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The emission consequences of using biodiesel and bio ethanol as a fuel for road transport in Denmark

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Abstract

This article explains the emission consequences of using biodiesel and bio ethanol as a fuel for road transport in Denmark calculated in the REBECa project. For the years 2004, 2010, 2015, 2020, 2025 and 2030, two fossil fuel baseline scenarios (FS) are considered characterised by different traffic growth rates. For each FS, two biofuel scenarios (BS1, BS2) are considered with a 5.75 % biodiesel/bio ethanol share in 2010 as a common starting point. From 2010, linear growths are assumed for BS1 (10 % in 2020) and BS2 (25 % in 2030).

The emissions presented in this study are vehicle based; a separate Well to Wheels (W-t-W) assessment of the total emission consequences of producing and using biofuels has been conducted in a different part of REBECa. The maximum CO_2 emission difference between FS and BS2 becomes 26 % in 2030. The NO_x and VOC emission variations between FS and both biofuel scenarios are 3 % or less. For CO and TSP the largest emission differences, 5 % and -12 %, respectively, occur between the FS and BS2 scenarios in 2030. The biofuel emission impacts are insignificant for NO_x,VOC, CO and TSP compared to the generally large emission reductions predicted in all scenarios driven by the gradual strengthened emission standards for new vehicles, by far outweighing the emission influence from biofuels and traffic growth.

The emission estimates for NO_X, VOC, CO and TSP presented in this study are less certain than for CO_2 due to the relatively scarce biofuel emission data implemented in the calculations. As a consequence, the obtained emission results must be assessed with care. Bearing in mind these uncertainties, the calculation approach for emissions from biofuel usage presented in this study can be used as a tool to carry out sensitivity analysis, environmental impact assessment studies, or for research purposes as such.

1. Introduction

The introduction of biofuels is seen as a very important measure to reduce the emissions of greenhouse gases from road transport; first of all because direct CO_2 emissions from biofuels used in the transport sector are regarded as CO_2 neutral fuels (EU Directive 2009/28/EC). Total direct CO_2 emission consequences of introducing biofuels depend on the amount of transport. This, together with fuel efficiency of vehicles, total vehicle fleet and composition with regard to age and size and decisions about the biofuel share of fuel consumption determines the direct CO_2 reduction potential.

In Denmark the biofuel target for the transport sector in Denmark is 5.75 % in 2010 (phased in until 2012). In 2020, 10 % of the energy consumption in the transport sector is to be covered by renewable energy, including biofuel. This is the background for the multi-disciplinary integrated impact assessment project 'Renewable Energy in the transport sector using Biofuels as an Energy Carrier' (REBECa), which was finalised recently. The aims of REBECa was to assess the impact on emissions, air quality and human health as well as resource and land-use change, and to consider economic and sociological aspects of the future use of biodiesel and bio ethanol in Danish road transport. The project period was 2007–2010.

An important task in REBECa was to estimate the fuel consumption and emissions for two fossil fuel based baseline scenarios (FS) for Danish road transport, characterised by different traffic growth rates. For each of the baseline scenarios, two biofuel scenarios (BS1 and BS2) were considered with different penetration rates of biodiesel and bioethanol. Fuel consumption and emission calculations of CO_2, SO_2, NO_x, TSP, CO and VOC were made for the baseline year 2004, and the scenario years 2010, 2015, 2020, 2025 and 2030.

The purpose of the present paper is to describe the emission inventory and the calculated results. A short methodology description will be given in terms of fleet specific mileage data, baseline emission factors, biofuel emission difference functions and calculation method. In the results part, baseline emission results will be given in time-series. Further, comparisons will be made for the baseline and biofuel scenarios in the discrete scenario years in order to assess the emission impact of biofuel usage. Selected emission results are also displayed on GIS maps for Denmark.

Increased consumption of biofuels also has indirect emission consequences related to the full chain of production, distribution and combustion of biofuels. The indirect consequences of re-allocating society's scarce resources are best analysed within an integrated Life Cycle and Well-to-Wheel (LCA/W-t-W) framework (e.g. Menichetti & Otto, 2008; UNEP, 2009; Hoefnagels et al., 2010; Londo et al., 2010; Whitaker et al., 2010). In another part of REBECA, a W-t-W assessment of the total emission consequences of producing and using biofuels is made, where it is combined with a welfare economic cost benefit analysis to assess the consequences for society's welfare of the different biofuel scenarios (Slentø et al., 2010). The main conclusions from this study with regard to CO_2 emissions are presented in the discussion part of this paper.

2. Activity data

2.1 Total mileage data

The mileage forecast used in the REBECa project is prepared by DTU Transport in Denmark. The mileage forecast which is based on an oil price of $65 pr barrel of oil (Fosgerau et al., 2007), is also used as an input to the Danish Infrastructure Commission (2008). Due to the very high oil prices in 2008 and the latest estimate of $100-120 pr barrel for the future oil price from IEA, an alternative mileage scenario for the REBECa project is also calculated by DTU Transport, based on an oil price of 100$ pr barrel. A documentation of the mileage forecast is given by Jensen and Winther (2009).

In order to make sufficiently detailed fuel consumption and emission estimates in REBECa, the DTU mileage figures must be grouped into vehicles with the same average fuel consumption and emission behaviour; the so-called layers. An internal model developed by DCE (Winther, 2008; Nielsen et al., 2009) uses a layer structure and calculation methodology similar to the model structure of the European emission calculation model COPERT (Table 1). The layer splits are made according to fuel type, engine size/weight class and EU emission legislation levels.

Table 1 - Model vehicle classes and sub-classes used in the emission model.

Veh. category	Fuel type	Engine size/weight	EU emission levels
Cars	Gasoline	< 1.4 l.	5 conv.; Euro 1-6
Cars	Gasoline	1.4 – 2 l.	5 conv.; Euro 1-6
Cars	Gasoline	> 2 l.	5 conv.; Euro 1-6
Cars	Diesel	< 2 l.	1 conv.; Euro 1-6
Cars	Diesel	> 2 l.	1 conv.; Euro 1-6
Cars	LPG		1 conv.; Euro 1-6
Cars	2-stroke		1 conv.
Vans	Gasoline		1 conv.; Euro 1-6
Vans	Diesel		1 conv.; Euro 1-6
Trucks	Gasoline		1 conv.
Trucks	Diesel	3.5 – 7.5 tonnes	1 conv.; Euro I-VI
Trucks	Diesel	7.5 – 16 tonnes	1 conv.; Euro I-VI
Trucks	Diesel	16 – 32 tonnes	1 conv.; Euro I-VI
Trucks	Diesel	> 32 tonnes	1 conv.; Euro I-VI
Urban buses	Diesel		1 conv.; Euro I-VI
Coaches	Diesel		1 conv.; Euro I-VI
Mopeds	Gasoline		1 conv.; Euro I-II
Motorcycles	Gasoline	2 stroke	1 conv.
Motorcycles	Gasoline	< 250 cc.	1 conv.; Euro I-III
Motorcycles	Gasoline	250 – 750 cc.	1 conv.; Euro I-III
Motorcycles	Gasoline	> 750 cc.	1 conv.; Euro I-III

Figure 1 shows the layer split of DTU mileage forecast, aggregated from engine size (cars) and weight class (trucks) though.

