Fuel use and emissions for non road machinery in Denmark 1985-2020

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Abstract

This paper explains the new Danish 1985-2020 emission inventory for non road machinery. Stock and operational data are from different statistical sources, research institutes, relevant professional bodies and machinery manufacturers. Updated fuel use and emission factors originate from various measurement programmes. Future factors are tailored to the current EU emission legislation. Beyond the basic calculation approach, the emission computations take into account the effects from engine deterioration, transient loads and gasoline evaporation. The major source of NO_x and PM emissions are diesel engines. Most of the HC and CO emissions come from gasoline machinery. From 1985 to 2020, the total fuel use and the emissions of HC, NO_x and PM decrease by 7, 43, 62 and 87%, respectively, whereas the CO emissions increase by 7%. In the forecast period from 2005-2020, the percentage NO_x and PM emission reductions are almost the same as for road traffic. For HC, the reduction percentage is somewhat smaller, whereas for CO the emission development is so poor, that non road machinery ends up being the largest source of emissions by the end of the forecast period. The availability of new non road emission factors is very useful for other European countries, and work should be done to include these data in the European EMEP/CORINAIR guidebook.
***Keys-words**: NO_x, HC, CO, PM, Diesel, Gasoline, Agriculture, Forestry, Industry, Household.*

Introduction

The emission contributions from non road mobile working machinery and equipment are significant and the non road shares of total transport NO_x, PM, HC and CO emissions where 22, 24, 29 and 36%, respectively, in 2004. Countries are obliged to make annual emission estimates for international bodies such as UNFCCC (United Nations Framework Convention of Climate Changes) and the UNECE CLRTAP (United Nations Economic Commission for Europe Convention of Long Range Transboundary Air Pollutants) conventions and the EU Monitoring Mechanism. The emission inventories for Denmark is made by the National Environmental Research Institute of Denmark (NERI).

Until now, the National Environmental Research Institute of Denmark (NERI) has used background data from separate national studies (Dansk Teknologisk Institut, 1992 and 1993; Bak et al., 2003). The reports documents an emission inventory for agricultural tractors and construction machinery (1992) and small working machinery in industry, household/gardening and recreational craft (1993). The report from Bak et al. (2003) contain updated results for the year 2000, with a special focus on agricultural machinery, fork lifts, household and gardening machinery, and recreational craft. The

NERI source for fuel use and emission factors is the European EMEP/CORINAIR guidebook (EMEP/CORINAIR, 2003). However, the relative importance of the non road emission sources and the fact that much of the operational data and fuel use/emission information is outdated, points out a strong need for a complete inventory revision.

This paper explains the new Danish fuel use and emission inventory of NO_x, HC, CO and PM for non road mobile machinery from 1985-2020. The inventory has been made in a research project upon request from the Danish Environmental Protection Agency, and detailed documentation is given by Winther et al. (2006), which also include recreational craft. In this paper, fuel use and emission results are grouped into the subsectors agriculture, forestry, industry and household/gardening (supporting national emission reports), and are further analysed by single source and as totals in cross-sectoral comparisons.

1. Method

Emission legislation and emission factors

The emission directives agreed by the EU relates to both diesel and gasoline fuelled non road machinery, and list specific emission limit values for NO_x, HC (or NO_x + HC), CO and PM. The limit values (g/kWh) depend on engine size (kW for diesel, ccm for gasoline) and date of implementation (referring to engine market date).

For diesel engines, the EU directives 97/68 (emission stage I and II) and 2004/26 (emission stage IIIA, IIIB and IV) regards non road machinery other than agricultural and forestry tractors, whereas for tractors the relevant directives are 2000/25 (emission stage I and II) and 2005/13 (emission stage IIIA, IIIB and IV). For gasoline engines, the EU directive 2002/88 (emission stage I and II) distinguishes between hand held (SH) and not hand held (NS) types of machinery.

The emission factors used in the Danish inventory are grouped into EU emission legislation categories. However, for engines older than directive first level implementation dates three additional emission level classes, <1981, 1981-1990 and 1991-stage I, are added so that a complete matrix of fuel use and emission factors underpins the inventory.

