Morten Winther, DMU, 5th of May, 2010

Road transport fuel consumption and emissions calculations in the REBECa project

1. Introduction

Funded by the Programme Commission on Energy and Environment under the Danish Strategic Research Council, the multi-disciplinary integrated impact assessment project 'Renewable Energy in the transport sector using Biofuels as an Energy Carrier' (REBECA) is currently under implementation in Denmark. The aim of REBECA is 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 bioethanol in Danish road transport. The project period is 2007–2010.

An important task of work package II (emission inventories) in REBECA is to estimate the fuel consumption and emissions for two fossil fuel based baseline scenarios for Danish road transport from 2004-2030, characterised by different traffic growth rates. For each of the baseline scenarios, two biofuel scenarios are considered with different penetration rates of biodiesel and bioethanol. Biofuel scenario 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 constant levels in the following years. In biofuel scenario 2, the biofuel share is also 5.75 % in 2010 and subsequently the biofuel share grows linearly to 25 % in 2030.

In the project, specific fuel consumption and emission calculations of CO_2, SO_2, NO_x, TSP, CO and VOC are made for the baseline year 2004, and the scenario years 2010, 2015, 2020, 2025 and 2030.

The purpose of the present paper is to explain the input data and the calculation method used in order to assess the emission impact of using biofuel as prescribed in the scenarios.

Section 2 and 3 of this paper explains the forecast of total mileage behind the calculations as well as the disaggregation of mileage into fleet layers defined by the calculation model. The scenario assumptions in terms of biofuel share of total fuels for road transport are briefly summarised in Section 4. The fuel consumption and emission factor differences between fossil based and biofuel blends are shown in Section 5. Section 6 explains the fuel consumption and emission calculation methodology, and fuel consumption and emission results are shown in Section 7.

2. Total mileage forecast

The basis for the mileage forecast for Danish road transport used in the REBECa project is a mileage forecast prepared by DTU Transport in Denmark used as an input to the Danish Infrastructure Commission (2008). The mileage forecast is based on an oil price of 65$ pr barrel of oil (Fosgerau et al., 2007). 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.

For the 65$ scenario, the growth in the total mileage from 2005-2030 is 1.41 % on an average yearly basis. By vehicle category, for buses, trucks and cars/vans, the average yearly growth rates are 0 %, 2.15 % and 1.38 %. Based on the 100$ mileage forecast, the estimated average yearly growth rate is 0.8 %, and by vehicle category the average yearly growth rates are 0 %, 1.5 %, 0.76 % and 0.81 %, respectively, for buses, trucks, cars and vans. Figure 1 show the mileage forecast for the basis scenario (65$/barrel) and the alternative scenario (100$/barrel) used in the RECECa project. A thorough documentation of the mileage forecast is given by Jensen and Winther (2009).

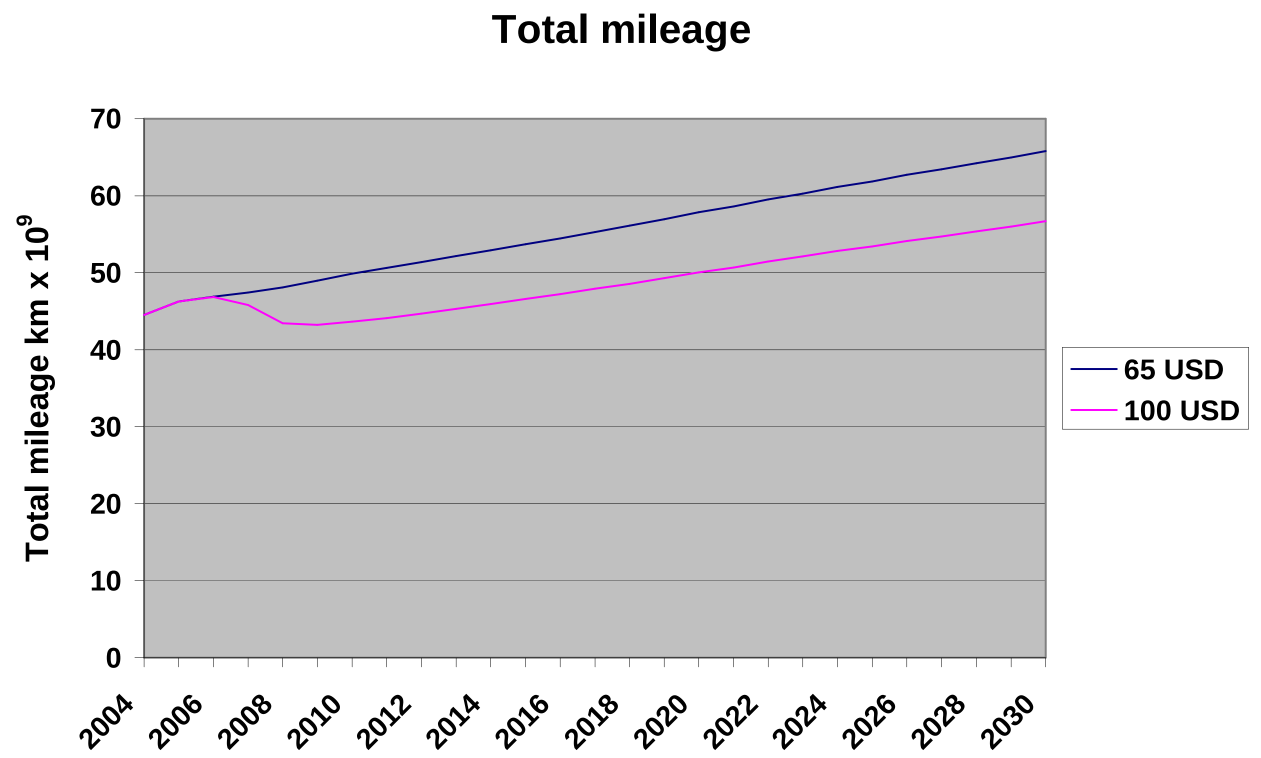

Figure 1. Mileage forecast for the 65$ and 100$ scenarios used in the REBECa project

In the following paragraph, in Figure 2, the 65$ mileage forecast is split into total mileage per vehicle category, fuel type and emission technology classes corresponding with the structure of the model used for the fuel consumption and emission calculations in the REBECa project.