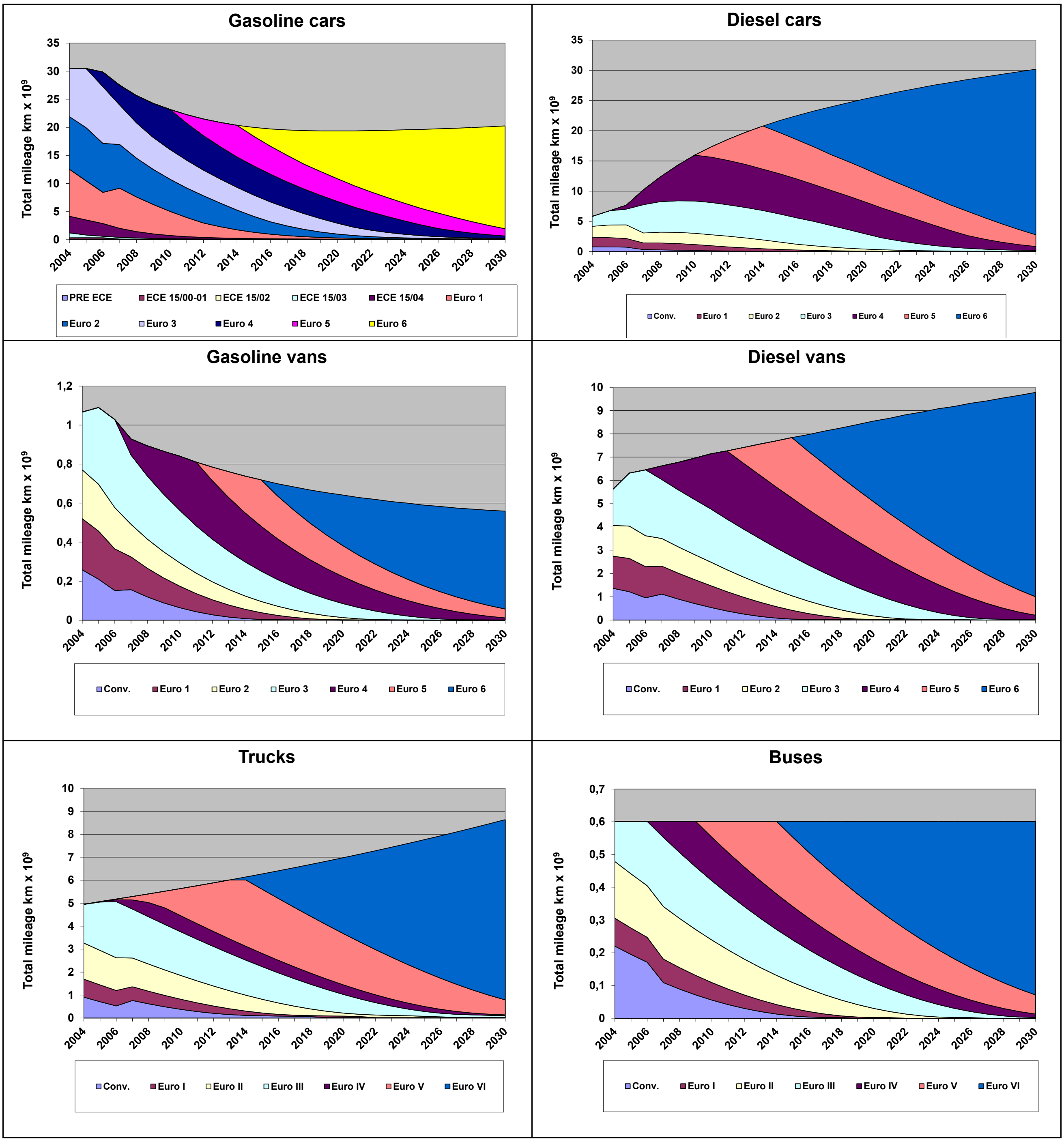


Figure 1 - Layer distribution of total mileage pr vehicle type in 2004-2030 (65 $ scenario)

2.2 Energy input data

BS 1 assumes an energy share of biodiesel and bio ethanol of 5.75 % in 2010, followed by a linear growth to 10 % in 2020, and with constant levels in the following years. In BS2 the biofuel share is also 5.75 % in 2010 and subsequently the biofuel share grows linearly to 25 % in 2030. For biodiesel full miscibility is assumed, whereas for bioethanol the definition is to use a 5 % mix by volume of bioethanol in the standard gasoline fuel (E5), and let the surplus of ethanol available be used by FFV's (Flexible Fuel Vehicles) running on E85 (85 vol % ethanol + 15 % gasoline).

By taking into account the differences in fuel density, ρ, and lower heating values (LHV) between fossil based fuels and biofuels[1], by simple transformation (Winther, 2010) the volume based biofuel percentage, $B\%_V$, and the resulting LHV's can be derived for the 2010-2030 scenario period for diesel-biodiesel and separately for E5/E85 (Figure 2).

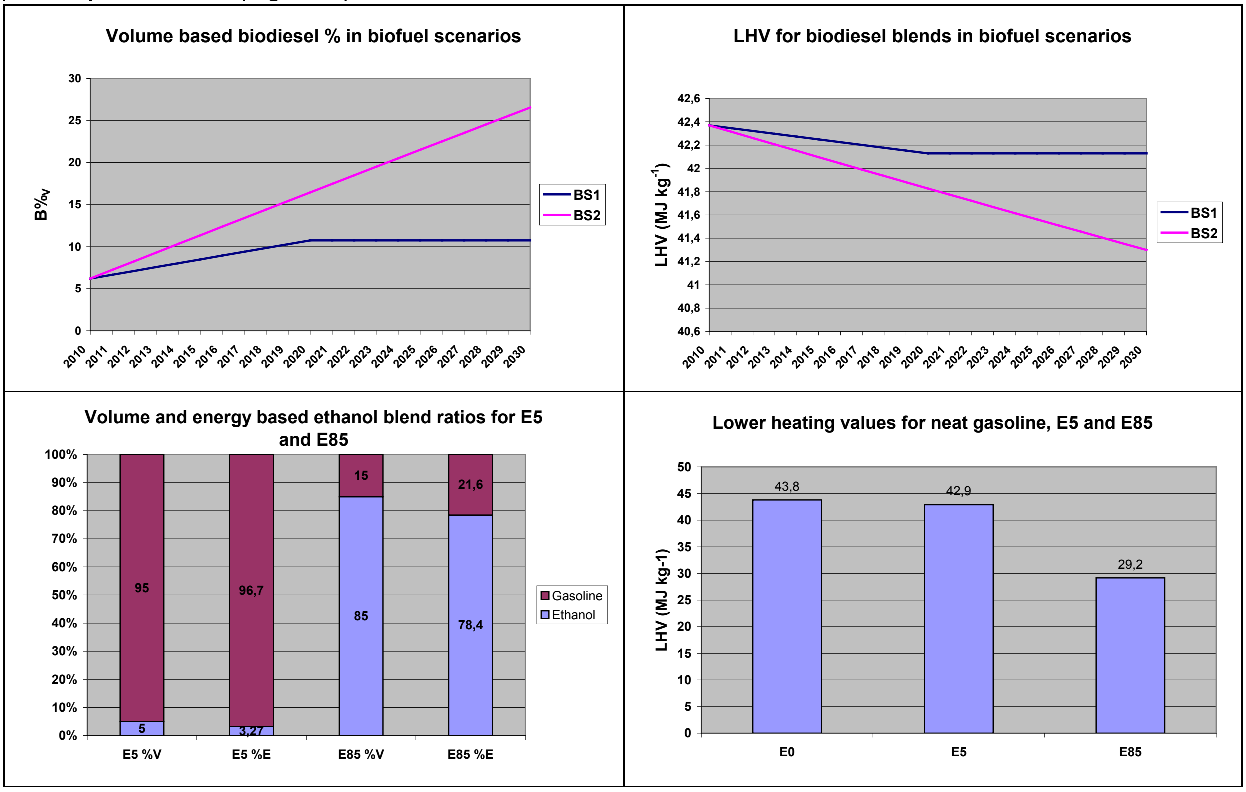


Figure 2 - Volume based biofuel % and lower heating values for biodiesel blends and E5/E85 in main scenarios

3. Fuel consumption and emission factors

3.1 Baseline fuel consumption and emission factors

For the baseline scenarios, fuel consumption and emission factors used in the calculation model come from the COPERT model version IV (EMEP/EEA, 2009). The COPERT model is a well established European road transport emission model used by many researchers, advisory companies and national inventory compilers in Europe and in the rest of the world to set up emission inventories at different geographical scales. Further COPERT IV is used as an emission data source for more targeted environmental impact assessment studies. In Denmark, COPERT model is also the emission data source for the national emission inventories reported annually.

Due to the very detailed COPERT fleet classification and the further split of mileage into driving situations, the number of emission factors is very big and hence it is not possible to show the emission factors in full details[2]. Figure 3 presents the layer specific NO_x (except diesel cars) and TSP (except gasoline cars) emission factors for gasoline and diesel cars, trucks and buses, which underpin the emission discussions in Section 6.

As engines become more modern the emission factors tend to decrease, in line with the gradually strengthened EU emission legislation standards. For gasoline cars the introduction of gradually improved catalytic converters from Euro 1 onwards has decreased the NO_x emission factors significantly. The low IV

[1] LHV (diesel[a], biodiesel[b], gasoline[a], bio ethanol[a]): 42.7, 37.6, 43.8, 26.7 MJ/kg; [a]) DEA (2008), [b]) Teknologirådet (2006) P (diesel, biodiesel, gasoline, bio ethanol): 0.84, 0.88, 0.75, 0.79 kg/l; DEA (2008)

[2] The fuel consumption and emission factors depend on vehicle category, fuel type, engine size or weight class, EU emission level and road type. For cars/vans, cold start influence the fuel consumption and CO, VOC, NO_x and TSP emissions. For gasoline catalyst cars/vans, catalyst wear has an impact on the CO, VOC and NO_x emissions

emission factors for trucks and buses have been reached by a combination of precise engine combustion control (TSP) and exhaust after treatment (NO_x). The very low TSP emission factors for Euro 5+ diesel cars and Euro VI trucks and buses are achieved with the use of particulate filters.