Fuel use and emission factors for stage II engines and prior technologies come from various emission measurement programmes and type approval tests (gasoline stage I and II), see IFEU (2004). The latter source also suggests factors for deterioration, transient engine loads and gasoline evaporation which are used in the present inventory.

The determination of emission factors for future diesel machinery is based on own judgement, taking into account today’s emission factors for new machinery and future EU emission legislation limits. If the emission factor constructed as 90% of the emission legislation value is higher than the stage II value, the stage II value is used. Otherwise, the 90% figure of the legislation value is used.

Table 1 shows the basis factors for fuel use, NO_x and PM in g/kWh used for diesel engines.

	Engine size [kW]	<1981	1981-1990	1991-Stage I	Stage I	Stage II	Stage IIIA	Stage IIIB	Stage IV
Fuel use	P<19	300	285	270	270	270	270	270	270
	19<=P<37	300	281	262	262	262	262	262	262
	37<=P<56	290	275	260	260	260	260	260	260
	56<=P<75	290	275	260	260	260	260	260	260
	75<=P<130	280	268	255	255	255	255	255	255
	130<=P<560	270	260	250	250	250	250	250	250
NO_x	P<19	12.0	11.5	11.2	11.2	11.2	11.2	11.2	11.2
	19<=P<37	18.0	18.0	9.8	9.8	6.5	6.2	6.2	6.2
	37<=P<56	7.7	8.6	11.5	7.7	5.5	3.9	3.9	3.9
	56<=P<75	7.7	8.6	11.5	7.7	5.5	4.0	3.0	0.4
	75<=P<130	10.5	11.8	13.3	8.1	5.2	3.4	3.0	0.4
	130<=P<560	17.8	12.4	11.2	7.6	5.2	3.4	3.0	0.4
PM	P<19	2.8	2.3	1.6	1.6	1.6	1.6	1.6	1.6
	19<=P<37	2	1.4	1.4	1.4	0.4	0.4	0.4	0.4
	37<=P<56	1.8	1.2	0.8	0.4	0.2	0.2	0.02	0.02
	56<=P<75	1.4	1	0.4	0.2	0.2	0.2	0.02	0.02
	75<=P<130	1.4	1	0.4	0.2	0.2	0.2	0.02	0.02
	130<=P<560	0.9	0.8	0.4	0.2	0.1	0.1	0.02	0.02

Table 1: Basis factors for fuel use, NO_x and PM for diesel engines (g/kWh)

In all years, most fuel is used by 75<=P<130 kW engines; in 2004 their fuel use share is 45%. However, during the inventory period relatively more and more fuel is being used by the two largest engine groups. From 1985 to 2020 their total fuel use share increase from 40 to 67%, mainly due to engine size increases for tractors and harvesters.

Table 2 shows the basis factors for fuel use, HC and CO in g/kWh used for the most commonly used gasoline engines in the inventory. Most fuel is used in the SN4 (around 50%; predominantly riders) and the SN3 (around 25%; mostly lawn movers and cultivators) groups.

	Engine type	SH/SN	Engine size [cm3]	<1981	1981-1990	1991-Stage I	Stage I	Stage II
Fuel use	2-stroke	SH2	20<=S<=50	882	809	735	720	500
		SH3	S>=50	665	609	554	529	500
	4-stroke	SH3	S>=50	496	474	451	406	406
		SN1	S<66	603	603	603	475	475
		SN3	100<=S<225	601	573	546	546	546
		SN4	S>=225	539	514	490	490	490
HC	2-stroke	SH2	20<=S<=50	305	300	203	188	44
		SH3	S>=50	189	158	126	126	64
	4-stroke	SH3	S>=50	33	27.5	22	22	22
		SN1	S<66	26.9	22.5	18	16.1	16.1
		SN3	100<=S<225	19.1	15.9	12.7	11.6	9.4
		SN4	S>=225	11.1	9.3	7.4	7.4	7.4
CO	2-stroke	SH2	20<=S<=50	695	579	463	379	379
		SH3	S>=50	510	425	340	340	340
	4-stroke	SH3	S>=50	198	165	132	132	132
		SN1	S<66	822	685	548	411	411
		SN3	100<=S<225	525	438	350	350	350
		SN4	S>=225	657	548	438	438	438

Table 2: Basis factors for fuel use, HC and CO for gasoline engines (g/kWh)

The deterioration and transient factors used are not shown. Deterioration effects are assumed for diesel machinery (all size classes) and for gasoline equipment except not hand held 4-stroke machinery. Transient factors (diesel only) are used for engines prior to stage IIIB, since the EU type approval test procedure for stage IIIB and IV takes into account transient engine loads.

