LARGE DIESEL ENGINES

SYNOPSIS SHEET

Prepared in the framework of EGTEI

1. Activity description and EGTEI contribution - summary

Large diesel engines are used in three domains of activities: agriculture, industry and construction and other uses (military, household…).

The typical diesel engine used in off-road applications operates on a four-stroke cycle. Near the end of the piston compression stroke, fuel is injected into the cylinder at high pressure and mixes with the cylinder content (air + residual combustion gases + Exhaust Gas Recirculation if EGR-equipped). The period of premixing is referred to as ignition delay. Ignition delay ends when the premixed cylinder content self-ignites due to the high temperature and pressure produced by the compression stroke in a relatively short, homogenous, premixed combustion event.

When the fuel mixes with the oxygen of the compressed air, the fuel auto-ignites and the multiple flame fronts spread through the combustion chamber.

NOx, TSP and SO_2 are the main pollutants emitted by diesel engines. Due to an excess of oxygen, VOC evaporating in the combustion chamber tend to be completely burned. Incomplete evaporation and burning of the fine droplets result in emissions of the very small particles of TSP. Small amounts of lubricating oil can also participate in TSP emissions. High NOx emissions are due to high temperatures in the combustion chamber. SO_2 emission levels are proportional to the sulphur content of the fuel used. Lowering sulphur content of the fuel is necessary to implement technologies reducing TSP emissions. The only way to reduce SO_2 emissions is to reduce the sulphur content of fuels.

At a EU25 level for the year 2000 (according to the RAINS model: version CP_CLE_Aug04(Nov04)), NOx emissions were about 1,111 kt representing 15.6% of NOx emissions from mobile sources and 183.8 kt of NMVOC being about 4.2% of NMVOC emissions from mobile sources.

Large diesel engines are addressed by the European Directives 97/68/EC [1], 2000/25/EC [2], 2004/26/EC [3] and 2005/13/EC [4], related to the reduction of air emissions from the use of diesel engines rated between 18 and 560 kW. Fuels used are also regulated by the Directives 99/32/EC [5], 99/32/EC [6] and 2003/17/EC [7]. In order to be able to better represent the impact of these Directives in terms of emission reductions and costs, this sector **has been considered as an individual activity by EGTEI [8]**.

This sector was already considered as three sub-sectors in the previous version of RAINS [9] but **EGTEI has been able to develop a specific approach defined on updated sources [10], [11]. The methodology for this sector is based on the engine types considered in the Directives.** Presently, RAINS has been modified to integrate some of EGTEI proposals concerning the cost definitions [12]. Emission factors defined in the EGTEI document are based on emission limit values implemented by the Directives. **The new RAINS version was used for the modelling work carried out in the scope of the CAFÉ programme and the revision of the Gothenburg Protocol and national emission ceiling Directive.**

The representative unit used is the amount of fuel consumed annually (PJ/year). Engine's sizes are based on the definitions of the Directives. Five sizes are considered in the EGTEI document.

Abatement technologies are defined as technique mixes to reach the different emission limit values implemented by the Directives. Four different stages are taken into account in the EGTEI background document [8]. An additional one has been released in the Directive 2004/26/EC. This last one has not been covered yet by EGTEI.

EGTEI provides default emission factors (EF) with abatement efficiencies, investments as well as unit costs (€/t pollutant abated) for the different measures. No information has been found concerning variable costs (corresponding to maintenance and repair and defined as a percentage (%) of investments in RAINS).

National experts have to collect engine specific parameters (either load factor, yearly operating hours and lifetime for each category of engines or annual consumption in GJ/engine) and fuel parameters (annual fuel consumption for the 3 sub-sectors from 2000 to 2020, fuel types and fuel costs according to the year).

Even if the representation of this sector in RAINS is only partly based on the EGTEI proposal (one average engine is defined to represent each of the 3 sub-sector considered by EGTEI), it is recommended to national experts to complete the Excel spreadsheets developed by EGTEI. Indeed, very few country specific data exist for off-road sectors and if more detailed data can be provided, more realistic data (in terms of emissions, costs and control strategy) will be used in RAINS.

In the future, any new stage of the regulation should be considered with corresponding emission factors and costs. At least, the stage IV (the fifth stage of the regulation) adopted recently (after the EGTEI background document [8] was released) should be considered.

