
EURO 3	71	542	38	12
EURO 4	69	343	44	2

→ **CO_2 consumption** as per EURO norms ranges from **69-72 g/tkm**
→ This corresponds to a **fuel consumption of approx. 22-24 g/tkm**
→ **BUT:** Calculation based on **theoretical approach** at **design conditions**
→ **No consideration of refrigeration**

Fuel Consumption: Comparison of different transportation modes

Mode of transport	Spec. Fuel consumption [g/tkm]	Spec. CO_2 Emission [g/tkm]	Type of Fuel
Aircraft	100 – 200	315 – 630	Jet A1
Truck	24	70	Diesel
Rail		25 – 50	Electrity/Diesel
Barge (up hill)	10 – 23	24	Diesel
Barge (down hill)	7 – 16	32 – 73	Diesel
Reefer Ship	7,5	24	HFO
Container Ship			
4.500 TEU	6,2	20	HFO
8.000 TEU	3	10	HFO

→ **CO_2 emissions** of ships **seem to be less** than for trucks an aircrafts
→ **BUT: All** calculations based on **theoretical approach** (**design conditions)**
→ Analysis of **real data** has shown **higher values for ships**
→ For a **reliable comparison, more details** about calculations are needed

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Reefer Cargo Transport (Air): Fuel Consumption / Distance Relation

Range maximation

Range	Payload	Fuel mass (start)	Specific fuel consumption	Spec. CO_2 emission
9.750 km	54,2 t	145,0 t	274 g/tkm	854 g/tkm
9.500 km	57,7 t	141,6 t	258 g/tkm	804 g/tkm
9.250 km	61,2 t	138,1 t	244 g/tkm	760 g/tkm
9.000 km	64,6 t	134,6 t	231 g/tkm	721 g/tkm
8.750 km	68,1 t	131,2 t	220 g/tkm	685 g/tkm
8.500 km	71,6 t	127,7 t	210 g/tkm	654 g/tkm
8.250 km	75,0 t	124,3 t	201 g/tkm	625 g/tkm
8.000 km	78,5 t	120,8 t	192 g/tkm	599 g/tkm
7.750 km	81,9 t	117,3 t	185 g/tkm	575 g/tkm
7.500 km	85,4 t	113,9 t	178 g/tkm	553 g/tkm
7.250 km	88,9 t	110,4 t	171 g/tkm	533 g/tkm
7.000 km	92,3 t	106,9 t	165 g/tkm	515 g/tkm
6.750 km	95,8 t	103,5 t	160 g/tkm	498 g/tkm
6.500 km	99,3 t	100,0 t	155 g/tkm	483 g/tkm
6.250 km	102,7 t	96,6 t	150 g/tkm	468 g/tkm
6.165 km	103,9 t	95,4 t	149 g/tkm	464 g/tkm

Specific emission minimiozation

Fuel consumption:	13,85 kg/km

Source for aircraft data:
http://www.fliegerweb.com/airliner/flugzeuge/lexikon.php?show=lexikon-552

Boeing 777-F technical data	
Deadweight:	148,2 t
Max. Payload:	103,9 t
Max. fuel mass (start):	145,0 t
Max. total mass:	347,5 t
Speed:	862 km/h
Maximum range:	9.750 km

Assumptions:

- 10 t fuel remaining (reserve) at landing
- Average fuel consumption (kg/km) is constant
- CO_2 emission kerosene combustion: 3.113 kg CO_2/kg