For diesel engines the total impact from deterioration and transient corrections is marginal for fuel use and NO_x whereas corrected PM emissions are generally 50-60% higher than baseline emissions. The deterioration adjustment of fuel use is marginal for gasoline engines, whereas corrected HC and CO emissions are 30-50% and 60-80% higher, respectively, than the baseline emissions. The difference between baseline and adjusted emissions increase during the time period, since stage I and II deterioration factors are generally the highest.

Stock and operational data

The types of machinery comprised in the Danish non road inventory are shown in Table 3.

Sector	Diesel	Gasoline/LPG
Agriculture	Tractors, harvesters, machine pool, other	ATV's (All Terrain Vehicles), other
Forestry	Silv. tractors, harvesters, forwarders, chippers	-
Industry	Construction machinery, fork lifts, building and construction, Airport GSE, other	Fork lifts (LPG), building and construction, other
Household/ gardening	-	Riders, lawn movers, chain saws, cultivators, shrub clearers, hedge cutters, trimmers, other

Table 3: Machinery types comprised in the Danish non road inventory

For agricultural tractors and harvesters, historical fleet numbers and new sales/engine size figures are provided by Statistics Denmark (1965-1981; 2005) and The Association of Danish Agricultural Machinery Dealers, respectively. The latter organisation has also provided new sales numbers for the most important types of construction machinery. Data regarding fork lift new sales/lifting capacity are provided by The Association of Producers and Distributors of Fork Lifts in Denmark (IFAG). For household and gardening equipment, total stock numbers and engine sizes per machinery type have been established through detailed discussions with relevant professional bodies, large engine manufacturers, research institutes etc.

The engine types for which new stock data has been obtained, cover most of the fuel use and emissions from Danish non road machinery. Stock data for the remaining machinery types, and data for load factors, annual working hours and engine lifetime are repeated from the previous inventory. In some cases, however, data have been updated and/or new data added after discussions with external non road experts. Future year’s (2005+) stock data have been produced by assuming new sales or total stock data as in 2004, and engine lifetimes control the phase-out of old technology.

Figure 1 shows the stock development in emission level groups from 1985 to 2020 for the three most important types of diesel machinery and the largest single source of gasoline fuel use and emissions. For diesel tractors, harvesters and fork lifts the new sales year determines the emission level for each vehicle. For tractors and harvesters the total stock has decreased considerably since the beginning of the 1990's, due to structural changes in the agricultural sector. A gradual shift is made towards fewer vehicles with larger engines, and this trend is likely to continue in the future.

For gasoline riders (as well as for many other types of gasoline working machinery) the total stock has increased significantly in the later years, mainly because of economic growth. The stock curves for gasoline riders (and other gasoline types) appear more artificial since the only data available are total stock estimates from key experts. Subsequently, emission level distributions are made by assuming equal shares of yearly new sales during the machinery lifetime.

