Energy and emission model for trucks

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Energy demand and emissions for trucks

Introduction

This report contains a description of a model for calculation of energy demand and emissions for trucks of different size. The model is a part of the so-called SHIP-DESMO generic models for 1) Ro-Ro cargo ships and 2) Ro-Ro passenger ships such that comparisons between sea and land transport can be carried out with respect to energy demand and the different types of emissions. The theoretical background for the two SHIP-DESMO models is described in four separate reports:

1. Report No. 1: *"Prediction of resistance and propulsion power of Ro-Ro ships"* by Hans Otto Kristensen

2. Report No. 2: *"Analysis of technical data of Ro-Ro ships"* by Hans Otto Kristensen

3. Report No. 3: *"Energy demand and exhaust gas emissions of marine engines*" by Hans Otto Kristensen

4. Report No. 4: *"Analysis of propulsion power data of Ro-Ro ships and analysis of the CEN standard 16258 for Ro-Ro ships"* by Hans Otto Kristensen

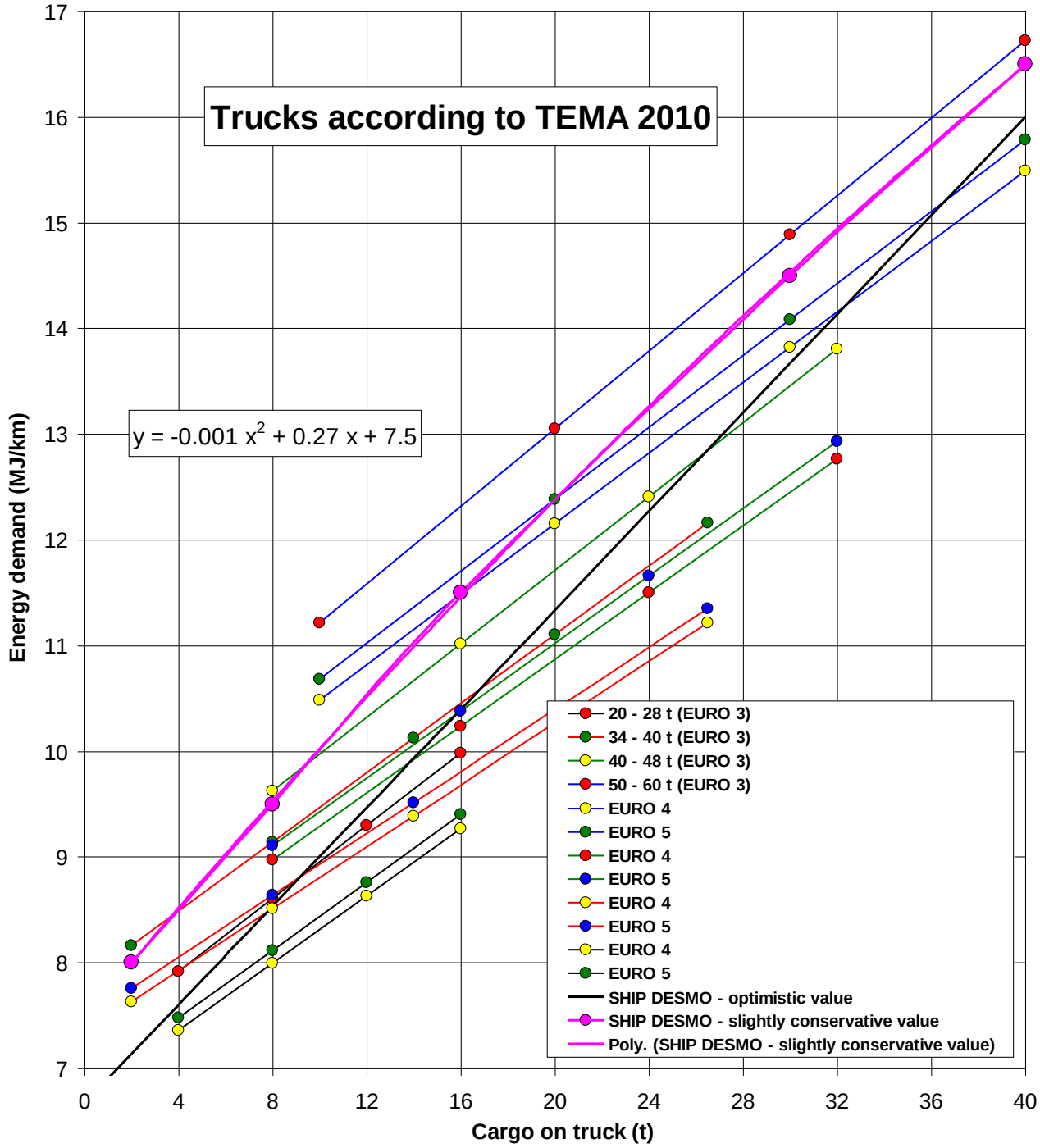
All four reports have been prepared as deliverables for the project no. 2014-122: Mitigating and reversing the side-effects of environmental legislation on Ro-Ro shipping in Northern Europe. Work Package 2.3 carried out for The Traffic Section of The Technical University of Denmark.