3. Fleet model layers and mileage data

In order to make sufficiently detailed fuel consumption and emission calculations in REBECa, it is necessary to distribute the mileage figures from DTU Transport further into groups of vehicles with the same average fuel consumption and emission behaviour; the so-called layers. An internal model developed by NERI use a detailed layer structure and calculation methodology similar to the model structure of the European road transport emission calculation model COPERT. In this model, the layer splits are made according to fuel type, engine size/weight class, and EU emission legislation levels.

Table 1 gives an overview of the different model classes and sub-classes present in the COPERT III version of the COPERT methodology, as well as trip speed figures and mileage split used for the Danish road traffic.

Table 1 Model vehicle classes and sub-classes, trip speeds and mileage split.

				Trip speed [km pr h]			Mileage split [%]		
Veh. category	Fuel type	Engine size/weight	EU emission levels	Urban	Rural	Highway	Urban	Rural	Highway
Cars	Gasoline	< 1.4 l.	5 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Gasoline	1.4 – 2 l.	5 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Gasoline	> 2 l.	5 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Diesel	< 2 l.	1 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Diesel	> 2 l.	1 conv.; Euro 1-6	40	70	100	35	46	19
Cars	LPG		1 conv.; Euro 1-6	40	70	100	35	46	19
Cars	2-stroke		1 conv.	40	70	100	35	46	19
Vans	Gasoline		1 conv.; Euro 1-6	40	65	80	35	50	15
Vans	Diesel		1 conv.; Euro 1-6	40	65	80	35	50	15
Trucks	Gasoline		1 conv.	35	60	80	32	47	21
Trucks	Diesel	3.5 – 7.5 tonnes	1 conv.; Euro I-VI	35	60	80	32	47	21
Trucks	Diesel	7.5 – 16 tonnes	1 conv.; Euro I-VI	35	60	80	32	47	21
Trucks	Diesel	16 – 32 tonnes	1 conv.; Euro I-VI	35	60	80	19	45	36
Trucks	Diesel	> 32 tonnes	1 conv.; Euro I-VI	35	60	80	19	45	36
Urban buses	Diesel		1 conv.; Euro I-VI	30	50	70	51	41	8
Coaches	Diesel		1 conv.; Euro I-VI	35	60	80	32	47	21
Mopeds	Gasoline		1 conv.; Euro I-II	30	30	-	81	19	0
Motorcycles	Gasoline	2 stroke	1 conv.	40	70	100	47	39	14
Motorcycles	Gasoline	< 250 cc.	1 conv.; Euro I-III	40	70	100	47	39	14
Motorcycles	Gasoline	250 – 750 cc.	1 conv.; Euro I-III	40	70	100	47	39	14
Motorcycles	Gasoline	> 750 cc.	1 conv.; Euro I-III	40	70	100	47	39	14

As input data for the NERI model in the 2004-2006 historical period, the Danish fleet and mileage data per vehicle category, fuel type and engine size/weight and first registration year is obtained from the Danish Road Directorate (Ekman, 2005; Foldager, 2007), Statistics Denmark (Dalbro, 2007) and The National Motorcycle Association (Markamp, 2007). Data for mileage split between urban, rural and highway driving and the respective average speeds is provided by from the Danish Road Directorate (Ekman, 2005). For more information regarding historical input data, please refer to Winther (2008).

The same resolution of fleet and mileage data as for the historical period is given in the 2007+ forecast data from the Danish Road Directorate (Trafikministeriet, 2002). The latter prognosis data has been modified for later Danish emission forecast projects, and the latest data adjustments were made by NERI in 2008 taking into account the latest significant increase in new sold diesel passenger cars and vans (see Nielsen et al., 2009).

Following the COPERT layer structure, the historical and forecasted fleet and mileage data are subsequently aggregated in the NERI model into groups of first registration year correspondent with the EU emission levels. Further, for all inventory years the annual mileage are summed up per vehicle category and equally scaled in order to maintain the total mileage figures per vehicle category forecasted by DTU Transport.

The 2004-2030 time series figures for the fleet and total mileage development is shown in Figure 2 split into vehicle category and fuel type. For cars, trucks and buses, aggregations are made for engine size, total weight categories and bus type, respectively.