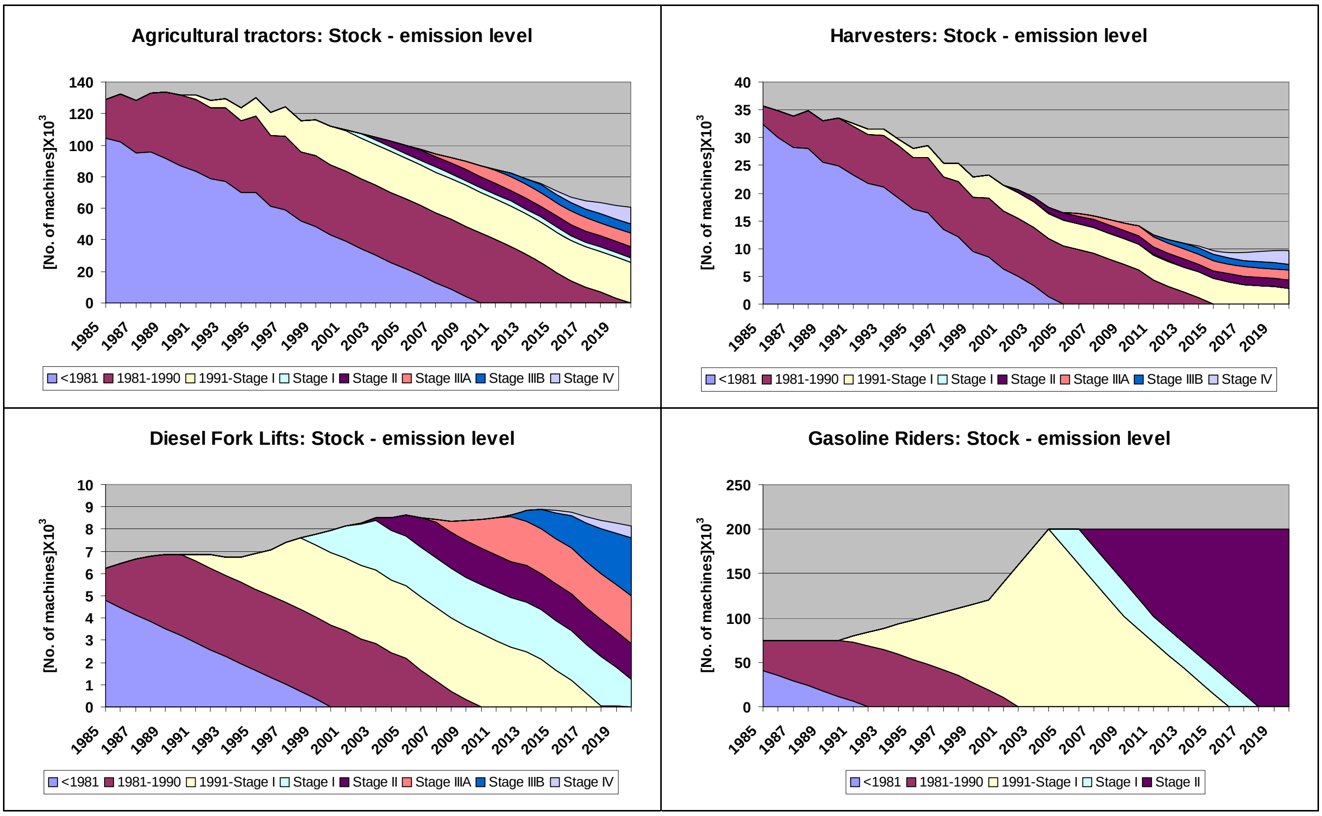

Figure 1: 1985-2020 stock per emission level for tractors, harvesters, diesel fork lifts and riders.

Calculation method

Prior to adjustments for deterioration effects and transient engine operations, the fuel use and emissions in year X, for a given machinery type, engine size and engine age, are calculated as:

$$E_{Basis}(X)_{i,j,k} = N_{i,j,k} \cdot HRS_{i,j,k} \cdot P \cdot LF_i \cdot EF_{y,z} \quad (1)$$

Where E_{Basis} = basis fuel use/emissions, N = number of engines, HRS = annual working hours, P = average rated engine size (kW), LF = load factor, EF = fuel use/emission factor (g/kWh), i = machinery type, j = engine size, k = engine age, y = engine size class and z = emission level.

The deterioration factor for a given machinery type, engine size and engine age in year X, depends on the engine size class (only for gasoline) and the emission level. The deterioration factors for diesel and gasoline 2-stroke engines are found from:

$$DF_{i,j,k}(X) = \frac{K_{i,j,k}}{LT_i} \cdot DF_{y,z} \quad (2)$$

Where DF = deterioration factor, K = engine age, LT = lifetime.