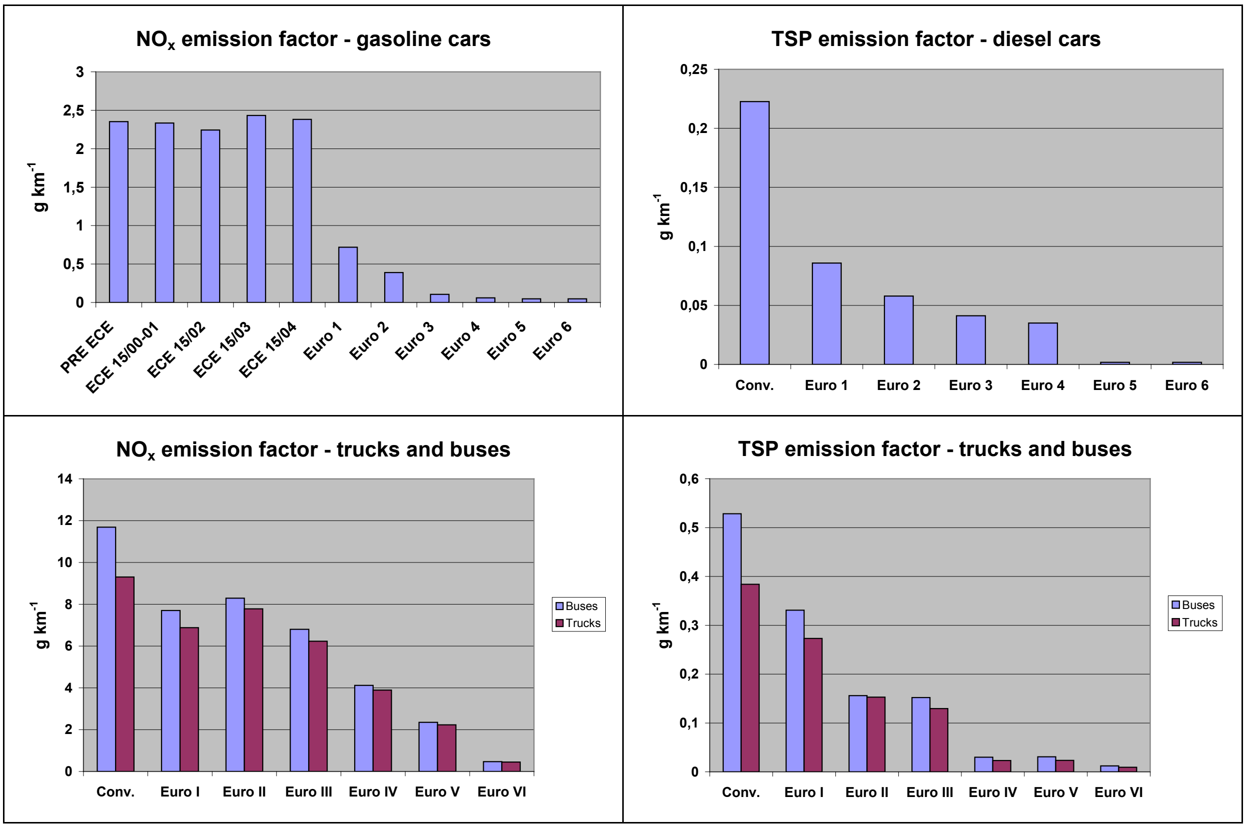


Figure 3 - Layer specific NO_x and TSP emission factors per vehicle category (emission data from the COPERT model)

3.2 Fuel consumption and emission factor changes as a function of blend ratio

For Euro 0-III heavy-duty engines the changes in fuel consumption and NO_x, PM, CO and VOC emissions as a function of the volume based biofuel percentage ($B\%_V$), is based on the findings from EPA (2002). The data from the latter source is also used for the future Euro VI engine technology, as assumed by Winther (2009). For Euro IV and V engines, the experimental basis behind the curves is measurement results from McCormick et al. (2005). The fuel consumption and the Euro 0-III/Euro IV-V emission curves for NO_x and PM are shown in Figure 4. For neat biodiesel, the CO*[VOC]* % emission changes are -48*[-67]* and -40*[-25]*, for Euro 0-3 and Euro IV-V, respectively.

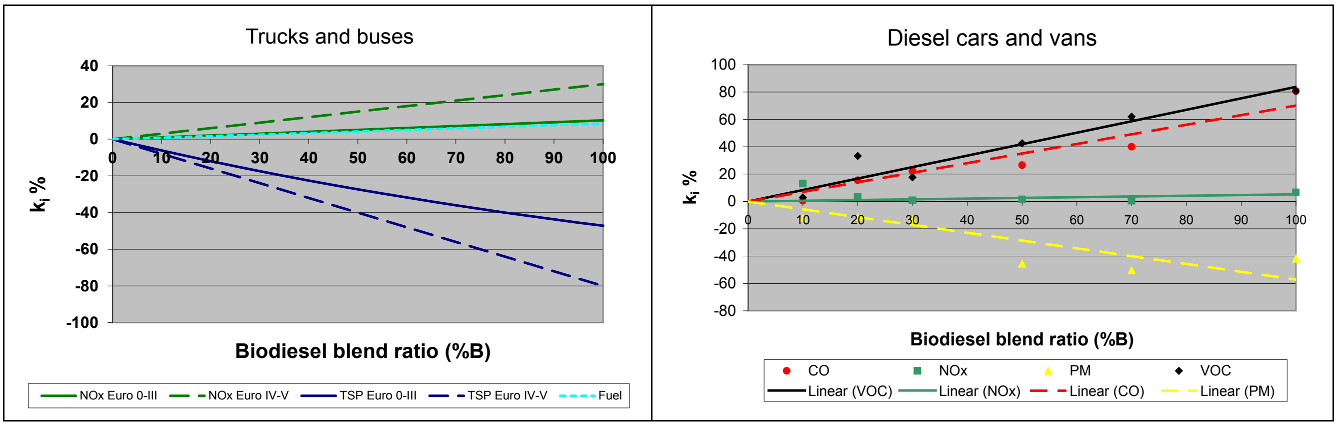


Figure 4 - Fuel consumption/emission changes (function of B%) for heavy-duty engines and diesel cars/vans

In the case of passenger cars and vans, average emission differences for B10, B20, B30, B50, B70 and B100 are calculated based on the results from four experimental studies (Martini et al. (2007a); Fontaras et al. (2007, 2008); Durbin et al. (2007)), see Winther (2009). The emission differences expressed as linear functions of $B\%_V$ are shown in Figure 4 for NO_x, CO, VOC and PM. For fuel consumption the relative changes were not derived explicitly for passenger cars and vans, due to lack of data. For these vehicle types, instead the general relations for heavy-duty vehicles are used. This decision is discussed in Winther (2009).

Table 2 shows the fuel consumption and emission changes and biofuel percentages (% energy and mass) as a function of the volume based biofuel percentage ($B\%_V$).

Table 2 - Fuel consumption and emission changes, and energy/mass biofuel %, as a function of $B\%_V$.