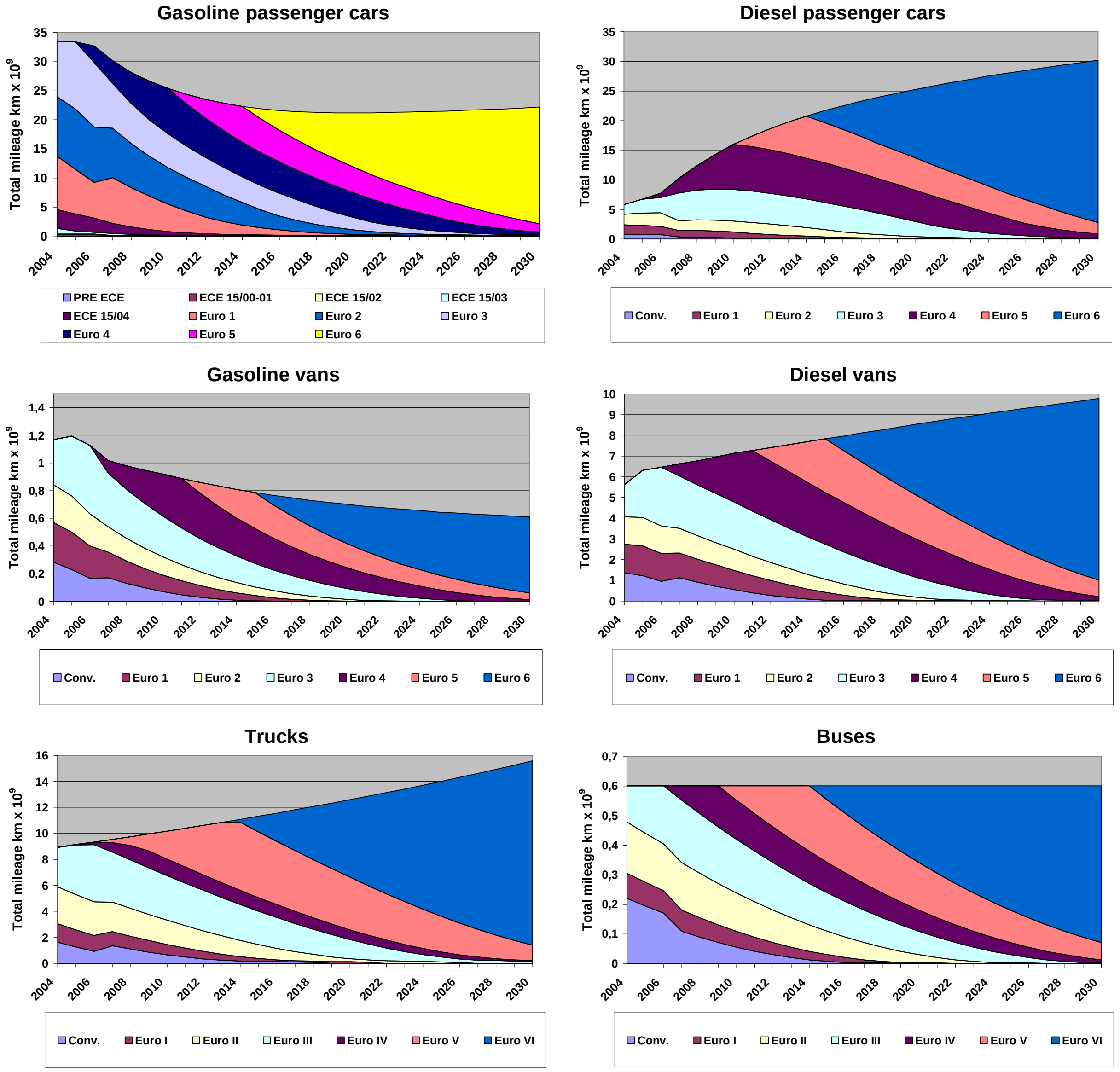

Figure 2 Layer distribution of total mileage pr vehicle type in 2004-2030.

4. Energy data

Biodiesel is fully miscible with fossil based diesel, and hence the biodiesel share of the diesel-biodiesel fuel is assumed to be the same as the overall scenario energy share percentages. For bioethanol, in REBECA the scenario definition is to use a five percent v/v mix of bioethanol in gasoline fuels (E5) by all gasoline vehicles, and then gradually increase the number of Flexible Fuel Vehicles (FFV) running on E85, in the passenger car segment of the fleet, as the share of bioethanol increases in the scenario period.

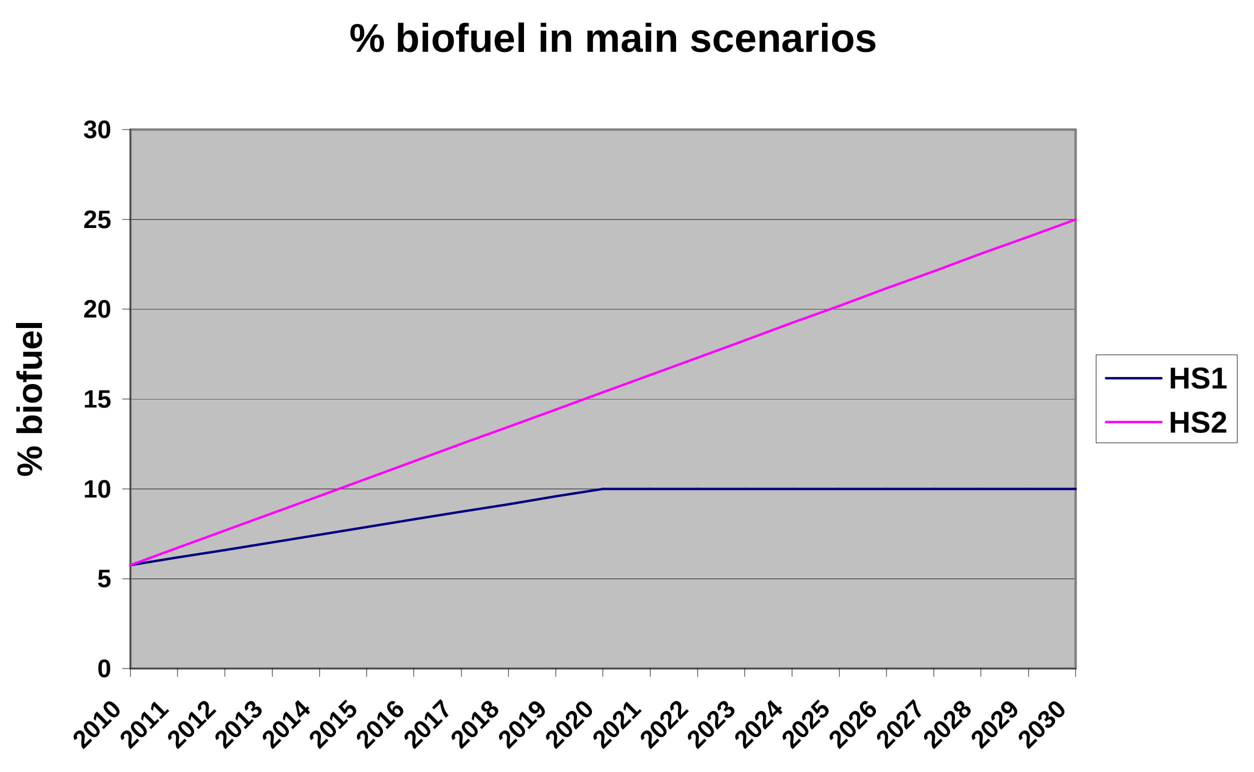

Figure 3 Blend percentage of biofuel from 2010-2030 given as energy units

Figure 3 shows the biofuel penetration for road transport fuels in Denmark for the two main scenarios in the REBECa project. Taking into account the differences in fuel density, ρ, and lower heating values (LHV), between fossil based fuels and biofuels, the volume based energy share is calculated as:

$$B\%_V = \frac{100 \cdot B\%_E \cdot \rho_{B0} \cdot LHV_{B0}}{\rho_{B100} \cdot LHV_{B100} \cdot (100 - B\%_E) + B\%_E \cdot \rho_{B0} \cdot LHV_{B0}} \qquad (1)$$