For gasoline 4-stroke engines the deterioration factors are calculated as:

$$DF_{i,j,k}(X) = \sqrt{\frac{K_{i,j,k}}{LT_i}} \cdot DF_{y,z} \quad (3)$$

No deterioration is assumed for fuel use (all fuel types) or for LPG engine emissions, and hence DF = 1 in these situations.

The transient factor for a given machinery type, engine size and engine age in year X, only rely on emission level and the load factor, and is denominated as:

$$TF_{i,j,k}(X) = TF_z \quad (4)$$

No transient corrections are made for gasoline and LPG engines, and hence $TF_z = 1$ in these cases.

The final calculation of fuel use and emissions in year X then becomes:

$$E(X)_{i,j,k} = E_{Basis}(X)_{i,j,k} \cdot TF(X)_{i,j,k} \cdot (1 + DF(X)_{i,j,k}) \quad (5)$$

The evaporation of gasoline hydrocarbon emissions is also estimated from the fuelling procedure and because of tank evaporation. The tank loading emissions are calculated as the product of total gasoline fuel use and evaporation factors (g NMHC/kg fuel), whereas tank evaporation emissions are found as the product of engine numbers and evaporation factors (g NMHC/year).

2. Results

The calculated fuel use and NO_x, HC, CO and PM emission results for 2004 are shown in Table 4 per sector and fuel type, together with the sectoral 2004-2020 percent reduction figures.

	Subsector	Fuel type	Fuel use [PJ]	NO_x [tons]	HC [tons]	CO [tons]	PM [tons]
2004	Agriculture	Diesel	13.4	11811	1367	6393	991
		Gasoline	0.3	27	362	8649	7
	Forestry	Diesel	0.2	131	11	58	7
		Gasoline	0.1	4	500	1233	6
	Industry	Diesel	11.2	9297	1297	5372	1029
		Gasoline	0.2	32	261	2116	2

		LPG	1.1	1415	164	112	5
	Household	Gasoline	4.1	317	9022	114073	87
	Total		30.5	23033	12983	138005	2135
%-change 2004-2020	Agriculture		-10	-72	-63	-42	-82
	Forestry		-4	-86	-45	-1	-49
	Industry		-3	-55	-53	-34	-70
	Household		-4	19	-34	12	3
	Total		-8	-70	-38	6	-75

Table 4: Fuel use and NO_x, HC, CO and PM emission results for 2004 (sector and fuel type) and sectoral 2004-2020 percent reduction figures.

The diesel fuelled machinery in agriculture and industry are the most important sources of fuel use and emissions of NO_x and PM in 2004. Agricultural tractors is the most dominant single source, with fuel use and NO_x and PM emission totals of around one third of the grand totals for non road machinery. Most of the HC and CO emissions come from gasoline fuelled working machinery. The largest single HC emission share is calculated for chain saws used in forestry and household/gardening (25%), and for CO the emission share for riders (private/professional) is 53%. From 1985 to 2004 the total non road fuel use and HC and PM emissions decrease by 1, 4 and 52%, respectively, whereas the emissions of NO_x and CO increase by 3%.

From 2004 to 2020, the total energy use decreases by 6% (20% for LPG, 6% for diesel, 5% for gasoline). The diesel fuel use decline is mainly due to a 16% reduction of the fuel use for tractors. This is visible from Figure 2, where the course of the fuel use curve for tractors is the result of the development towards fewer tractors, with larger and more fuel efficient engines. The main reason for the large emissions decreases for NO_x and PM are the gradually strengthened diesel emission standards during the period (Table 1). The total emission reductions from 2004 to 2020 are 63 og 72% for NOx and PM, respectively, and the largest absolute emission reductions are noted for diesel machinery in agriculture and industry.

The strengthened emission standards also cause PM emission reductions before 2004, whereas for NO_x, the general emission lift in the 1990's is caused by the somewhat higher 1990-stage I emission factors compared to older technologies, for the engine size groups with large fuel consumptions.