								$k_i(B\%_V)$				$k_{fc}(B\%_V)$
Main scenario	Forecast year	Veh. Category	Tech.	$B\%_E$	$B\%_V$	$B\%_M$	LHV	$NO_x\%$	CO%	VOC%	TSP%	FC%
BS1	2010	Cars/vans	All	5.75	6.20	6.48	42.37	0.32	4.41	5.33	-3.67	0.51
BS1	2010	Trucks/buses	Euro 0-III	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
BS1	2010	Trucks/buses	Euro IV-V	5.75	6.20	6.48	42.37	1.86	-2.48	-1.55	-4.96	0.51
BS1	2010	Trucks/buses	Euro VI	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
BS1	2015	Cars/vans	All	7.88	8.48	8.85	42.25	0.44	6.04	7.28	-5.01	0.70
BS1	2015	Trucks/buses	Euro 0-III	7.88	8.48	8.85	42.25	0.83	-5.41	-9.06	-5.27	0.70
BS1	2015	Trucks/buses	Euro IV-V	7.88	8.48	8.85	42.25	2.54	-3.39	-2.12	-6.78	0.70
BS1	2015	Trucks/buses	Euro VI	7.88	8.48	8.85	42.25	0.83	-5.41	-9.06	-5.27	0.70
BS1	2020	Cars/vans	All	10.00	10.75	11.20	42.13	0.56	7.65	9.23	-6.36	0.88
BS1	2020	Trucks/buses	Euro 0-III	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
BS1	2020	Trucks/buses	Euro IV-V	10.00	10.75	11.20	42.13	3.22	-4.30	-2.69	-8.60	0.88
BS1	2020	Trucks/buses	Euro VI	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
BS1	2025	Cars/vans	All	10.00	10.75	11.20	42.13	0.56	7.65	9.23	-6.36	0.88
BS1	2025	Trucks/buses	Euro 0-III	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
BS1	2025	Trucks/buses	Euro IV-V	10.00	10.75	11.20	42.13	3.22	-4.30	-2.69	-8.60	0.88
BS1	2025	Trucks/buses	Euro VI	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
BS1	2030	Cars/vans	All	10.00	10.75	11.20	42.13	0.56	7.65	9.23	-6.36	0.88
BS1	2030	Trucks/buses	Euro 0-III	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
BS1	2030	Trucks/buses	Euro IV-V	10.00	10.75	11.20	42.13	3.22	-4.30	-2.69	-8.60	0.88
BS1	2030	Trucks/buses	Euro VI	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
BS2	2010	Cars/vans	All	5.75	6.20	6.48	42.37	0.32	4.41	5.33	-3.67	0.51
BS2	2010	Trucks/buses	Euro 0-III	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
BS2	2010	Trucks/buses	Euro IV-V	5.75	6.20	6.48	42.37	1.86	-2.48	-1.55	-4.96	0.51
BS2	2010	Trucks/buses	Euro VI	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
BS2	2015	Cars/vans	All	10.56	11.35	11.83	42.10	0.59	8.08	9.74	-6.71	0.93
BS2	2015	Trucks/buses	Euro 0-III	10.56	11.35	11.83	42.10	1.12	-7.18	-11.93	-6.99	0.93
BS2	2015	Trucks/buses	Euro IV-V	10.56	11.35	11.83	42.10	3.40	-4.54	-2.84	-9.08	0.93
BS2	2015	Trucks/buses	Euro VI	10.56	11.35	11.83	42.10	1.12	-7.18	-11.93	-6.99	0.93
BS2	2020	Cars/vans	All	15.38	16.45	17.10	41.83	0.85	11.71	14.13	-9.73	1.36
BS2	2020	Trucks/buses	Euro 0-III	15.38	16.45	17.10	41.83	1.62	-10.23	-16.82	-9.97	1.36
BS2	2020	Trucks/buses	Euro IV-V	15.38	16.45	17.10	41.83	4.94	-6.58	-4.11	-13.16	1.36
BS2	2020	Trucks/buses	Euro VI	15.38	16.45	17.10	41.83	1.62	-10.23	-16.82	-9.97	1.36
BS2	2025	Cars/vans	All	20.19	21.52	22.31	41.56	1.12	15.31	18.48	-12.72	1.78
BS2	2025	Trucks/buses	Euro 0-III	20.19	21.52	22.31	41.56	2.13	-13.17	-21.41	-12.84	1.78
BS2	2025	Trucks/buses	Euro IV-V	20.19	21.52	22.31	41.56	6.46	-8.61	-5.38	-17.21	1.78
BS2	2025	Trucks/buses	Euro VI	20.19	21.52	22.31	41.56	2.13	-13.17	-21.41	-12.84	1.78
BS2	2030	Cars/vans	All	25.00	26.54	27.46	41.30	1.38	18.89	22.79	-15.69	2.20
BS2	2030	Trucks/buses	Euro 0-III	25.00	26.54	27.46	41.30	2.63	-15.98	-25.71	-15.59	2.20
BS2	2030	Trucks/buses	Euro IV-V	25.00	26.54	27.46	41.30	7.96	-10.62	-6.64	-21.23	2.20
BS2	2030	Trucks/buses	Euro VI	25.00	26.54	27.46	41.30	2.63	-15.98	-25.71	-15.59	2.20

To characterise the energy consumption and emission factor differences between neat gasoline and E5 and E85, respectively, average differences are calculated by Winther et al. (2012) from eight European studies (E5: Martini et al. (2007b), Delgado (2003), Hull et al. (2005); E85: de Serves et al. (2005), Westerholm et al. (2008), Martini et al. (2009), Pelkmans et al. (2010), AVL MTC (2011)[3]). In the experiments using E85 fuels, the base fuel was E5[4]. However, noting the small average differences between neat gasoline and E5 - and due to lack of experimental data for modern European cars using neat gasoline and E85 - the E5 vs. E85 differences are used in REBECa for the neat gasoline vs. E85 case as well. This decision is discussed in more details by Winther (2012).

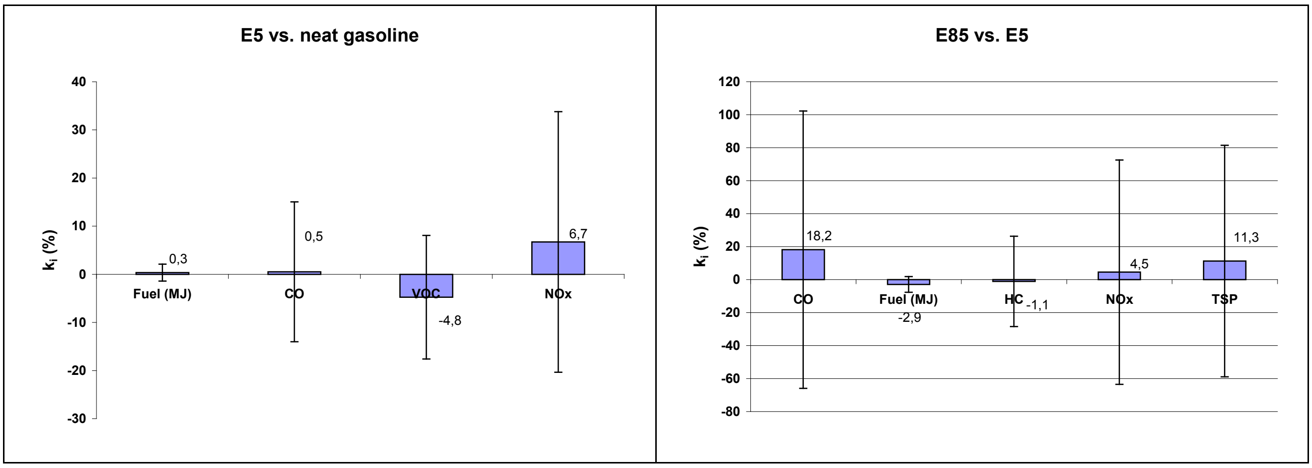


Figure 5 - Fuel consumption and emission changes for neat gasoline and E5/E85 for gasoline cars and vans

4. Fuel consumption and emission calculations

For each inventory year and vehicle layer, fuel consumption and emissions are calculated as the product of fuel consumption/emission factors and total mileage (Figure 1). The emissions are calculated as:

$$E_{i,j,y} = emf_{i,j,y} \cdot (100 + k_i(B\%_V))/100 \cdot M_{j,y} \quad (1)$$

E = emission (tons), emf = emission factor (g/km), k_i = emission change function, i = emission component, $B\%_V$ = vol. based biofuel % (Fig. 2), y = year, j = layer, M = total mileage (mio km; Fig. 2).

The fuel consumption by energy for diesel-biodiesel is calculated as:

$$E_{i,j,y} = fc_{M,B0} \cdot LHV(B\%_V) \cdot (100 + k_{fc}(B\%_V))/100 \cdot M_{j,y} \quad (2)$$

E = Energy consumption (GJ), fc_M = fuel consumption factor (g/km), LHV = lower heating value (MJ/kg; Fig. 2), k_{fc} = fuel consumption change function (Fig. 4).

The fuel consumption by energy for E5/E85 is calculated as:

$$E_{i,j,y} = fc_{M,E0} \cdot LHV_{E0} \cdot (100 + k_{fc}(E\%))/100 \cdot M_{j,y} \quad (3)$$

E = Energy consumption (GJ), $fc_{M,E0}$ = fuel consumption factor for neat gasoline (g/km), LHV_{E0} = lower heating value for neat gasoline (MJ/kg; Fig. 2), E% = E5/E85, k_{fc} = energy consumption change function (Fig. 5).

[3] AVL MTC emission test data for 17 FFV vehicles expanded the emission database after REBECa was finalised
[4] From 2011, E5 is the baseline fuel quality in Denmark.