$B\%_V$ = Biofuel blend ratio in volume units
$B\%_E$ = Biofuel blend ratio in energy units
ρ_{B0} = density for normal diesel/gasoline (kg/l)
ρ_{B100} = density for neat biodiesel/bioethanol (kg/l)
LHV_{B0} = lower heating value for normal diesel/gasoline (MJ/kg)
LHV_{B100} = lower heating value for neat biodiesel/bioethanol (MJ/kg)

Further, LHV is calculated for a given blend ratio, B%, as follows:

$$LHV(B\%) = (B\%_M \cdot LHV_{B100} + (100 - B\%_M) \cdot LHV_{B0})/100 =$$

$$(\rho_{B100} \cdot B\%_V \cdot LHV_{B100} + (100 - \rho_{B0} \cdot B\%_V) \cdot LHV_{B0})/100 \qquad (2)$$

$LHV(B\%_E)$= lower heating value (MJ/kg) for biofuel blend with blend ratio $B\%_E$
$B\%_M$ = Biofuel blend ratio in mass units
LHV_{B0} = lower heating value for normal diesel/gasoline (MJ/kg)
LHV_{B100} = lower heating value for neat biodiesel/bioethanol (MJ/kg)

The following Table 2 shows the values for density and lower heating values which go into the equations 1 and 2. The figures are taken from the Danish Energy Authority (DEA, 2008), except for the biodiesel density, which come from Teknologirådet (2006).

Table 2 Fuel density and lower heating values for diesel, gasoline, biodiesel and bioethanol

	LHV (B0, E0) MJ/kg	LHV (B100, E100) MJ/kg	ρ (B0, E0) kg/l	ρ (B100, E100) kg/l
Diesel-biodiesel	42.7	37.6	0.84	0.88
Gasoline-bioethanol	43.8	26.7	0.75	0.79

As mentioned in the beginning of this section, the biodiesel share of the diesel-biodiesel fuel follows the overall scenario percentages. The volume based energy shares for biodiesel in diesel-biodiesel, and the lower heating value for the diesel-biodiesel blend as a function of biodiesel blend ratio, are shown in Figure 4.

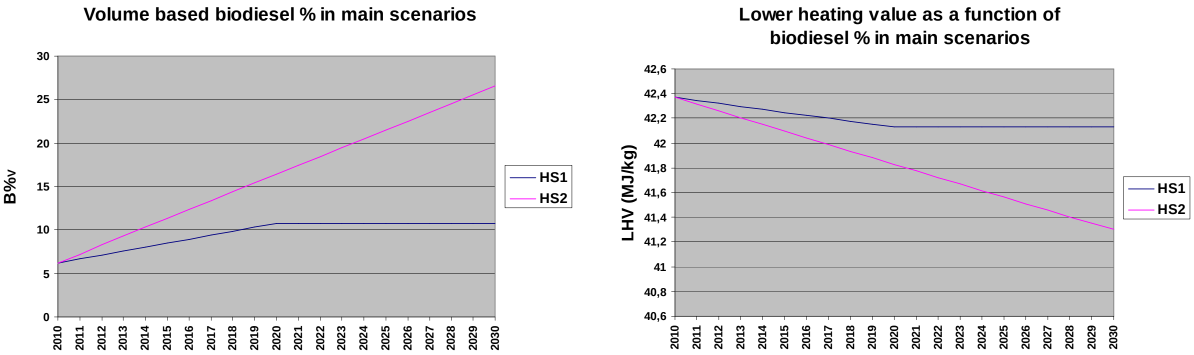

Figure 4 Volume based biodiesel % and lower heating value for biodiesel blends in main scenarios

In Table 3, the specific figures for B%$_V$ and LHV, as a function of energy based B% for diesel are shown for the specific scenario calculation years 2010, 2015, 2020, 2025 and 2030.

Following the REBECA scenario definitions, the usage of E5 and E85 as the only gasoline-bioethanol fuel blends is a prerequisite for the subsequent project calculations. Figure 5 shows the volume and energy based blend percentages for E5 and E85, as well as the lower heating values for neat gasoline, E5 and E85.

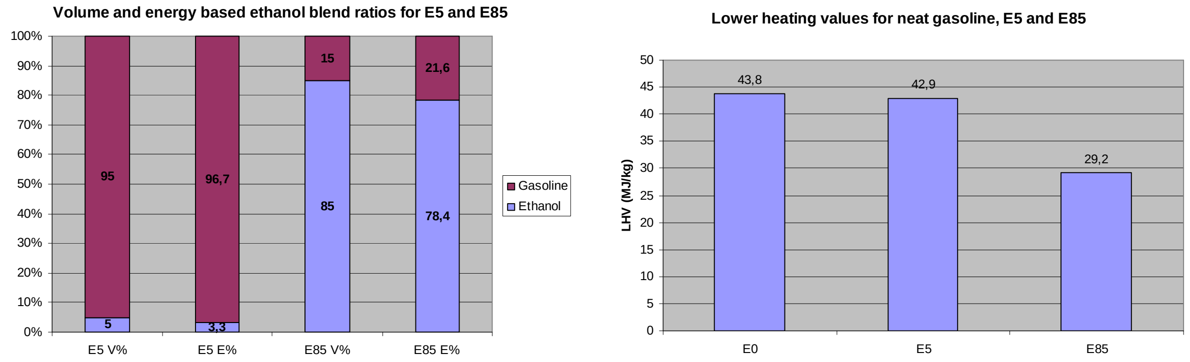

Figure 5 Volume and energy based ethanol blend ratios, and lower heating value for E5 and E85 gasoline-ethanol blends

5. Fuel consumption and emission factors

5.1 Basis 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)[1]. The fuel consumption and emission data cover the fleet and mileage resolution shown in Table 1, per vehicle category, fuel type, engine size or weight class, EU emission level, and road type.