The growth in gasoline fuel use is 39% from 1985 to 2004, and is more powerful after 2000, especially due to the increased use of riders (Figure 2). The fuel use by lawn movers and chain saws is smaller, significant fuel use inclines are, however, also noticed for these machinery types after 2000. From 1985-2004 an almost total phase out of the use of gasoline fuelled tractors is also expected. After 2004, the gasoline fuel use is almost constant since total stock figures and operational data remain unchanged in the forecast period. Though, the 5% reduction in gasoline fuel use from 2004 to 2020, is the benefit from the improved fuel efficiency for 2-stroke engines.

CO and HC emissions predominantly come from gasoline engines, and between 1985 and 2004 their gradual emission factor improvements (Table 2) more than outbalances the emission deterioration, giving smaller growth rates for emissions compared to fuel use. This is also the case for riders where significant emission increases are found. Between 2004 and 2020, the total emissions of HC and CO decrease by 41% and increase by 4%, respectively (Table 4). Small or zero emission factor reductions for stage I and II engines in combination with higher deterioration factors cause the CO emissions for gasoline machinery to increase even after the time of stage I (2005) and II (2007) engines entering the market (most visible for riders). For HC, the same explanation applies for chain saw and lawn mover stage I engines; their emissions continue to increase until the emission efficient stage II engine technology enter into the market in 2008.