2. European regulation

Four Directives have been implemented to limit emissions of large diesel engines. They are presented in table 2.1. Emission limit values are implemented for different pollutants according to the engine's size.

Table 2.1: Scopes of the Directives

Directive References	Scope	Exemptions
97/68/EC [1]	Internal Combustion (IC) engines rated between 18 and 560 kW (i.e. industry and construction, household and gardening…)	- Ship engines - Railway locomotive engines - Aircraft engines - On-road vehicles - Agricultural and forestry tractor engines
2004/26/EC [3]	Internal Combustion (IC) engines rated between 18 and 560 kW (i.e. industry and construction, household and gardening…)	- Aircraft engines - On-road vehicles - Agricultural and forestry tractor engines
2000/25/EC [2]	Agricultural and forestry tractor engines rated between 18 and 560 kW	All other engines
2005/13/EC [4]	Agricultural and forestry tractor engines rated between 18 and 560 kW	All other engines

Spark ignition (SI) engines are also regulated as described in the Directive 2002/88/EC

Off-road fuels are most commonly supplied as heating oil quality with dye/marker, at a lower duty rate than road fuels. In some countries, road fuel quality is supplied to part or all of the non-road mobile machinery fuel market. Sulphur contents in the different types of fuels are defined in the following Directives:

Table 2.2: Regulations on sulphur content of fuels

Directive References	Scope	Exemptions
98/70/EC [5] *2003/17/EC [7]*	Quality of gasoline and diesel fuels	-
99/32/EC [6]	Sulphur content of fuels : gas-oil and heavy fuel	Diesel and gasoline as defined in Directive 98/70/CE

Table 2.3: Sulphur content of fuels: standards (ppm) implemented by the Directives

Fuels	2000	2005	2008
Diesel	350	50	10
Gas-oil and heavy fuels	2,000	2,000	1,000

3. Methodology developed within EGTEI to represent the sector

3.1 Definition of reference engines

Four engine categories are defined in the European Directives. In the EGTEI background document [8], five categories are considered: the engine category “130 to 560 kW” is split into two sub-categories (i.e. 130 to 450 kW and 450 to 560 kW) because investments are very different for these two power ranges.

Table 3.1.1: Reference engines

Reference engine code (REC)	Power range	Average rated power of reference engines
01	18-37 kW	27.5 kW
02	37-75 kW	56 kW
03	75-130 kW	102.5 kW
04	130-450 kW	290 kW
05	450-560 kW	505 kW

3.2 Definition of emission abatement techniques

3.2.1 Generalities

Controlling both TSP and NOx requires different and sometimes opposing strategies. NOx can be reduced by reducing the combustion temperatures when TSP can be reduced by higher temperatures in the combustion chamber or by faster burning. To control both NOx and TSP, manufacturers need to combine approaches using the many variables to achieve optimum performance.

SO_2 emission levels are proportional to the sulphur content of the fuel used. Lowering sulphur content of the fuel is necessary to implement technologies reducing TSP emissions. The only way to reduce SO_2 emissions is to reduce the sulphur content of fuels.

3.2.2 Aggregated measures

Measures are defined as a mix of techniques to reach the different emission limit values defined in the Directives. Technologies have been defined from the references [10] and [11].

Table 3.2.2.1: Aggregated measures

Measure codes MC	Description
00	None
01	Mix of technologies to reach Stage I emission limit values
02	Mix of technologies to reach Stage II emission limit values
03	Mix of technologies to reach Stage III A emission limit values
04	Mix of technologies to reach Stage III B emission limit values

4. Country specific data to be collected

National experts do not have to calculate emissions per vehicle category. Calculations will be done in RAINS. However, experts are requested to provide country-specific data for calculations. The formulas used and the appropriate coefficients are presented below (2 options are available):

- <u>Option I</u>: annual NOx, VOC and TSP emissions per engine can be calculated with the following equation:

$$E\ [t/y] = \text{Load Factor} \times \text{Power [kW]} \times \text{Annual use [h/y]} \times \text{Emission Factor [g/kWh]} / 10^6$$

Country specific data (engine characteristics) are required for each Reference Engine <u>for the three sub-sectors</u> (agriculture, industry and others):

- Load factor (<1 : gives the average power delivered by the engine),
- Annual use (h/y),
- Operating lifetime (year).