According to the guidelines for United Nations Framework Convention on Climate Change (UNFCCC) and the UNECE Convention on Long Range Transboundary Air Pollutants (CLRTAP) reporting, the biofuel part of the combusted fuel is regarded as CO_2 neutral. By following this definition, the CO_2 emissions are calculated as the product of the energy related emission factor for CO_2 (kg/GJ) and the fossil part of total energy consumption (Eq. 2/3; Fig. 2).

For bioethanol it is assumed that in 2010 FFV's that belong to the most modern Euro layer for gasoline cars (Euro 4) uses the amount of ethanol not being used as E5 blends by gasoline vehicles as such. In 2015 the share of Euro 4 vehicles being FFV's is maintained, hence assuming approximately the same rate of scrapping of vehicles irrespective of technology. Further, the remaining ethanol surplus is assumed to be used by the most modern Euro classes in 2015 (Euro 5 and 6). This step wise ethanol allocation principle is used for the years 2020, 2025 and 2030 also.

4. Fuel consumption and emission results

5.1 Total fuel consumption and emissions

The calculated totals for fuel consumption, CO_2, NO_x, TSP, CO and VOC are shown in Table 1 for the baseline (FS) and biofuel (BS1, BS2) scenarios based on the 65 $ and 100 $ mileage forecasts, respectively.
The total mileage increase is higher for the 65 $ forecast than for the 100 $ forecast and this is also reflected in the calculated results.

Table 1 - Fuel consumption and emission results for the baseline and biofuel scenarios calculated in the present study

		Mileage forecast: 65 $						Mileage forecast: 100 $					
Scenario	Year	Energy PJ	NO_x Tons	VOC Tons	CO Tons	CO_2 kTons	TSP Tons	Energy PJ	NO_x Tons	VOC Tons	CO Tons	CO_2 kTons	TSP Tons
FS	2004	164.8	75960	29470	200099	12114	2854	164.8	75960	29470	200099	12114	2854
FS	2010	178.8	60389	16824	116153	13170	2297	161.1	56186	15431	103520	11868	2087
FS	2015	190.4	44868	10957	70500	14035	1430	169.0	40830	10142	63007	12460	1279
FS	2020	204.8	29011	8364	48727	15101	847	180.0	25866	7785	43766	13268	750
FS	2025	220.0	18959	7155	39462	16220	465	191.3	16593	6638	35341	14105	410
FS	2030	235.5	14197	6566	36135	17370	304	202.7	12244	6046	32071	14946	267
BS1	2010	178.5	61301	16408	116654	12387	2216	160.8	57006	15061	103923	11162	2013
BS1	2015	189.8	45548	10787	70983	12889	1361	168.5	41446	9991	63402	11444	1217
BS1	2020	204.0	29510	8325	49353	13534	797	179.2	26313	7749	44293	11893	706
BS1	2025	219.0	19280	7167	40147	14538	439	190.5	16874	6648	35925	12644	388
BS1	2030	234.5	14406	6595	36855	15568	289	201.8	12424	6071	32688	13397	253
BS2	2010	178.5	61301	16408	116654	12387	2216	160.8	57006	15061	103923	11162	2013
BS2	2015	189.6	45699	10795	71124	12498	1338	168.3	41586	9995	63517	11098	1197
BS2	2020	203.5	29714	8367	49697	12694	770	178.8	26498	7784	44583	11156	683
BS2	2025	218.0	19517	7280	40891	12831	414	189.6	17084	6745	36560	11161	366
BS2	2030	233.0	14599	6782	38016	12884	267	200.5	12591	6231	33682	11091	235

In the case of CO_2, the FS baseline emissions become significantly higher than the emissions estimated for BS1 and BS2, and most markedly for the most ambitious BS2 case. This is clear from the relative emission changes between 2004 and 2030; for FS, BS1 and BS2 (results in brackets) these figures become [43 %, 28 %, 6 %] and [23 %, 10 %, -9 %], for the 65 $ and 100 $ mileage forecast, respectively. Of course, this result is due to according to conventional inventory guidelines, biofuels are regarded as CO_2 neutral for exhaust emissions (vehicle based emissions). However, even if the CO_2 consequences of all activities within the entire W-t-W chain from agricultural production to manufacturing, distribution and engine combustion of the biofuel are included, the total CO_2 emissions will in most cases decrease, see (Slentø et al., 2010).

For each mileage case and for each of the remaining emission components/fuel consumption, the calculated changes between 2004 and 2030 become very similar for FS, BS1 and BS2. For FS, the following differences are calculated for fuel consumption, NO_x, TSP, CO and VOC in the 65 \$[100 \$] mileage case; 43 %[23 %], -81 %[-84 %], -89 %[-91 %], -82 %[-84 %] and -78 %[-79 %]. The percentage differences between FS and the BS1/BS2 scenarios are shown in section 5.3 (Table 6), and more thoroughly discussed in this part of the paper.

5.2 Fuel consumption and emissions for the baseline scenarios

For the 65 \$ mileage forecast the calculated results are shown per vehicle category in Figure 6. For the 100 \$ mileage forecast, the emission trends are similar, the total emissions however being somewhat lower due to a smaller traffic growth throughout the forecast period (c.f. Table 1).

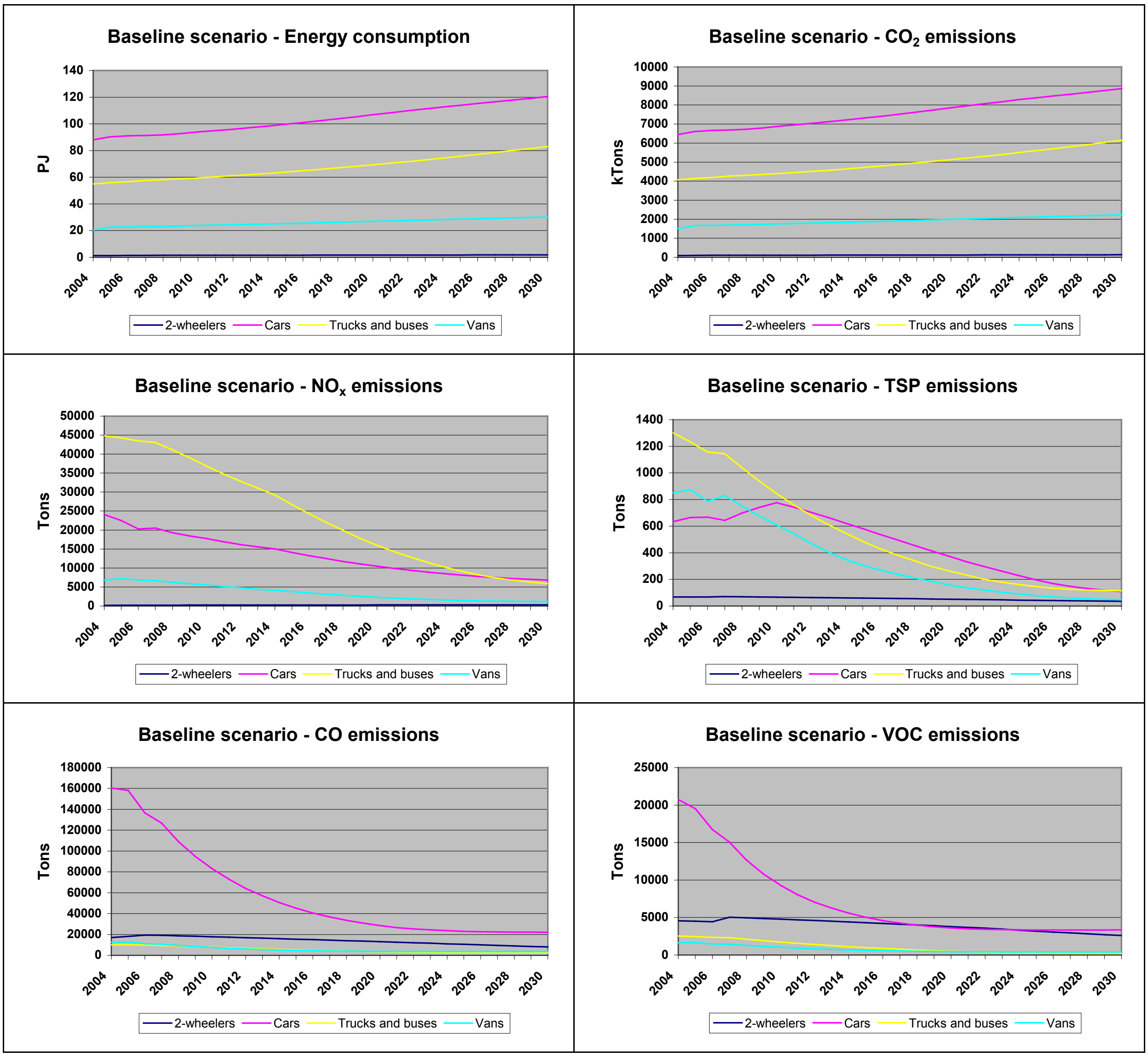


Figure 6 - Total energy consumption and emission results per vehicle type for the baseline scenario 2004-2030

In general, the emission development for the different vehicle categories is explained by the development in vehicle mileage and the layer specific emission factors. Significant emission reductions are noted for the combustion related emissions of NO_x, TSP, CO and VOC. The emission impact from the gradual strengthened emission standards for new sold vehicles is greater than the emission impact from traffic growth during the forecast period.