Selection of data and background for the truck model

In order to have a reliable official comparison basis, truck calculations based on the so-called TEMA 2010 model developed for the Danish Ministry of Transport by COWI have been used as basis for the development of the truck calculation model described in this report. Systematic calculations with TEMA 2010 have been carried out by selection of different sizes and types of trucks. Both short and long articulated lorries have been investigated and the final result, of these calculations are shown in Fig. 1, showing the energy demand for the truck as function of the weight of the load carried on the truck.

A realistic but also slightly conservative curve covering the whole load range and most of the truck categories is shown in the figure and this curve is given by following equation:

Energy demand per km in MJ/km = $7.5 + 0.27 \cdot (\text{truck load in tons}) - 0.001 \cdot (\text{truck load in tons})^2$



EURO norms

During more than 20 years there have been different emission norms for heavy duty diesel engines of which many are used in trucks. In Appendix A is given an overview of the different so-called EURO norms and their implementation dates. The specific emission demands according to these norms are taken into account in the emission calculation model for trucks. Furthermore emissions results from measurements carried out by DCE - Danish Centre for Environment and Energy has been taken into account. All emission data are shown in Appendix A.

Correction for short distance driving

Using the features of the TEMA 2010 model it has been possible to calculate the extra energy demand at shorter routes between 0 and 400 km. The results of these calculations are shown in fig. 2 for 3 truck loads 5, 10 and 15 tons.

The final correction factor (red curve in Fig. 2) is given by following equation:

Correction factor = MAX[1,(If(distance<20,140-distance*1.4,If(distance<55,112-(distance-20)*0.25,If(distance<205,103.25-(distance-55)*0.015,100.7-(distance-225)*0.005))))/100]

This equation is implemented in the truck model, such that the influence of the driving distance is also taken into account in the calculation of energy demand and emissions for trucks.