Due to the very detailed 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 per layer and road type. In addition, for cars and vans, the driving during cold start influence the fuel consumption and CO, VOC, NO_x and PM emissions, and for gasoline catalyst cars and vans in particular, the wear of the catalytic converter have an impact on the CO, VOC and NO_x emissions as well. Hence, for these vehicle types, the emission factors for a given vehicle layer, deviate to some extent from year to year.

Figure 6 presents the NO_x emission factors as an example for the vehicle groupings used in Figure 2, weighted according to the mileage driven per road type as well. The emission factors are derived from the inventory year 2015, for Euro 6 vans the data corresponds to the 2020 situation, though.

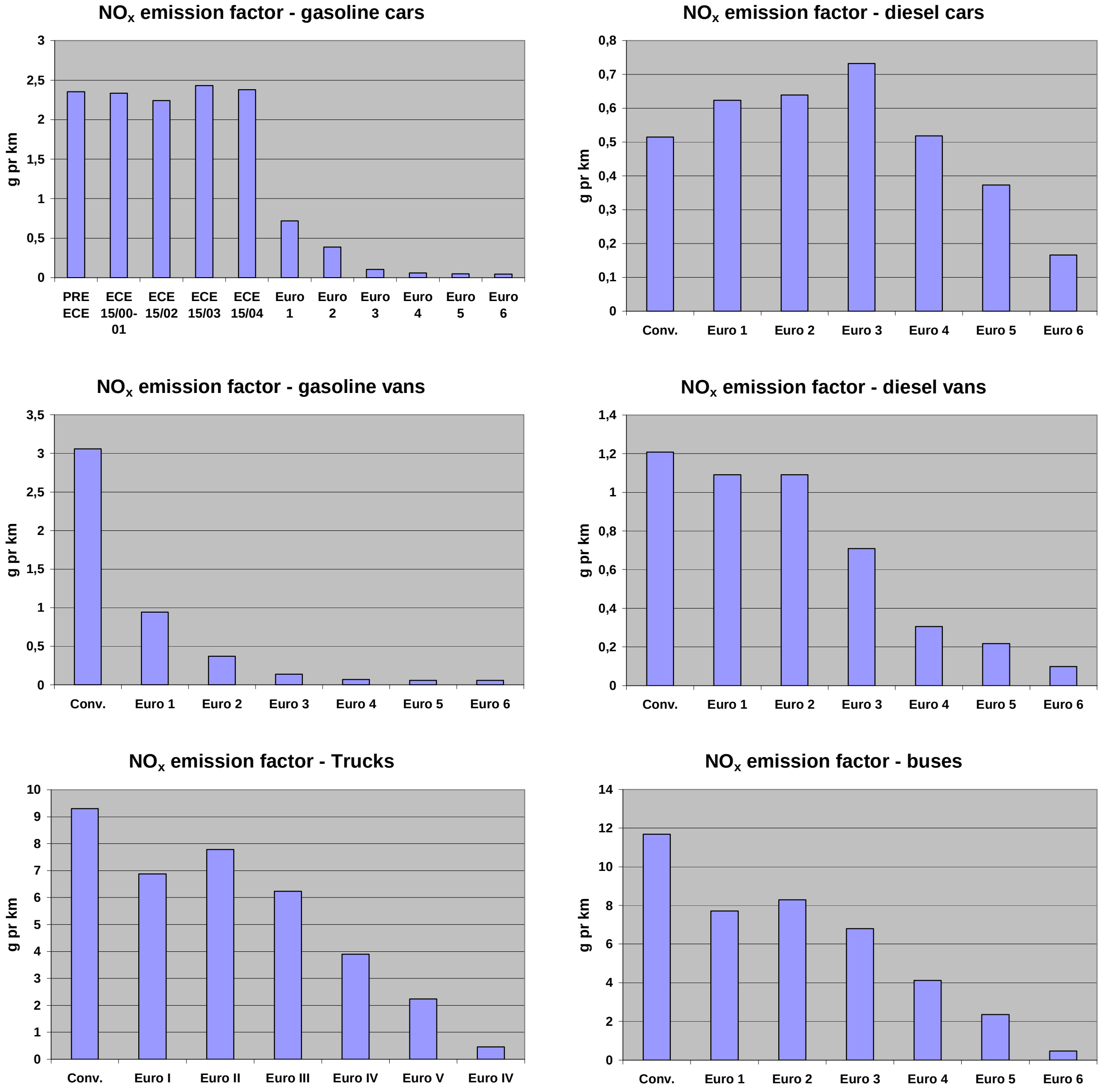

Figure 6 Layer specific NO_x emission factors per vehicle category

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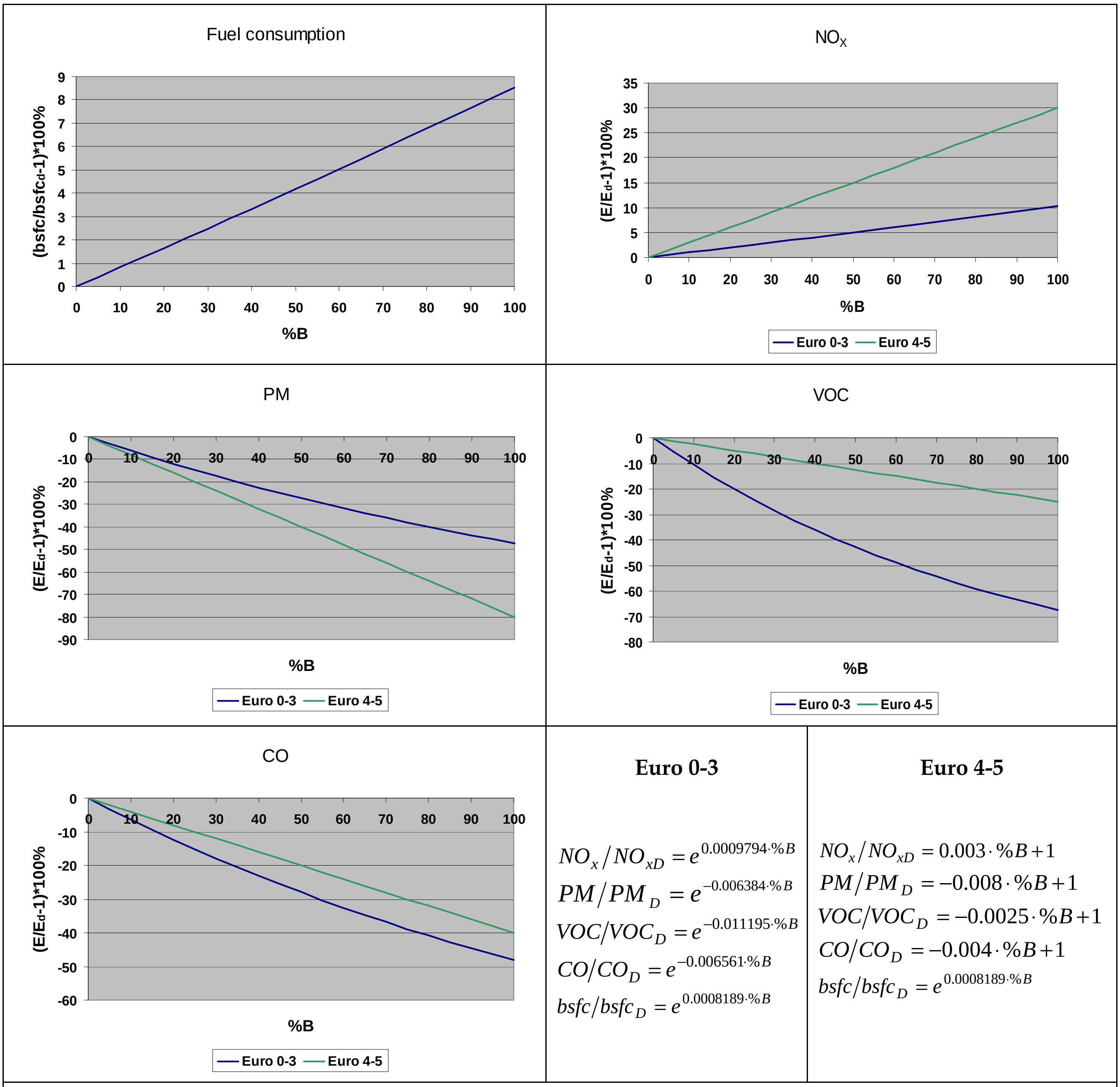
[1] For trucks and buses COPERT IV incorporates many more vehicle weight categories compared to COPERT III. However, due to less detailed fleet and mileage data available in Denmark, average factors are aggregated from the detailed COPERT IV gross vehicle weight categories into the four[two] COPERT III categories for trucks[buses], by using appropriate assumptions (Winther, 2008).

5.2 Fuel consumption and emission factor differences between fossil fuel and biofuel blends