The fuel consumption and CO_2 emissions increase by 43 % from 2004 to 2030. Cars is the most important source followed by trucks/buses and vans. The emission increase is highest for trucks/buses and vans, 51 % and 48 %, respectively, due to a larger traffic growth for trucks and diesel vans in particular (Figure 1).

For NO_x and TSP, the total emissions decrease by 81 % and 89 %, respectively, from 2004 to 2030. Trucks and buses as a single group, and cars, are the most important sources of NO_x and TSP emissions. Trucks and buses have the highest NO_x*[TSP]* emissions until 2027*[2012]*, from this year onwards cars becomes the largest emission source. For cars, the NO_x*[TSP]* emissions decrease of 72 %*[83 %]*, are somewhat smaller than the total emission decline due to a gradually larger share of diesel cars expected in the future vehicle fleet.

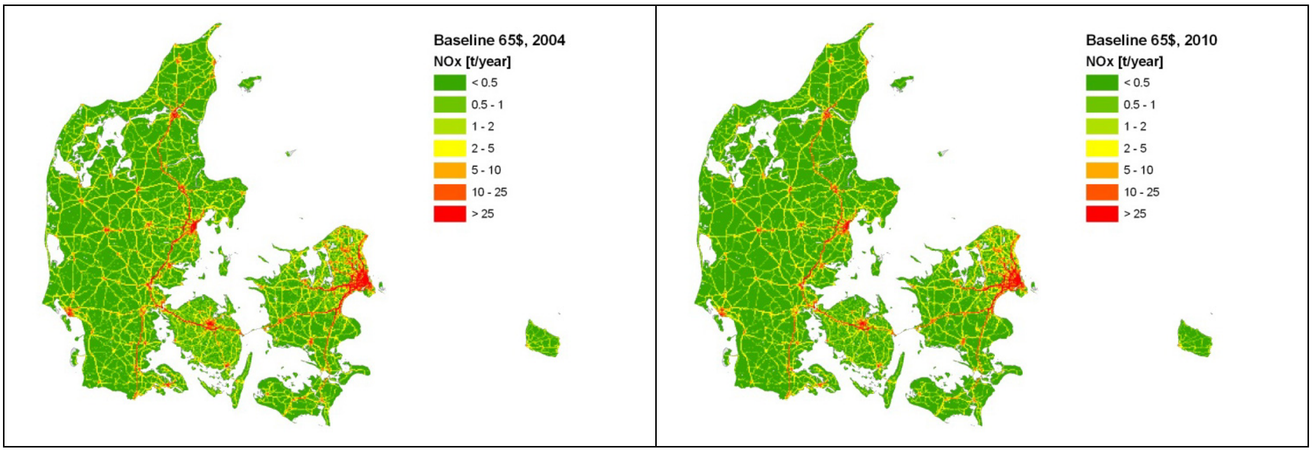
The total CO and VOC emissions decrease are 82 and 78%, respectively, in the same time period. For VOC, the relative emission importance of 2-wheelers becomes large due to less stringent emission legislation standards for these vehicle types compared to the remaining vehicle categories.

The particulate emissions from the wear of brakes, tyres and road asphalt (non exhaust emissions) are shown in Table 2. The non exhaust emissions increases correspond with the increase in traffic. This emission development is in opposition to the exhaust related particulate emissions which are being reduced as a result of the introduction of improved emission reduction technologies. Hence, for the TSP, PM_{10} and $PM_{2.5}$ size fractions, the non exhaust emission shares of total road transport particulate emissions significantly change from 47 %, 37 % and 24 % in 2004, to 93 %, 89 % and 81 % in 2030.

Table 2 - Non exhaust emission totals for the 65 $ and 100$ mileage forecast

Mileage forecast: 65 $				Mileage forecast: 100 $			
Year	TSP Tons	PM_{10} Tons	$PM_{2.5}$ Tons	Year	TSP Tons	PM_{10} Tons	$PM_{2.5}$ Tons
2004	2556	1644	895	2004	2556	1644	895
2010	2836	1825	994	2010	2566	1651	899
2015	3060	1969	1072	2015	2726	1754	955
2020	3312	2131	1160	2020	2917	1877	1021
2025	3575	2300	1252	2025	3112	2002	1089
2030	3846	2474	1346	2030	3308	2128	1158

The spatial distribution of the road transport NO_x emissions are shown in Figure 7 for the 65 $ baseline scenario, as an example. The step wise emission reductions from 2004, 2010, 2020 and 2030 are clearly visible from the maps. The spatially distributed emission results are further used as input for air dispersion modelling purposes, subsequently carried out in REBECa.



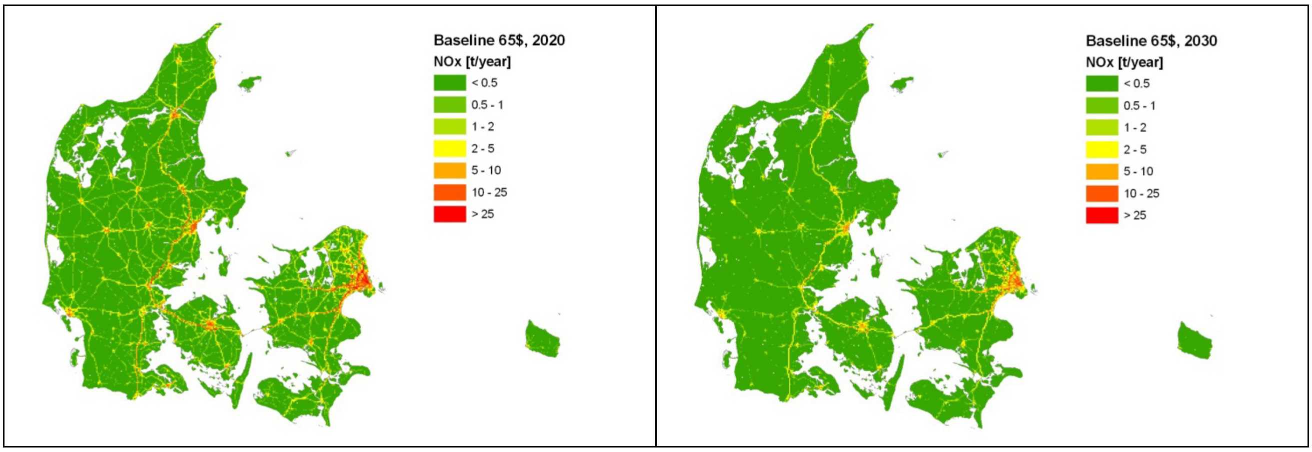


Figure 7 - Baseline NO_x emissions for Danish road transport in 2004, 2010, 2020 and 2030

5.3 Fuel consumption and emissions differences between baseline and biofuel scenarios

In relation to the following Figures 8-10, some of the most important fuel consumption and emission differences between the 65 $ baseline scenario and the most ambitious biofuel scenario, BS2, are explained in the following. The trend and emission difference explanations given for the 65 $ forecast results, are valid for the 100 $ forecast also. In the latter case the emission levels are only somewhat lower due to less mileage in the underlying traffic forecast.