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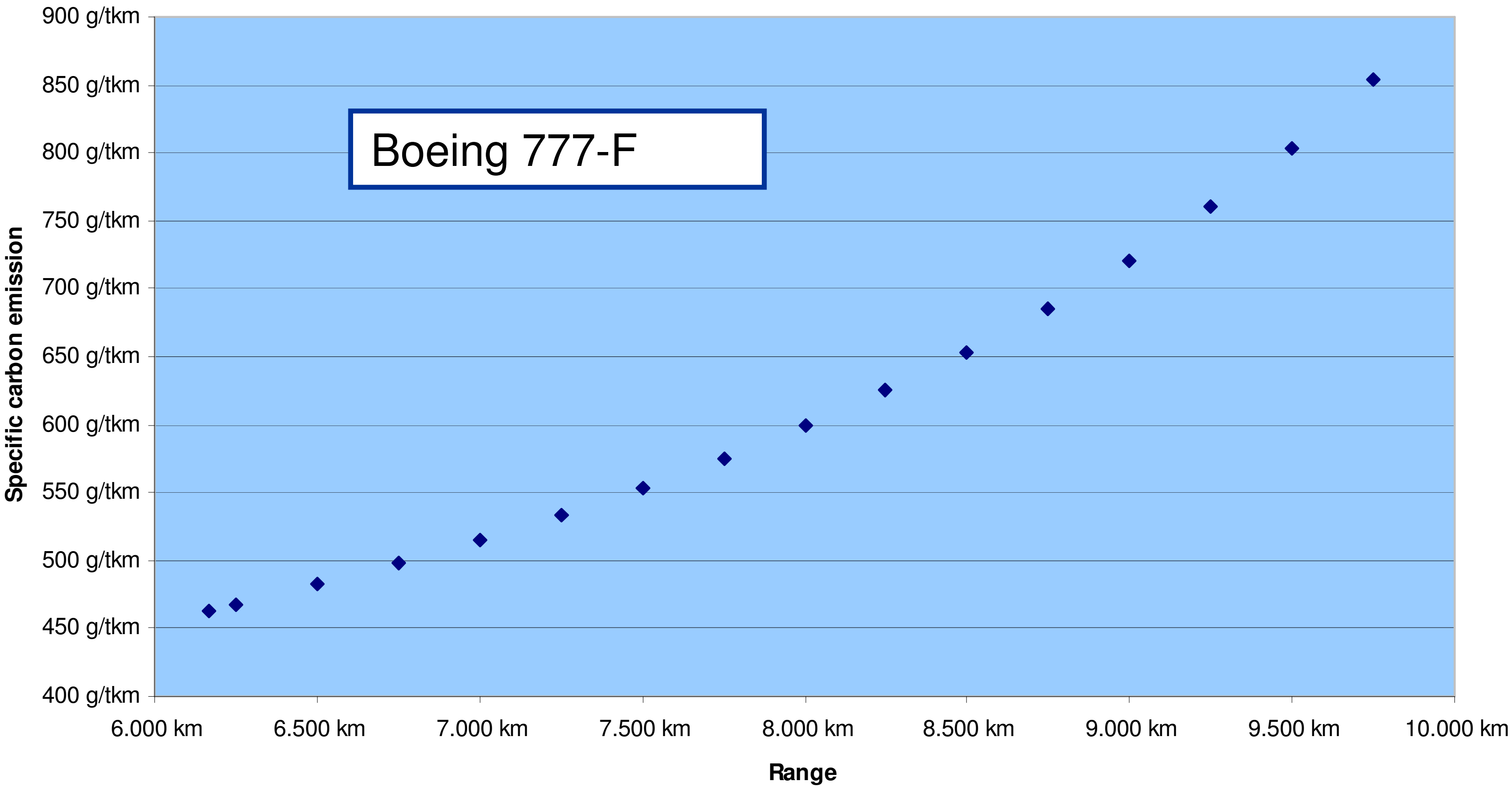