Extensive literature reviews have been made in the REBECa project in order to examine the fuel consumption and emission factor differences between fossil based fuels and biofuels (Winther 2009 and 2010). For diesel engines, the fuel consumption and emission factor differences have been determined by Winther (2009), as functions of the biodiesel blend ratio. For gasoline engines, the fuel consumption and emission factor differences between neat gasoline and E5/E85 have been characterised by Winther (2010). In the following sections 5.2.1 and 5.2.2, the difference functions and data values are shown together with the references for the underpinning measurement data.

5.2.1 Diesel engines

For heavy-duty vehicles equipped with Euro 3 and earlier engines, the relationship between fuel consumption as well as NO_x, PM, CO and VOC emission changes as a function of B%V is based on the findings from EPA (2002). The data from the latter source is also used for the future Euro 6 engine technology, as assumed by Winther (2009). For Euro 4 and 5 engines, the experimental basis behind the curves is measurement results from McCormick et al. (2005). The fuel consumption and emission curves for the Euro 0-3 and Euro 4-5 engines, and the mathematical expressions of the functions are shown in Figure 7.



Euro 0-3

$$NO_x / NO_{xD} = e^{0.0009794 \cdot \%B}$$

$$PM / PM_D = e^{-0.006384 \cdot \%B}$$

$$VOC / VOC_D = e^{-0.011195 \cdot \%B}$$

$$CO / CO_D = e^{-0.006561 \cdot \%B}$$

$$bsfc / bsfc_D = e^{0.0008189 \cdot \%B}$$

Euro 4-5

$$NO_x / NO_{xD} = 0.003 \cdot \%B + 1$$

$$PM / PM_D = -0.008 \cdot \%B + 1$$

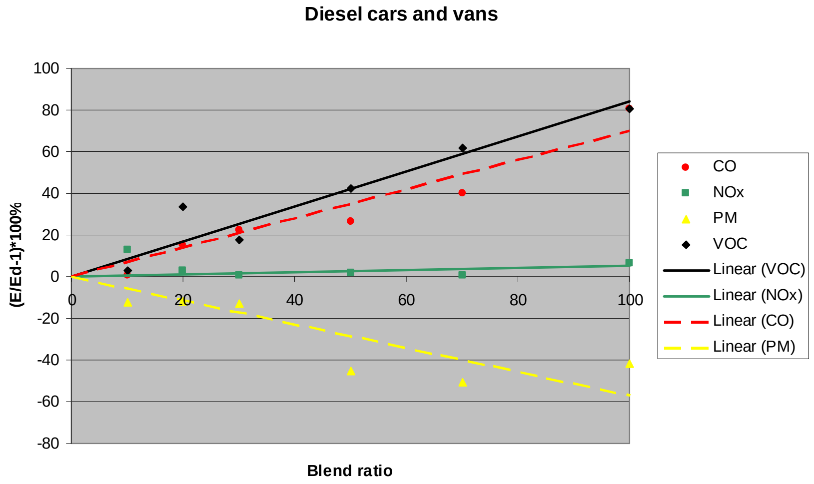
$$VOC / VOC_D = -0.0025 \cdot \%B + 1$$

$$CO / CO_D = -0.004 \cdot \%B + 1$$

$$bsfc / bsfc_D = e^{0.0008189 \cdot \%B}$$

Figure 7 Fuel consumption and emission changes as a function of volume based B% for heavy-duty engines.