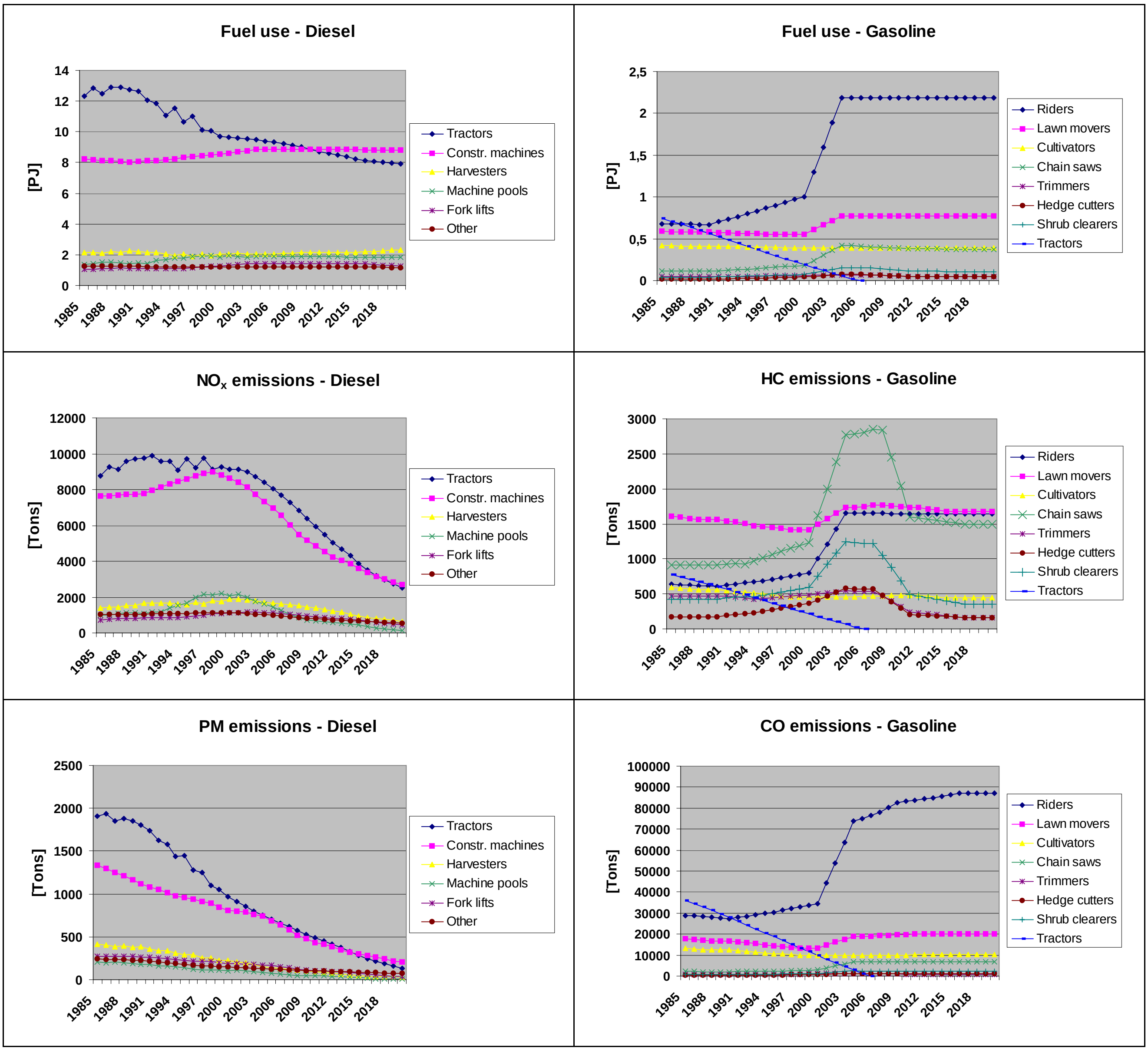

Figure 2: 1985-2020 Fuel use and emissions of NO_x, PM, HC and CO in sub sectors of diesel and gasoline non road machinery in Denmark

In 2004, the fuel use estimate obtained with the new model becomes 10% bigger, compared to the previous model estimate. This is due to an increase of around 300% in the calculated gasoline fuel use. For HC and CO, the new results become 9 and 74% higher, whereas the NO_x and PM emissions become 21 and 22% lower, respectively, than previous model results. The model differences for HC and CO are due to the large gasoline fuel use increase in the new model, since the derived HC and CO emission factors are somewhat lower. The reason for the NO_x and PM differences are the generally lower emission factors in the new model.

Figure 3 shows the total Danish NO_x, PM, HC and CO emissions from mobile sources in the forecast period 2005-2020. In the beginning of the forecast period non road machinery is the second largest emission source, in all four cases. The largest emission decreases are expected for NO_x and PM. Here the non road emissions reduce by 61 and 71%, respectively, from 2005 to 2020, due to the gradually strengthened diesel emission standards (Table 1). The non road emission reductions are almost the same as for road transport, (69 and 77% respectively, for NO_x and PM), and the emission contributions from both sectors become smaller than for internal marine (national sea transport, small boats, fishing vessels). This occurs in 2008 for non road NO_x, and by the end of the forecast period for PM and road traffic NO_x.

The reduction percentage for non road HC emissions are somewhat smaller (40%), whereas for CO the emission development is so poor, that non road machinery ends up being the largest source of emissions after 2015. This is due to small or zero CO emission factor reductions for stage I and II engines (Table 2) and higher deterioration factors for the same emission technology levels.