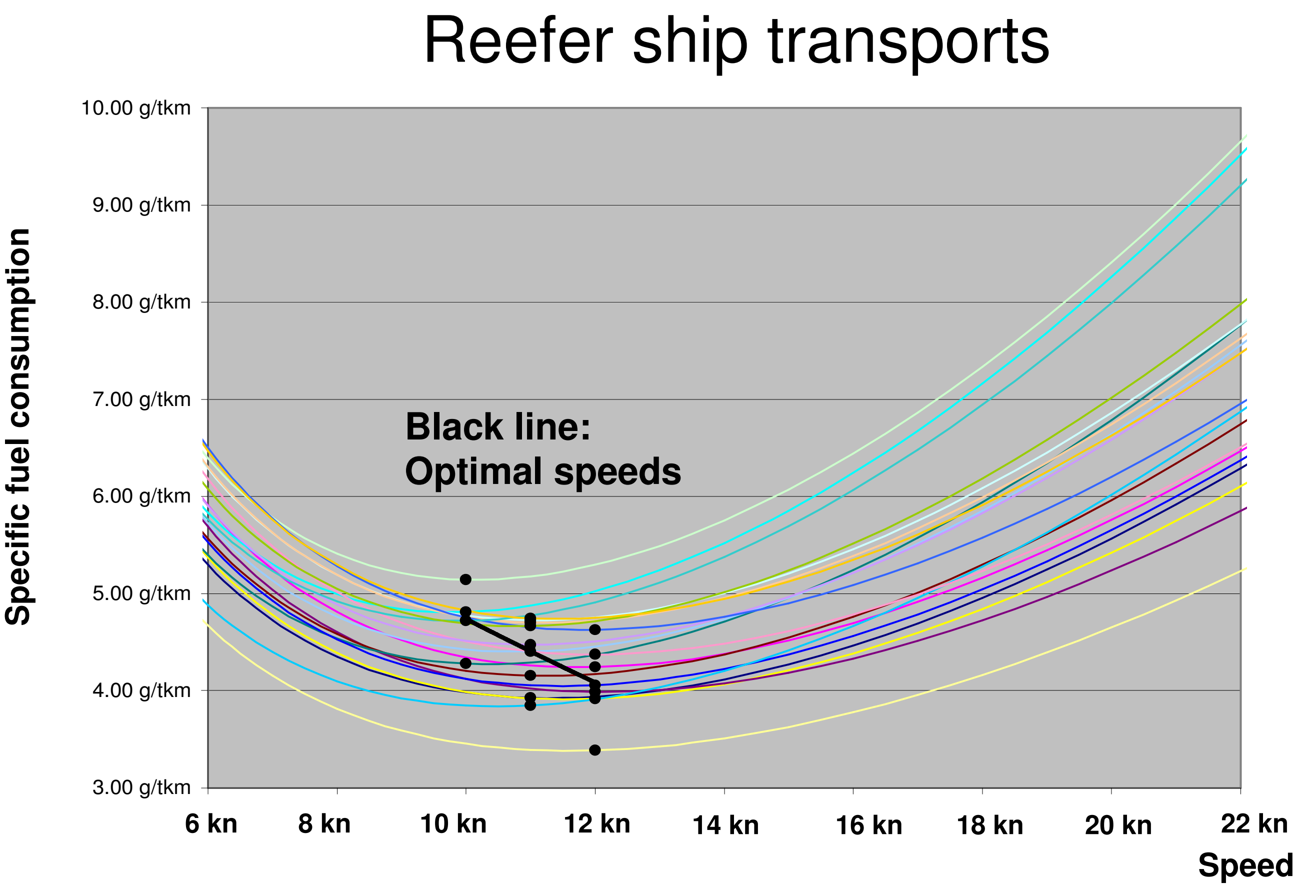
Reefer Cargo Transport (Air): Fuel Consumption / Distance Relation