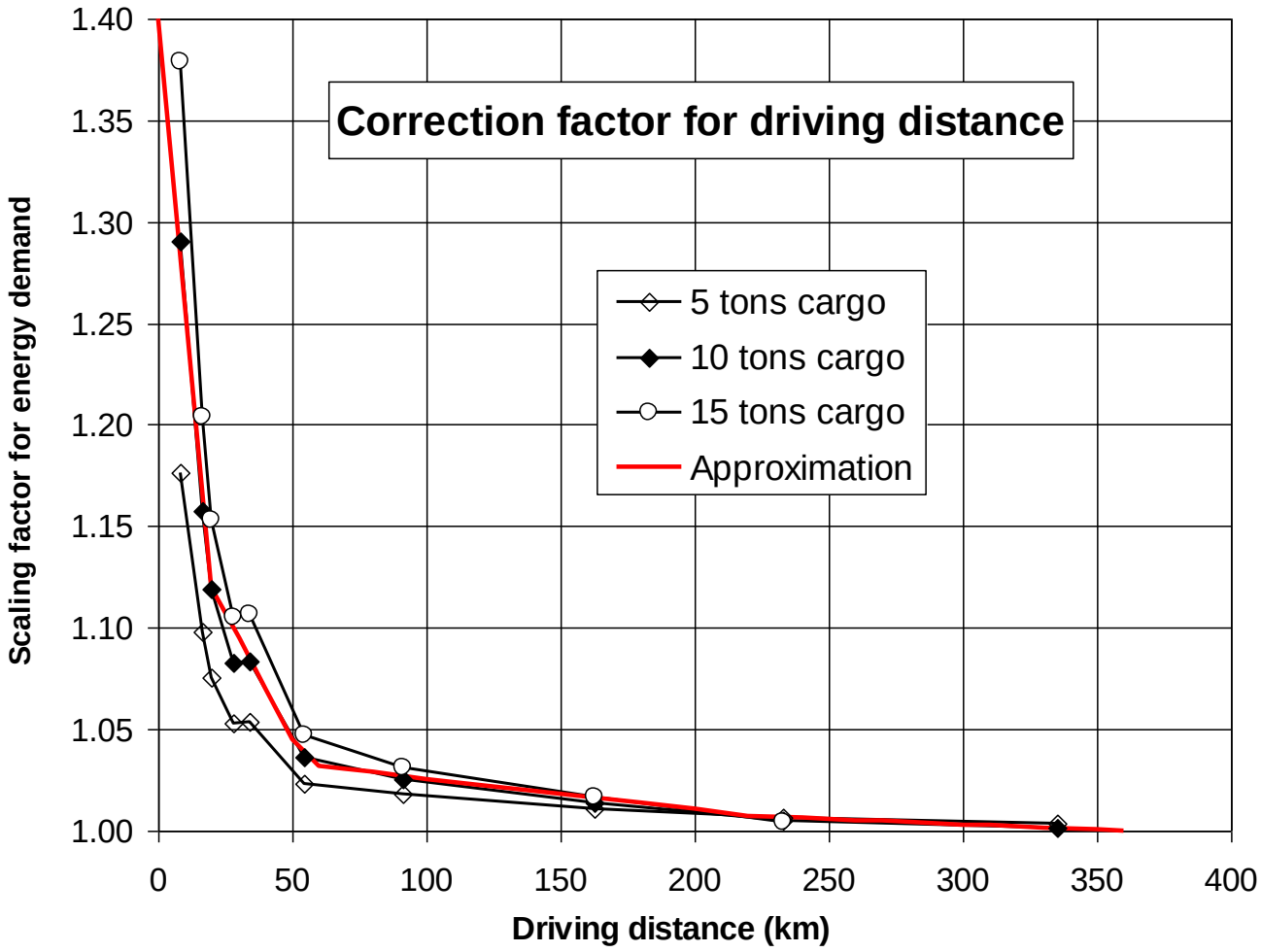


Fig. 2 Correction factor for short distance driving

Appendix A – European truck engine emission standards

https://www.dieselnet.com/standards/eu/hd.php

Emission Standards

The following tables contain a summary of the emission standards and their implementation dates. Dates in the tables refer to *new type approvals*—the dates for all vehicles are in most cases one year later.

There are two sets of emission standards, with different type of testing requirements:

- Steady-State Testing: Table 1 lists emission standards applicable to diesel (compression ignition, CI) engines only, with steady-state emission testing requirements.
- Transient Testing: Table 2 list standards applicable to both diesel and gas (positive ignition, PI) engines, with transient testing requirements.

Table 1
EU Emission Standards for Heavy-Duty Diesel Engines: Steady-State Testing

Stage	Date	Test	CO	HC	NOx	PM	PN	Smoke
			g/kWh				*1/kWh*	*1/m*
Euro I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8.0	0.612		
	1992, > 85 kW		4.5	1.1	8.0	0.36		
Euro II	1996.10		4.0	1.1	7.0	0.25		
	1998.10		4.0	1.1	7.0	0.15		
Euro III	*1999.10 EEV only*	ESC & ELR	*1.5*	*0.25*	*2.0*	*0.02*		*0.15*
	2000.10		2.1	0.66	5.0	0.10[a]		0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2.0	0.02		0.5
Euro VI	2013.01	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}	

a - PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}

Table 2
EU Emission Standards for Heavy-Duty Diesel and Gas Engines: Transient Testing