Average emission differences for B10, B20, B30, B50, B70 and B100 are calculated based on the results from Martini et al. (2007a), Fontaras et al. (2007, 2008) and Durbin et al. (2007), and these averages are then applied in the case of passenger cars and vans. The emission differences expressed as linear functions are shown in Figure 8 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).



$$NO_x / NO_{xD} = 0.000524 \cdot \%B + 1$$

$$PM / PM_D = -0.005719 \cdot \%B + 1$$

$$VOC / VOC_D = 0.008386 \cdot \%B + 1$$

$$CO / CO_D = 0.007007 \cdot \%B + 1$$

Figure 8 Emission changes as a function of volume based B% for diesel cars and vans.

The following Table 3 lists the values for fuel consumption and emission factor changes used for the different vehicle types/engine technologies in the specific scenario years, as a function of volume based B% for diesel.

Table 3 fuel consumption/emission factor 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%	PM%	FC%
HS1	2010	Cars/vans	All	5.75	6.20	6.48	42.37	0.32	4.41	5.33	-3.67	0.51
HS1	2010	Trucks/buses	Euro 0-III	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
HS1	2010	Trucks/buses	Euro IV-V	5.75	6.20	6.48	42.37	1.86	-2.48	-1.55	-4.96	0.51
HS1	2010	Trucks/buses	Euro VI	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
HS1	2015	Cars/vans	All	7.88	8.48	8.85	42.25	0.44	6.04	7.28	-5.01	0.70
HS1	2015	Trucks/buses	Euro 0-III	7.88	8.48	8.85	42.25	0.83	-5.41	-9.06	-5.27	0.70
HS1	2015	Trucks/buses	Euro IV-V	7.88	8.48	8.85	42.25	2.54	-3.39	-2.12	-6.78	0.70
HS1	2015	Trucks/buses	Euro VI	7.88	8.48	8.85	42.25	0.83	-5.41	-9.06	-5.27	0.70
HS1	2020	Cars/vans	All	10.00	10.75	11.20	42.13	0.56	7.65	9.23	-6.36	0.88
HS1	2020	Trucks/buses	Euro 0-III	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
HS1	2020	Trucks/buses	Euro IV-V	10.00	10.75	11.20	42.13	3.22	-4.30	-2.69	-8.60	0.88
HS1	2020	Trucks/buses	Euro VI	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
HS1	2025	Cars/vans	All	10.00	10.75	11.20	42.13	0.56	7.65	9.23	-6.36	0.88
HS1	2025	Trucks/buses	Euro 0-III	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
HS1		s/buses	Euro IV-V	10.00	10.75	11.20	42.13	3.22	-4.30	-2.69	-8.60	0.88
HS1		s/buses	Euro VI	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
HS1	2030	Cars/vans	All	10.00	10.75	11.20	42.13	0.56	7.65	9.23	-6.36	0.88
HS1	2030	Trucks/buses	Euro 0-III	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
HS1	2030	Trucks/buses	Euro IV-V	10.00	10.75	11.20	42.13	3.22	-4.30	-2.69	-8.60	0.88
HS1	2030	Trucks/buses	Euro VI	10.00	10.75	11.20	42.13	1.06	-6.81	-11.34	-6.63	0.88
HS2	2010	Cars/vans	All	5.75	6.20	6.48	42.37	0.32	4.41	5.33	-3.67	0.51
	2010	Trucks/buses	Euro 0-III	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51

NO_x Euro 0-3

HS2												
HS2	2010	Trucks/buses	Euro IV-V	5.75	6.20	6.48	42.37	1.86	-2.48	-1.55	-4.96	0.51
HS2	2010	Trucks/buses	Euro VI	5.75	6.20	6.48	42.37	0.61	-3.99	-6.71	-3.88	0.51
HS2	2015	Cars/vans	All	10.56	11.35	11.83	42.10	0.59	8.08	9.74	-6.71	0.93
HS2	2015	Trucks/buses	Euro 0-III	10.56	11.35	11.83	42.10	1.12	-7.18	-11.93	-6.99	0.93
HS2	2015	Trucks/buses	Euro IV-V	10.56	11.35	11.83	42.10	3.40	-4.54	-2.84	-9.08	0.93
HS2	2015	Trucks/buses	Euro VI	10.56	11.35	11.83	42.10	1.12	-7.18	-11.93	-6.99	0.93
HS2	2020	Cars/vans	All	15.38	16.45	17.10	41.83	0.85	11.71	14.13	-9.73	1.36
HS2	2020	Trucks/buses	Euro 0-III	15.38	16.45	17.10	41.83	1.62	-10.23	-16.82	-9.97	1.36
HS2	2020	Trucks/buses	Euro IV-V	15.38	16.45	17.10	41.83	4.94	-6.58	-4.11	-13.16	1.36
HS2	2020	Trucks/buses	Euro VI	15.38	16.45	17.10	41.83	1.62	-10.23	-16.82	-9.97	1.36
HS2	2025	Cars/vans	All	20.19	21.52	22.31	41.56	1.12	15.31	18.48	-12.72	1.78
HS2	2025	Trucks/buses	Euro 0-III	20.19	21.52	22.31	41.56	2.13	-13.17	-21.41	-12.84	1.78
HS2	2025	Trucks/buses	Euro IV-V	20.19	21.52	22.31	41.56	6.46	-8.61	-5.38	-17.21	1.78
HS2	2025	Trucks/buses	Euro VI	20.19	21.52	22.31	41.56	2.13	-13.17	-21.41	-12.84	1.78
HS2	2030	Cars/vans	All	25.00	26.54	27.46	41.30	1.38	18.89	22.79	-15.69	2.20
HS2	2030	Trucks/buses	Euro 0-III	25.00	26.54	27.46	41.30	2.63	-15.98	-25.71	-15.59	2.20
HS2	2030	Trucks/buses	Euro IV-V	25.00	26.54	27.46	41.30	7.96	-10.62	-6.64	-21.23	2.20
HS2	2030	Trucks/buses	Euro VI	25.00	26.54	27.46	41.30	2.63	-15.98	-25.71	-15.59	2.20