→ **The higher the range** of an aircraft, **the higher** are **the specific CO_2 emissions** for the cargo transportation

Reefer cargo transport at sea: Speed optimization (1)



Calculation basis:

- *Empirical study about reefer ship data*
- *Consumption at design speed (theoretical approach)*
- *Consideration of the "third power law"*
- *Refrigeration considered*

→ Optimal speed for reefer ships: **10 to 12 knots**

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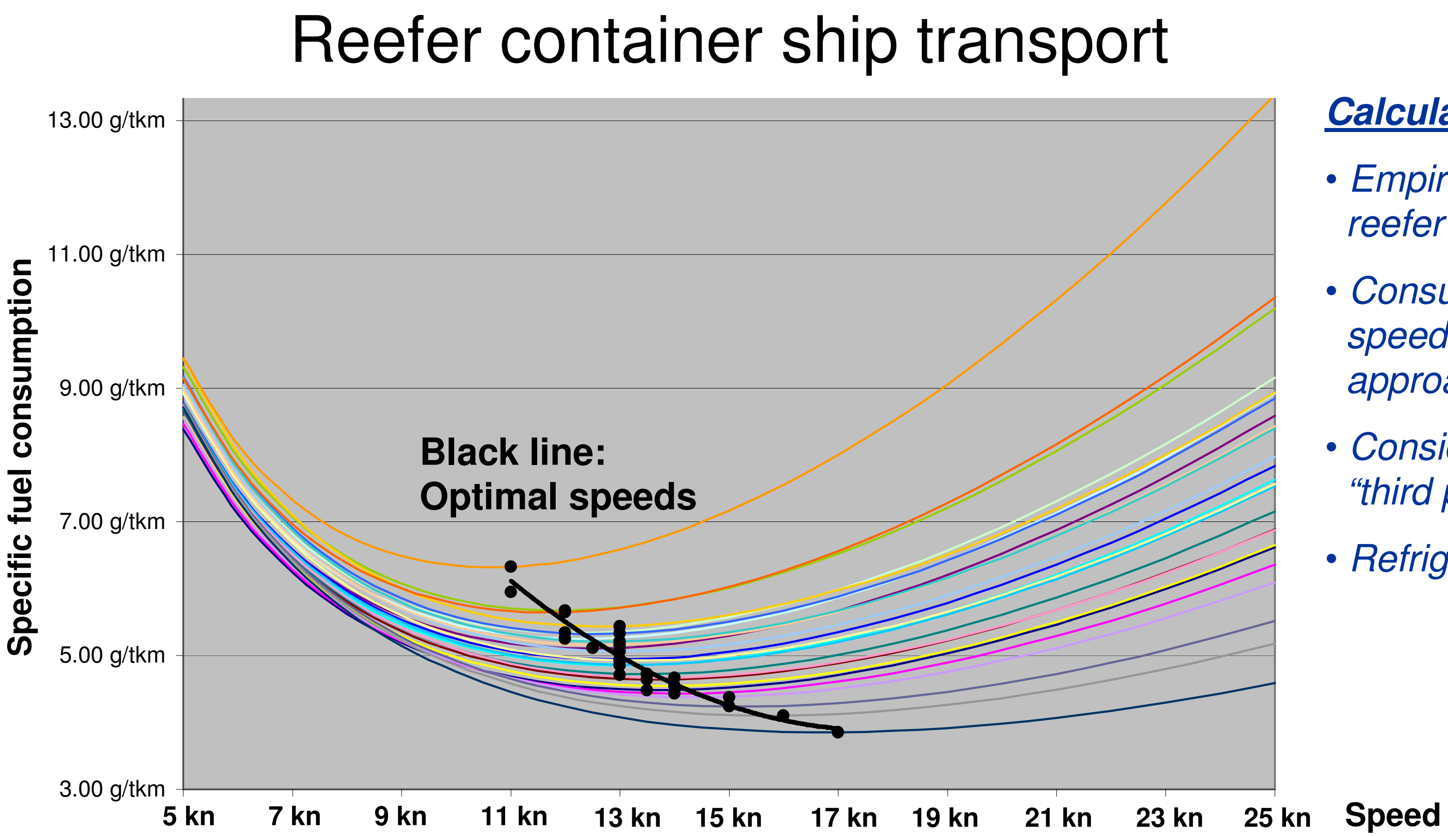
Reefer cargo transport at sea: Speed optimization (2)



Calculation basis:

- *Empirical study about reefer container ship data*
- *Consumption at design speed (theoretical approach)*
- *Consideration of the "third power law"*
- *Refrigeration considered*

→ Optimal speed for container ships: **11 to 17 knots**

Summary...

Key Conclusions (1)

1. **Design indices**
   → are not adequate for an analysis of actual CO_2 emissions
   → base on many assumptions
2. **Indices based on real operational data**
   → lead to more reasonable results, but
   → there might be missing commitment for benchmarking
3. **Emissions caused by cargo refrigeration generally consist of two parts:**
   → A pure transport related part (Main engines / turbines)
   → A refrigeration related part
4. **Results given for specific carbon emissions may vary widely**, dependent on
   → The chosen calculation approach
   → Taken assumptions and boundary settings
5. **Carbon emission calculation depends on many conditions**, e.g.
   → Calculation methodology (nominal approach or Analysis or actual data)
   → Ship / aircraft / truck size and Speed
   → Type and mass of cargo
   → Distance and Trade route (e.g. climate conditions)
6. **CO_2 emissions of ships seem to be less than for trucks an aircrafts.**
7. **Optimization potentials for minimized fuel consumption / carbon emission:**
   → Optimal speeds: 10-12 kn (reefer ships) and 11-17 kn (container ships)
   → The higher the range of an aircraft, the higher are the specific carbon emissions

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Key Conclusions (2)

Pure results of carbon footprint studies are nearly worthless without looking into the underlying calculation methodologies!


The End
for further information:
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