<u>Option II (consumption method)</u>: emission factors are expressed in g of pollutant/GJ using the engine's efficiency. This method is used to estimate emissions in RAINS because it is a simplified approach.

According to CIAM [9], <u>engine's efficiency</u> is considered to be about <u>40%</u> for diesel engines. Currently, no better data have been provided.

$$E\ [t/y] = \text{Fuel consumption [GJ/y]} \times \text{Emission Factor [g/GJ]} / 10^6$$

In this case, only the total fuel consumption and the operating lifetime per size of engines have to be provided.

Default values for all types of use are based on reference [11]. They are presented hereafter. Annual use (h/year) can be derived from the operating lifetime in hours divided by the operating lifetime in years.

Table 4.1: Default values to calculate emissions per engine

Type of engine REC	Load factor	Estimated average load [kW]	Operating lifetime (hours)
01	0.33	9.2	5,000
02	0.33	18.7	6,700
03	0.33	34.2	8,000
04	0.33	96.7	10,000
05	0.33	168.3	10,000

These data have been used to calculate annual emissions per engine and then unit costs presented in table 5.1. A lifetime of 15 years is considered for all engines.

5. Default emission factors and cost data defined with the EGTEI methodology

Table 5.1.1 gives an overview of all data provided by EGTEI: default emission factors (EF), investments as well as unit costs per t pollutant abated.

5.1 Reduction of VOC, NOx and TSP

To calculate unit costs, annual emissions per engine are first calculated with the equation given in paragraph 4. Then, total investments are annualised (taking into account a lifetime of 15 years and an interest rate of 4%) to calculate abatement costs for the three pollutants.

When the technique does not reduce a pollutant, no abatement cost is calculated.

Table 5.1.1: Emission factors (EF), investments and abatement costs for each combination

REC MC	VOC EF [g/outp.kWh]	NOx EF [g/outp.kWh]	TSP EF [g/outp.kWh]	Invest. [€/engine]	Unit costs [€/t VOC]*	Unit costs [€/t NOx]*	Unit costs [€/t TSP]*
01 00	2.91	14.36	1.80	0	0	0	0
01 02	1.50	8.00	0.80	77	1,624	360	2,289
01 03	1.00	6.50	0.60	220	3,425	832	5,451
02 00	2.28	14.36	1.51	0	0	0	0
02 01	1.30	9.20	0.85	95	1,056	201	1,568
02 02	1.30	7.00	0.40	480	5,337	711	4,712
02 03	1.00	3.70	0.40	1,035	8,811	1,058	-
02 04	1.00	3.70	0.02	4,285	-	-	31,336
03 00	1.67	14.36	1.23	0	0	0	0
03 01	1.30	9.20	0.70	185	2,493	179	1,740
03 02	1.00	6.00	0.30	1,520	11,311	906	8,149
03 03	0.50	3.50	0.30	2,450	10,440	1,125	-
03 04	0.50	3.50	0.02	6,950	-	-	28,637
04 00	1.30	14.36	1.10	0	0	0	0
04 01	1.30	9.20	0.54	510	-	139	1,284
04 02	1.00	6.00	0.20	1,725	8,106	291	2,702
04 03	0.50	3.50	0.20	2,905	5,119	377	-
04 04	0.50	3.50	0.02	9,905	-	-	12,929
05 00	1.30	14.36	1.10	0	0	0	0
05 01	1.30	9.20	0.54	890	-	140	1,287
05 02	1.00	6.00	0.20	4,585	12,373	444	4,124
05 03	0.50	3.50	0.20	7,600	7,691	567	-
05 04	0.50	3.50	0.02	14,600	-	-	10,944

* Only investments are taken into account in the calculations

5.2 Sulphur content of fuels

According to [13] low sulphur fuel will be required to meet stage III B limit values on TSP. This type of fuel is not required for 18-37 kW engines since no after-treatment device is needed. However in practice, it will be difficult to distribute two types of fuels.

The additional cost of a fuel with 10 ppm sulphur is 0.015 €/liter compared to a fuel with 1000 ppm [13] (European average value).