Stage	Date	Test	CO	NMHC	CH_4[a]	NOx	PM[b]	PN[e]
			g/kWh					*1/kWh*
Euro III	*1999.10 EEV only*	ETC	*3.0*	*0.40*	*0.65*	*2.0*	*0.02*	
	2000.10		5.45	0.78	1.6	5.0	0.16[c]	
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03	
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03	
Euro VI	2013.01	WHTC	4.0	0.16[d]	0.5	0.46	0.01	6.0×10^{11}

a - for gas engines only (Euro III-V: NG only; Euro VI: NG + LPG)
b - not applicable for gas fueled engines at the Euro III-IV stages
c - PM = 0.21 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}
d - THC for diesel engines
e - for diesel engines; PN limit for positive ignition engines TBD

Additional provisions of the Euro VI regulation include:

- An ammonia (NH_3) concentration limit of 10 ppm applies to diesel (WHSC + WHTC) and gas (WHTC) engines.
- A maximum limit for the NO_2 component of NOx emissions may be defined at a later stage.

Some Euro VI provisions, including OBD and certain testing requirements are phased-in by 2016/2017 (new types/all vehicles).

Test Cycles. The regulatory emission test cycles have been changed several times, as indicated in Table 1 and Table 2. Since the Euro III stage (2000), the earlier steady-state engine test ECE R-49 has been replaced by two cycles: the European Stationary Cycle (ESC) and the European Transient Cycle (ETC). Smoke opacity was measured over the European Load Response (ELR) test. The following testing requirements applied:

- Euro III: (1) ESC/ELR test for conventional diesel engines, (2) ESC/ELR + ETC testing for diesel engines with "advanced aftertreatment" (NOx aftertreatment or DPFs) and for EEVs, and (3) ETC test for positive ignition (NG, LPG) engines.
- Euro IV-V: (1) ESC/ELR + ETC testing for diesel engines, and (2) ETC test for positive ignition engines.

Since the Euro VI stage, diesel engines are tested over the WHSC + WHTC tests, while positive ignition engines are tested over the WHTC only.

Off-Cycle Testing. Euro VI regulation introduced off-cycle emissions (OCE) testing requirements. OCE measurements, performed during the type approval testing, follow the NTE (not-to-exceed) limit approach. A control area is defined on the engine map (there are two definitions, one for engines with a rated speed < 3000 rpm, and another for engines with a rated speed ≥ 3000 rpm). The control area is divided into a grid. The testing involves random selection of three grid cells and emission measurement at 5 points per cell.

In-Service Conformity Testing. Euro VI regulation also introduced in-use testing requirements that involve field measurements using PEMS. The testing is conducted over a mix of urban (0-50 km/h), rural (50-75 km/h) and motorway (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category. First in-use test should be conducted at the time of type approval testing.

Emission Durability. Effective 2005.10/2006.10, manufacturers should demonstrate that engines comply with the emission limit values for useful life periods which depend on the vehicle category, as shown in the following table.

Table 3: Truck engine emission in calculation model

Truck engine data	**EU 1996 EURO 2**	**EU 2001 EURO 3**	**EU 2006 EURO 4**	**EU 2011 EURO 5**	**EU 2015 EURO 6**
Specific oil consumption (kg/kWh)	0.20	0.20	0.20	0.20	0.20
NOx emission (g/kWh)	7.0	5.0	3.5	2.0	0.4
CO emission (g/kWh)	1.20	1.20	0.10	0.10	0.10
HC emission (g/kWh)	0.30	0.25	0.015	0.015	0.004
Particulate emission (g/kWh)	0.15	0.10	0.02	0.02	0.01
Sulphur content in oil (pct.)	0.001	0.001	0.001	0.001	0.001
SO_2 emission (g/kWh)	0.004	0.004	0.004	0.004	0.004
CO_2 emission (g/kg)	3206	3206	3206	3206	3206
NOx emission (g/kg)	35.0	25.0	17.5	10.0	2.0
CO emission (g/kg)	6.0	6.0	0.5	0.5	0.5
HC emission (g/kg)	1.50	1.25	0.075	0.075	0.02
Particulate emission (g/kg)	0.75	0.50	0.10	0.10	0.05
SO_2 emission (g/kg)	0.02	0.02	0.02	0.02	0.02
NOx emission (g/MJ)	0.82	0.58	0.41	0.23	0.05
CO emission (g/MJ)	0.14	0.14	0.01	0.01	0.01
HC emission (g/MJ)	0.035	0.029	0.00175	0.00175	0.0005
Particulate emission (g/MJ)	0.018	0.012	0.002	0.002	0.001
SO_2 emission (g/MJ)	0.0005	0.0005	0.0005	0.0005	0.0005
Calorific value for diesel oil (MJ/kg)	42.8	42.8	42.8	42.8	42.8