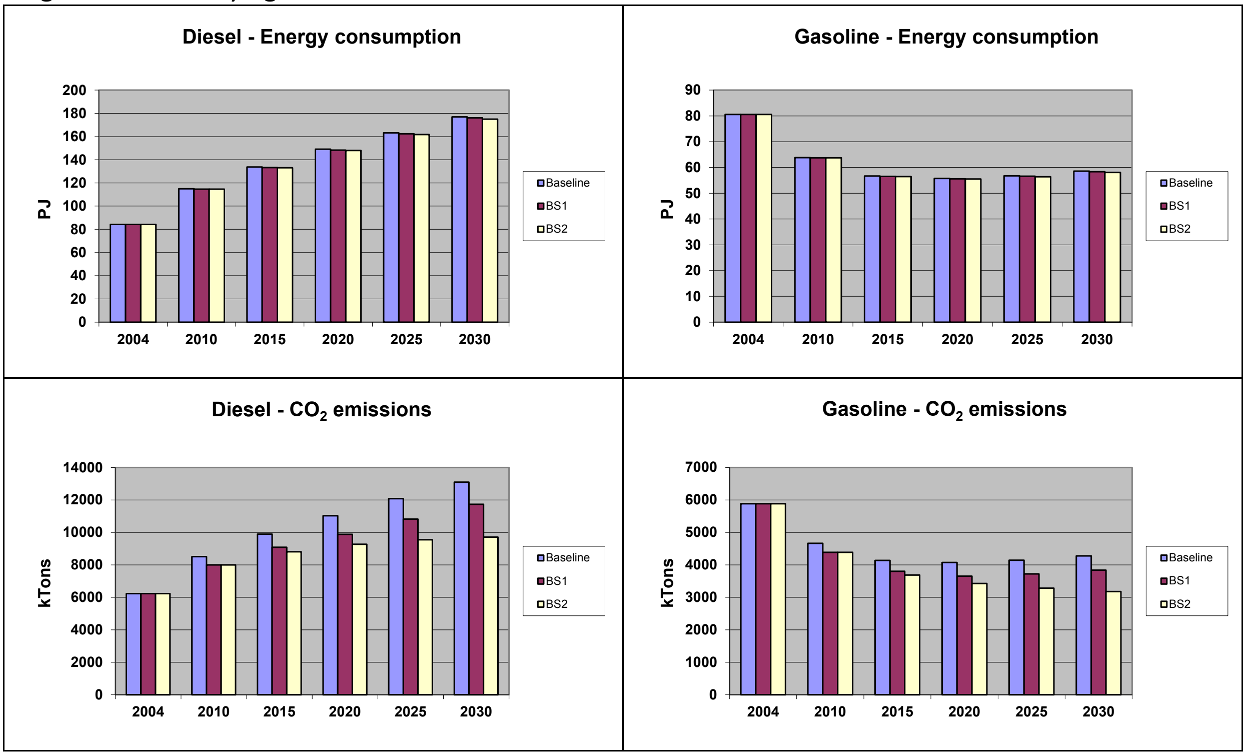


Figure 8 - Baseline, BS1 and BS2 energy consumption and CO_2 emission results per fuel type in the scenario years

As shown in Figure 8, the consumption of gasoline decreases until 2020, whereas an increase in the diesel consumption is expected during the entire forecast period, due to the envisaged dieselification of the car fleet in the future. For the individual scenario years small fuel consumption declines (c.f. Table 3 below) are calculated due to the small improvement in thermal efficiency for the engines using biofuel at different blend ratios.

For CO_2 the same trends are visible for the baseline scenario as for fuel consumption. For the biofuel scenarios the growth in CO_2 emissions from diesel vehicles become smaller than the growth in fuel consumption, and for gasoline vehicles direct emissions decline are noted for BS2 during the forecast period. As mentioned above, the reason is that according to conventional inventory guidelines, biofuels are regarded as CO_2 neutral for exhaust emissions (vehicle based emissions).

For the important NO_x sources trucks and buses (c.f. Section 5.2), the emissions are shown on Figure 9, for BS2 as totals as well as the absolute changes between BS2 and the baseline scenario. Please note the significant scaling difference for the secondary axis between BS2 totals and BS2/baseline changes; the latter emission changes are small and in relative terms the highest calculated emission penalties never exceed 4.5 % being calculated for 2027.

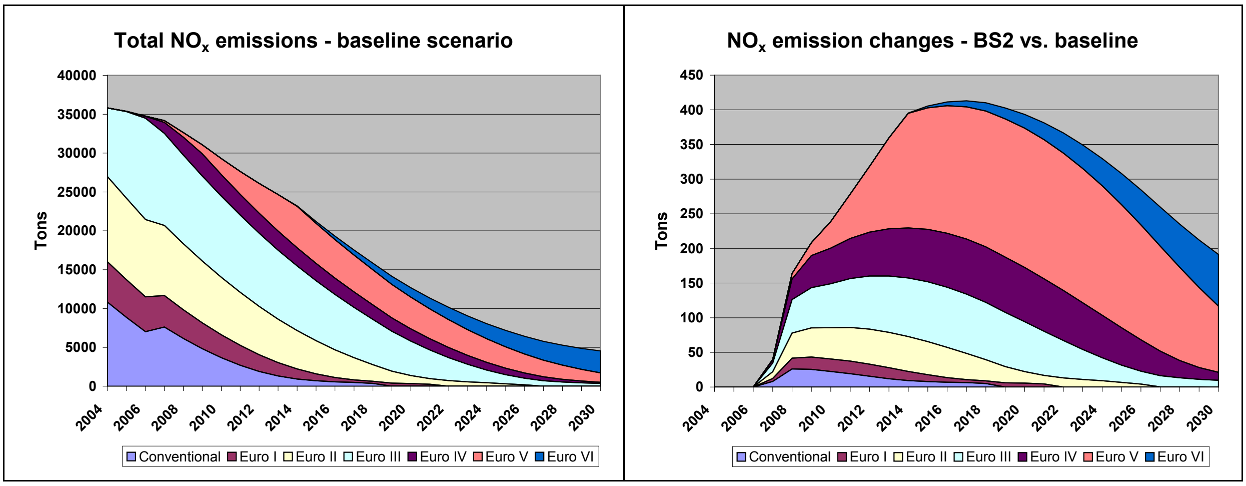


Figure 9 Layer distributions of NO_x emissions for trucks and buses for the baseline and BS2 scenarios

From a maximum NO_x emission difference in 2017 corresponding to a biofuel share of 12.5 % (Figure 2), the emission penalties shown in Figure 9 gradually become smaller as total emissions decrease further until 2030. This decrease in total emissions have a much higher impact on the calculated emission penalties than the increasing emission factor differences between neat diesel and biodiesel (Figure 4), for biofuel shares going up to 25 % in 2030.

From 2012 onwards, the largest part of the extra emissions of NO_x due to biofuel usage is calculated for Euro V vehicles, which have the highest emission factor changes (Figure 4). As years pass, the emission importance for Euro V vehicles becomes less and less important due to their decreasing mileage (Figure 1). In 2030, the NO_x emission factor differences become 8 % and 2.6 %, respectively, for Euro V and VI vehicles (Figure 4). However, by the end of the forecast period the latter vehicle group comprise by far most of the mileage being driven with trucks and buses.

From 2012 diesel cars become the largest source of TSP emissions (Figure 6). For this vehicle type, the total emissions are shown in Figure 10 for the baseline scenario and BS2. The expected emission savings gradually increase to 16 % in 2030, as predicted by the emission factor differences between neat diesel and biodiesel in Figure 4 for diesel cars as such. However, due to the trade-off between these latter emission factor differences and the total emissions calculated in the baseline scenario, the maximum absolute emission savings are reached already in 2016 (57 tons) and by 2030 the annual emission savings have reduced to 22 tons.

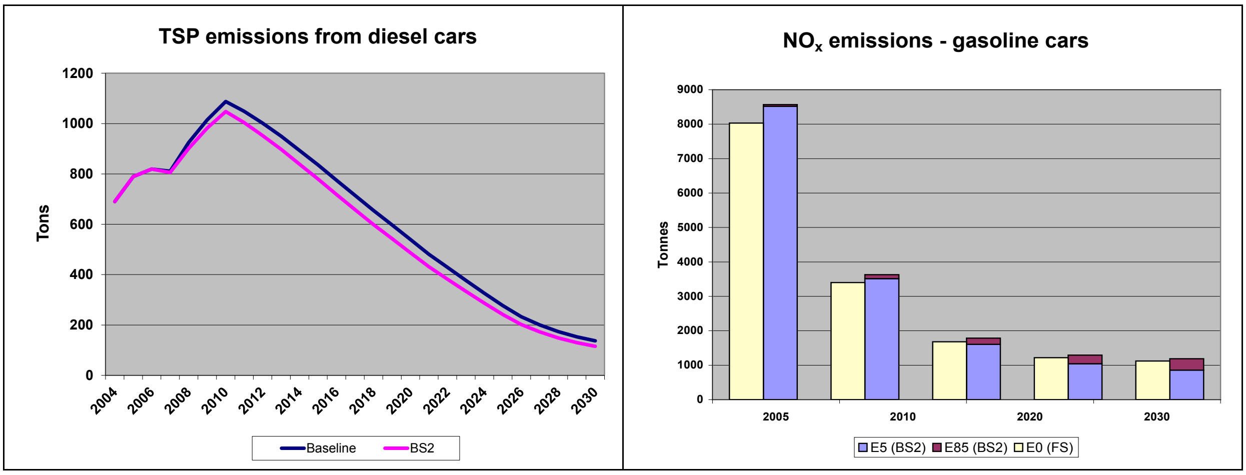


Figure 10 TSP emissions for diesel cars and NO_x emissions for gasoline cars for the baseline and BS2 scenarios, 65 $ mileage forecast

For gasoline cars, the NO_x emissions are shown in Figure 10 for the baseline scenario and BS2. The emissions decrease significantly throughout the forecast period due to gradually lower NO_x emission factors (Figure 5), and total mileage reductions until 2020 (Figure 1). Being based on the emission factor differences in Figure 5, the relative emission differences between neat gasoline and the use of E5 and E85 is expected to be small. The largest emission penalty is calculated for 2010 (537 tons), and the smallest emission penalty reaches 68 tons in 2030.