According to Industry, sulphur removal by itself is not enough. A full fuel modification is also required so a cost range of 0.026 to 0.029 €/litre will be incurred. Total additional cost is required.

Table 5.2.1: Additional costs for the use of low sulphur fuel

Description	Cost (€/l)
Reduction of S from 1000 ppm to 10 ppm	0.015
Full fuel modification	0.026-0.029

6. Relevance of EGTEI information for Integrated Assessment Modelling (IAM)

In the previous RAINS version [9], large diesel engines were already considered in 3 sub-categories: agriculture, construction and other engine types. The new RAINS version [12] takes into account some of the EGTEI proposals (especially on cost issues).

A simplified approach is used in RAINS due to a lack of country specific data. Detail information for off-road sectors is very difficult to find.

Only one engine category is used to represent each sub-sector: an average engine of 55 kW is defined for agriculture and 120 kW for construction. Costs are based on EGTEI proposals for these reference engines. Unabated emission factors in RAINS (g/GJ) are based on unabated EF given in EGTEI (g/kWh): the calculation is made using an efficiency of 40% for diesel engines. Specific abatement efficiencies are used in RAINS: they are based on on-road engines. Then, annual fuel consumptions (GJ/year) are defined per type of engines (agriculture, industry and other) enabling calculating unit costs for each pollutant.

Data provided by national experts at a more detail level (as defined in the EGTEI background document) will help defining more precisely the situations in each country. If national experts have more specific data, they can be used in RAINS to redefine average power rates (which will have an influence on costs) and annual fuel consumptions for the 3 sub-sectors. The control strategy in each country has also to be defined as it has a great influence on emissions. This control strategy has to be defined for the 3 sub-sectors and depends greatly on the operating lifetime of each engine types considered.

If national experts have more data, they can also review emission factors used in the RAINS model as they are calculated with an engine efficiency of 40%. This factor has a big influence on total emissions.

This is then very important for national experts to fill in EGTEI spreadsheet with detail information to facilitate the discussion during the bilateral consultations with CIAM.

7. Perspective for the future

In the future, any new regulation should be considered by EGTEI in the background document to continuously improve the sector representation. Research on country specific data such as fuel consumption per sub-sector or fleet definition (number of engines per category of power rate) could also be part of the work.

8. Bibliography

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[12] Review of data used in RAINS model http://www.iiasa.ac.at/web-apps/tap/RainsWeb/
[13] Rough cost benefit analyses of the implementation of stage III limit values on emissions from Non-road Mobile Machinery (Directive 97/68/CE). Draft 11/10/02.

ANNEXE: Example of data collection and use of EGTEI data – Case of France

A. Country specific data collection and scenarios developed

Activity levels are derived from the French national statistics on fuel consumption per sector (after a pre-treatment of the data). Fuel consumption is defined for 2 sub-sectors: agriculture and industry (the sector “other” is not considered as such in the French inventory).

Fuel consumption forecasts are based on a scenario developed by France in June 2004. This exercise is under revision for the CAFÉ programme so data presented in tables A.1 and A.2 are provisional. It appears that growth will be limited in agriculture and inexistent in industry between 2000 and 2020. These figures have not been validated by the French expert yet. For the years 2005 and 2015, average figures are taken into account.

Table A.1: Fuel consumption in agriculture (PJ / y)

Activity	2000	2005	2010	2015	2020
Diesel [PJ]	81.8	86.6	91.3	91.3	91.3

Table A.2: Fuel consumption in industry (PJ / y)

Activity	2000	2005	2010	2015	2020
Diesel [GJ]	3.1	3.1	3.1	3.1	3.1

Fuel parameters for 2000 are based on annual data provided by the French Petroleum association (UFIP). No-sulphur fuel is assumed to be used from 2015 onwards with introduction of stage IV of the regulation.

Table A.3: Fuel parameters

	2000	2005	2010	2015	2020
Sulphur content diesel (%)	0.2	0.2	0.1	0.001	0.001
Heat value of diesel [GJ/t]	42	42	42	42	42

Fuel costs should be provided by the French Ministry of economy and industry (MINEFI).

French specific data are available at different level of detail according to the sub-sector:

For the agriculture sector, the number of each engine type is known from enquiries released every 4 years. Knowing the consumption per engine (defined from engine characteristics), respective shares (PJ/y) of total activity level carried out on each reference engine from 2000 to 2020 are derived.