Table 4

Emission data (g/kg oil) from DCE - Danish Centre for Environment and Energy (2009)

	Truck capacity: 3.5 - 7.5 tons			Truck capacity: > 32 tons			DTU
NOx data	**Urban**	**Rural**	**Highway**	**Urban**	**Rural**	**Highway**	**model**
Euro 0	35.1	39.5	40.4	42.0	43.8	42.7	
Euro 1	30.3	33.3	33.2	33.6	34.6	33.8	
Euro 2	34.3	35.7	34.4	35.9	36.5	35.6	**35**
Euro 3	25.1	24.9	24.0	27.8	28.3	27.6	**25**
Euro 4	16.3	16.9	16.7	18.4	18.8	18.9	**17.5**
Euro 5	9.1	9.5	9.4	10.4	10.6	10.6	**10**
Euro 6	1.8	1.9	1.9	2.1	2.1	2.1	**2**
PM data	**Urban**	**Rural**	**Highway**	**Urban**	**Rural**	**Highway**	
Euro 0	3.004	2.523	2.119	1.738	1.626	1.609	
Euro 1	1.435	1.132	0.933	1.514	1.347	1.313	
Euro 2	0.649	0.595	0.565	0.706	0.646	0.865	**0.75**
Euro 3	0.658	0.487	0.381	0.632	0.560	0.547	**0.50**
Euro 4	0.133	0.093	0.070	0.124	0.105	0.099	**0.10**
Euro 5	0.132	0.093	0.070	0.124	0.105	0.099	**0.10**
Euro 6	0.053	0.037	0.028	0.050	0.042	0.039	**0.05**
CO data	**Urban**	**Rural**	**Highway**	**Urban**	**Rural**	**Highway**	
Euro 0	16.82	13.97	11.60	8.00	7.36	7.36	
Euro 1	6.90	5.56	5.15	7.69	7.26	7.24	
Euro 2	6.06	5.04	4.45	6.43	6.39	6.68	**6.0**
Euro 3	6.79	4.89	3.86	7.21	6.66	6.71	**6.0**
Euro 4	0.57	0.42	0.34	0.53	0.48	0.46	**0.5**
Euro 5	0.56	0.42	0.33	0.52	0.48	0.46	**0.5**
Euro 6	0.56	0.42	0.33	0.52	0.48	0.46	**0.5**
HC data	**Urban**	**Rural**	**Highway**	**Urban**	**Rural**	**Highway**	
Euro 0	14.946	9.941	5.932	2.440	1.904	1.622	
Euro 1	3.695	2.467	1.599	2.567	2.075	1.790	
Euro 2	2.519	1.630	1.031	1.677	1.341	1.124	**1.5**
Euro 3	2.132	1.385	0.845	1.424	1.140	0.991	**1.25**
Euro 4	0.089	0.056	0.037	0.077	0.064	0.059	**0.075**
Euro 5	0.089	0.056	0.037	0.077	0.064	0.059	**0.075**
Euro 6	0.026	0.016	0.011	0.022	0.018	0.017	**0.02**
SOx data	**Urban**	**Rural**	**Highway**	**Urban**	**Rural**	**Highway**	
Euro 0	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**
Euro 1	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**
Euro 2	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**
Euro 3	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**
Euro 4	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**
Euro 5	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**
Euro 6	0.020	0.020	0.020	0.020	0.020	0.020	**0.020**