The summary Table 3 shows the percentage differences between baseline and biofuel scenario 1 and 2 for fuel consumption and emissions calculated in REBECa.

Table 3 - Fuel consumption and emission percentage differences between baseline and biofuel scenario 1 and 2

		Mileage forecast: 65 $									Mileage forecast: 100 $								
	Year	En	NO_x	VOC	CO	CO_2	TSP Exh.	TSP Exh. + Non exh.	PM_{10} Exh. + Non exh.	$PM_{2.5}$ Exh. + Non exh.	En	NO_x	VOC	CO	CO_2	TSP Exh.	TSP Exh. + Non exh.	PM_{10} Exh. + Non exh.	$PM_{2.5}$ Exh. + Non exh.
BS1	2010	-0.2	1.5	-2.5	0.4	-5.9	-3.6	-1.6	-2.0	-2.5	-0.2	1.5	-2.4	0.4	-5.9	-3.6	-1.6	-2.0	-2.5
	2015	-0.3	1.5	-1.5	0.7	-8.2	-4.8	-1.5	-2.0	-2.8	-0.3	1.5	-1.5	0.6	-8.2	-4.8	-1.5	-2.0	-2.8
	2020	-0.4	1.7	-0.5	1.3	-10.4	-5.9	-1.2	-1.7	-2.5	-0.4	1.7	-0.5	1.2	-10.4	-5.9	-1.2	-1.7	-2.5
	2025	-0.4	1.7	0.2	1.7	-10.4	-5.6	-0.6	-0.9	-1.5	-0.4	1.7	0.2	1.7	-10.4	-5.5	-0.6	-0.9	-1.5
	2030	-0.4	1.5	0.4	2.0	-10.4	-5.1	-0.4	-0.6	-0.9	-0.4	1.5	0.4	1.9	-10.4	-5.0	-0.4	-0.6	-0.9
BS2	2010	-0.2	1.5	-2.5	0.4	-5.9	-3.6	-1.6	-2.0	-2.5	-0.2	1.5	-2.4	0.4	-5.9	-3.6	-1.6	-2.0	-2.5
	2015	-0.4	1.9	-1.5	0.9	-10.9	-6.5	-2.1	-2.7	-3.7	-0.4	1.9	-1.5	0.8	-10.9	-6.4	-2.1	-2.7	-3.7
	2020	-0.7	2.4	0.0	2.0	-15.9	-9.0	-1.8	-2.6	-3.8	-0.7	2.4	0.0	1.9	-15.9	-9.0	-1.8	-2.6	-3.8
	2025	-0.9	2.9	1.8	3.6	-20.9	-11.0	-1.3	-1.9	-3.0	-0.9	3.0	1.6	3.5	-20.9	-10.9	-1.3	-1.9	-3.0
	2030	-1.1	2.8	3.3	5.2	-25.8	-12.2	-0.9	-1.3	-2.2	-1.1	2.8	3.1	5.0	-25.8	-12.0	-0.9	-1.3	-2.2

The emission consequences of using biofuel in road transport even at blend ratios up to 25 % are small. For NO_x and VOC the emission deviations between the baseline and biofuel scenarios are 3 % or less. For CO and exhaust TSP the largest emission differences, 5 % and -12 %, respectively, occur between the baseline and biofuel scenario 2 in 2030, related to a biofuel share of 25 %. CO is, however, of less environmental importance, and if for TSP the emission contribution coming from non exhaust is included in a total TSP assessment, the emission differences between baseline and biofuel scenarios become considerably smaller (c.f. Section 5.2).

6. Summary and conclusion

With CO_2 as an exception, the emission consequences of using biofuel in road transport even at blend ratios up to 25 % are small. For NO_x and VOC the emission variations between the baseline and biofuel scenarios are 3 % or less. For CO and exhaust TSP the largest emission differences, 5 % and -12 %, respectively, occur between the FS and BS2 scenarios in 2030. The biofuel emission impacts are insignificant for NO_x,VOC, CO and TSP compared to the generally large emission reductions predicted in all scenarios driven by the gradual strengthened emission standards for new vehicles, by far outweighing the emission influence from biofuels and traffic growth.

For CO_2 significant emission differences are calculated between FS and the biofuel scenarios; the largest difference of 26 % occurs between FS and BS2 in 2030. The reason for these differences is that the present inventory follows the calculation approach prescribed by the UNFCCC and UNECE CLRTAP conventions. For road transport, only the vehicle based emissions are made up, and further, the biofuel part of the combusted fuel are regarded as CO_2 neutral. Emissions associated with e.g. biofuel production and alternative use of biomass are treated in other relevant UNFCCC/UNECE inventory categories. The focus on direct vehicle emissions for road transport as a single sector makes sense for the combustion related emissions of NO_x, TSP, CO and VOC, which have important environmental impacts on local air quality and health. For CO_2, however, the calculated emission differences cannot be assessed by regarding road transport alone.

Being a greenhouse gas, the emission impacts of CO_2 must be seen from a global warming and policy perspective. So, to answer the question if bio fuels is profitable from a society point of view an integrated W-t-W analysis and welfare economic Cost Benefit Analysis is necessary (EU Directive 2009/28/EC). Such an integrated analysis describes the emission and welfare effects for the full chain of production, distribution and combustion of bio fuels, and especially all the indirect consequences of re-allocating society's scarce resources (land, real capital and labour) for bio fuel production. The most important parts of the W-t-W analysis are agricultural land use change, decreasing biomass resources available for heat and power production and the actual economic and environmental impacts of the bio fuel refining process .

For 1. generation biodiesel and bio ethanol Slentø et al. (2010) based on primary products rape and wheat respectively find that even if fossil fuel is used in the production process there will still be a decrease in total CO_2 emissions. For 2. generation bio ethanol based on secondary product wheat straw the total CO_2 emissions increase. This is due to an assumption that wheat straw which has been used for heat and power production has to be substituted by coal. Of course these results depend on the chosen system delimitation and assumptions about alternative land use, resource use in the refining of bio fuel and the use of secondary products from agricultural production and the refining process. Another system delimitation and other assumptions may lead to other results.

Slentø et. al. (2010) also analyses the welfare economic consequences of producing and consuming biodiesel and bio ethanol. The result is highly dependable on the oil price, the price of agricultural production that is lost and the shadow price of CO_2. Under realistic price assumptions biodiesel and 1. generation bio ethanol is not profitable to society while 2. generation bio ethanol is. The result, however, will change if the prices of agricultural products change relative to oil. If agricultural products become relative more expensive bio fuel products become even less profitable while lower prices on agricultural products makes bio fuel products relative more profitable.

The calculation method related to biofuel usage in road transport is well established for vehicle based CO_2 emissions alone and hence the estimated emissions presented in this study are regarded as very precise based on the present forecast data for fleet composition and vehicle mileage. The emission estimates for NO_x, VOC, CO and TSP presented in this study are less certain than for CO_2 due to the relatively scarce biofuel emission data implemented in the calculations. As a consequence, the obtained emission results must be assessed with care, it is, however, important to remember the large emission impact from improved emission standards for new vehicles during the forecast period.

Bearing in mind the uncertainties discussed above, the calculation approach for emissions from biofuel usage presented in this study can be used as a tool to carry out sensitivity analysis, environmental impact assessment studies, or for research purposes as such. The work presented in this paper may also serve as an input for policy makers dealing with the introduction of biodiesel and bio ethanol for road transport vehicle propulsion. The GIS distributed emissions of NO_x, TSP, CO and VOC are further used as input for air dispersion modelling purposes, subsequently carried out in REBECa.

Acknowledgements

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