About 2.2% of total activity is consumed in engines with a rated power below the Directive’s threshold of 18 kW.

Table A.4: Activity levels per Reference Engine (PJ / year) in the agriculture sector

REC	2000	2005	2010	2015	2020
Under the Directive threshold	1.8	1.9	2.0	2.0	2.0
01	68.9	72.9	76.8	76.8	76.8
02	0.51	0.5	0.5	0.5	0.5
03	0.9	0.9	1.0	1.0	1.0
04	11.5	10.3	10.9	10.9	10.9
05	0	0	0	0	0
Total (PJ)	81.8	86.6	91.3	91.3	91.3

For the industry sector, as no detail is available, an average power rate between 75 and 130 kW is considered for all engines (same as in RAINS).

Table A.5: Activity levels per Reference Engine (PJ / year) of the industry sector

REC	2000	2005	2010	2015	2020
03	3.1	3.1	3.1	3.1	3.1
Total (PJ)	3.1	3.1	3.1	3.1	3.1

In the French inventory, the different pollutant emissions are calculated by using emission factors in g/GJ (calculated from emission factors in g/kWh based on the EGTEI document and the engine-specific characteristics such as the load factor, operating hours…) multiplied by the activity share corresponding to each engine type and each stage of the regulation.

Assuming a lifetime of 15 years for all engines, 6.67% of the fleet is replaced each year: new engines have to comply with the emission limit values corresponding to a given year. This makes it possible to calculate emissions from 2000 to 2020.

An example is given for the industry sector which is the simplest one (the same exercise is done for all engine categories of the agriculture sector):

Table A.6: Application rates of the different technology mixes in the industry sector (% of activity)

REC	2000	2005	2010	2015	2020
None	86.66	53.31	13.29	0	0
Stage I	13.34	26.68	26.68	6.62	0
Stage II	0	20.01	33.35	33.35	6.62
Stage IIIA	0	0	26.68	26.68	26.68
Stage IIIB	0	0	0	26.68	26.68
Stage IV	0	0	0	6.67	40.02
Total	100	100	100	100	100

At the end of 2000, 13.34% of the activity was complying with stage I which entered into force at the end of 1998 (this corresponds to 2 years x 6.67%). The same argument can be applied for all the years (stage IV will come into force at the end of 2014…).

B. Trends in emission factors and emissions

Average emission factors are derived from the shares of the different engines complying with different control stages. Average emission factors for each pollutant are given in tables B.1 and B.3. They decline as engines are more and more controlled.

Table B.1: Emission factors from the agriculture sector

REC	2000	2005	2010	2015	2020
NMVOC (g/GJ)	212.8	189.1	143.2	85.7	46.9
NOX (g/GJ)	1,323.6	1,166.2	889.8	554.7	290.1
TSP (g/GJ)	138	114.9	80.8	39.2	17.9
SO_2 (g/GJ)	95	95	48	0.5	0.5

Emissions in the agriculture sector are presented in table B.2.

Table B.2: Emissions from the agriculture sector

REC	2000	2005	2010	2015	2020
NMVOC (kt)	17.4	16.4	13.1	7.8	4.3
NOX (kt)	108.3	100.9	81.2	50.6	26.5
TSP (kt)	11.3	9.9	7.4	3.6	1.6
SO_2 (kt)	7.8	8.2	4.4	0.04	0.04

The same exercise can be done for the industry sector:

Table B.3: Emission factors from the industry sector

REC	2000	2005	2010	2015	2020
NMVOC (g/GJ)	163.6	145.1	100.1	57.7	28.5
NOX (g/GJ)	1,105.9	914.3	592.9	362.7	194.9
TSP (g/GJ)	128.6	101.1	58.8	25.9	12.8
SO_2 (g/GJ)	95	95	48	0.5	0.5

Emissions in the industry sector are presented in table B.4.

Table B.4: Emissions from the industry sector

REC	2000	2005	2010	2015	2020
NMVOC (kt)	0.50	0.44	0.31	0.18	0.09
NOX (kt)	3.4	2.8	1.8	1.1	0.6
TSP (kt)	0.39	0.31	0.18	0.08	0.04
SO_2 (kt)	0.29	0.29	0.15	0	0