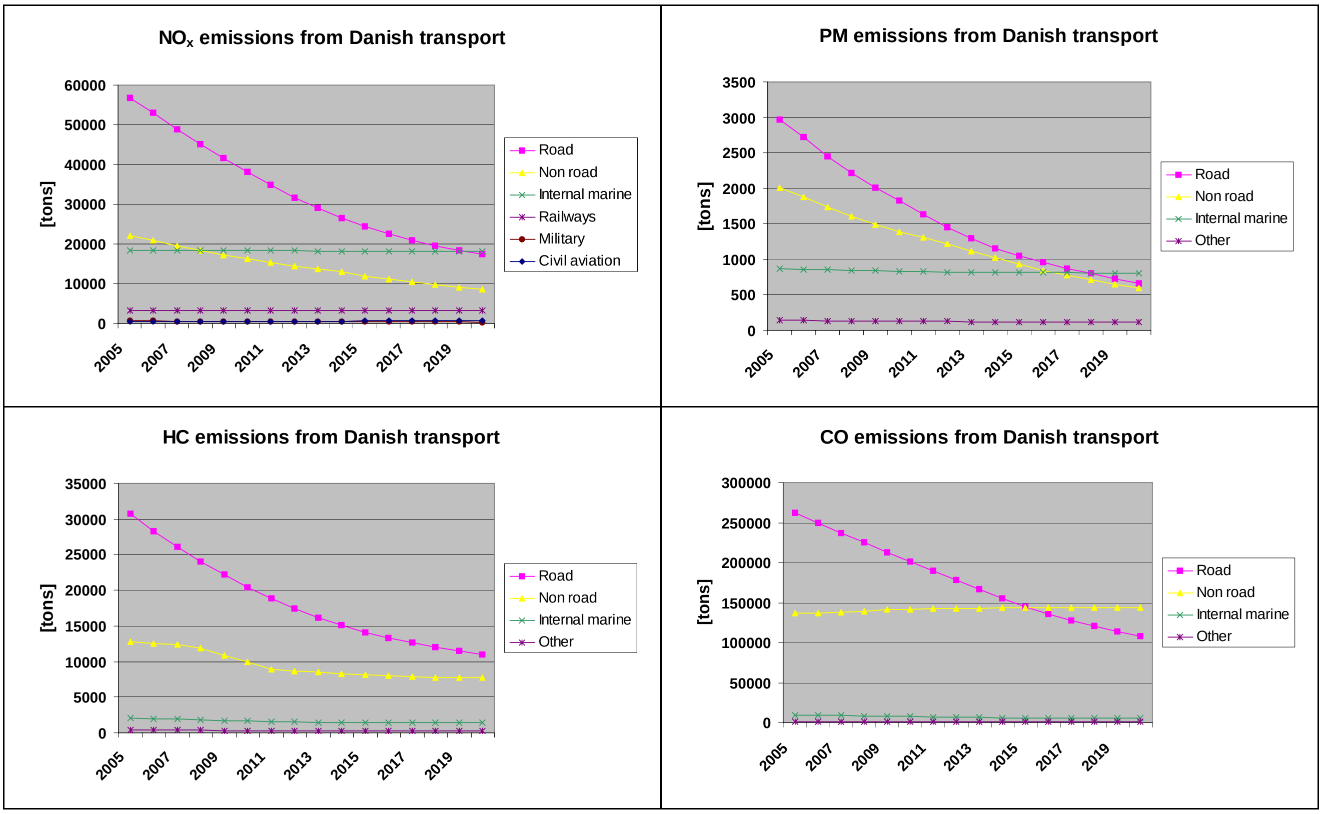

Figure 3: Total Danish NO_x, PM, HC and CO emissions from mobile sources from 2005-2020.

3. Conclusion

The trends in fuel use and emissions rely on the development in stock numbers, operational data and the estimated fuel use and emission factors. From 1985 to 2020, the total fuel use and the emissions of HC, NO_x and PM are expected to decrease by 7, 43, 62 and 87%, respectively. For CO, the emissions are expected to increase by 7%. In 2004, the fuel use estimate obtained with the new model becomes 10% bigger, compared to the previous model estimate. For HC and CO, the new results become 9 and 74% higher, whereas the NO_x and PM emissions become 21 and 22% lower, respectively, than previous model results. In the forecast period from 2005-2020, the non road NO_x and PM emission reductions are almost the same as for road transport. The emission reduction for non road HC are somewhat smaller, whereas for CO the emission development is so poor, that from 2015, non road machinery becomes a larger emission source than road traffic.

This project has added new important knowledge in terms of stock and operational data, fuel use and emission factors, and total fuel use and emissions for non road machinery and recreational craft in Denmark. Moreover, the project has fostered contacts to Danish statistical experts, research institutions, different professional bodies, large engine manufacturers etc. The new non road model sets up experimental data and future EU emission legislation limits in a data matrix which underpins the calculation of fuel use and emissions, and in addition the model output fulfils the international emission reporting format.

On a European level, the purpose of the European EMEP/CORINAIR guidebook is to provide inventory support for country estimates, however, for non road machinery the guidebook data are more than ten years old. Consequently there is an urgent need for new data which is clearly demonstrated by the present work, looking at the differences in old and new estimates for Denmark. The fuel use and emission data used in the German inventory (IFEU, 2004) and in the present Danish inventory are able to cover the data need, and work should therefore be done to include these data in the EMEP/CORINAIR guidebook.

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