5.2.2 Gasoline engines

To characterise the energy consumption and emission factor differences between neat gasoline and E5, average differences are calculated from the test figures measured by Martini et al. (2007b), Delgado (2003) and Hull et al. (2005). The corresponding differences between neat gasoline and E85 are derived from experimental data obtained by de Serves et al. (2005) and Westerholm et al. (2008). It must be noted, that in these two latter studies E5 was used as a base fuel for the experiments, since in Sweden the baseline fuel quality for petrol is predominantly E5. However, noting the small average differences between neat gasoline and E5, and due to lack of experimental data for modern European cars with neat gasoline and E85 as test fuels, the E5 vs. E85 differences are used in the present project for the neat gasoline vs. E85 case as well. This decision is discussed in more details by Winther (2010).

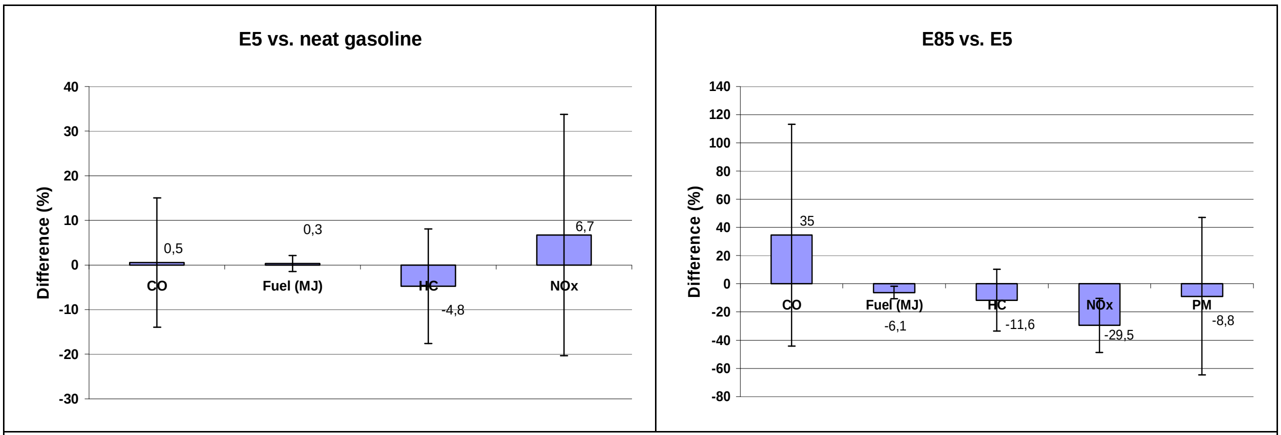


Figure 9 Fuel consumption and emission changes for neat gasoline and E5/E85 for gasoline cars and vans

5.3 Resulting fuel consumption and emission factors

5.3.1 Diesel engines

5.3.1.1 Fuel consumption factor functions

The function $k_{fc}(B\%_V)$ established by Winther (2009), and shown for heavy duty engines and cars/vans in the Figures 1 and 2, respectively, predicts the fuel consumption change in percentage as a function of the volume based biodiesel blend ratio ($B\%_V$).

The mass based fuel consumption factor, fc_M in g/km is calculated by using the $k_{fc}(B\%_V)$ function in combination with the mass based fuel consumption factor for normal diesel, $fc_{M,B0}$:

$$fc_M(B\%_V) = fc_{M,B0} \cdot (100 + k_{fc}(B\%_V))/100 \quad (3)$$

Where:

$fc_M(B\%_V)$ = fuel consumption factor (g/km) as a function of $B\%_V$
$fc_{M,B0}$ = fuel consumption factor (g/km) for normal gasoline/diesel
$k_{fc}(B\%_V)$ = fuel consumption change (%) as a function of $B\%_V$

The fuel consumption factor in MJ/km, $fc_E(B\%_V)$ is found from:

$$fc_E(B\%_V) = fc_M(B\%_V) \cdot LHV(B\%_V) \quad (4)$$

Where

$fc_E(B\%_V)$ = fuel consumption factor (MJ/km) as a function of $B\%_V$
$fc_M(B\%_V)$ = fuel consumption factor (g/km) as a function of $B\%_V$
$LHV(B\%_V)$= lower heating value (MJ/kg) for biofuel blend with blend ratio $B\%_V$

$B\%_V$ as a function of $B\%_E$ is given in equation 1, and LHV values for the different scenario years are calculated from equation 2, and listed in Table 2.

5.3.1.2 Emission factor functions for CO, VOC, NO_x and PM

The km based emission factor, emf_{km}, in g/km for CO, VOC, NO_x and PM, is calculated by using the $B\%_V$ emission change functions, $k_i(B\%_V)$ established by Winther (2009) in combination with the km based emission factor for normal diesel, $emf_{km,B0}$:

$$emf_{km,i}(B\%_V) = emf_{km,i,B0} \cdot (100 + k_i(B\%_V))/100 \quad (5)$$

Where:

$emf_{km,i}(B\%_V)$ = emission factor (g/km) for the emission component i, as a function of $B\%_V$
$emf_{km,i,B0}$ = emission factor (g/km) for the emission component i, for normal diesel
i = emission component, i = CO, VOC, NO_x, PM

5.3.1.3 Emission factor functions for CO_2 and SO_2

The neat biodiesel is CO_2 and SO_2 neutral, and hence, as a function of $B\%_E$, the fuel related emission factors, emf_E, become:

$$emf_E(B\%_E) = emf_{E,B0} \cdot (100 - B\%_E) \quad (6)$$

Where

$emf_E(B\%_E)$ = fuel related emission factor (g/MJ) as a function of $B\%_E$
$emf_{E,B0}$ = fuel related emission factor (g/MJ) for normal diesel

5.3.2 Gasoline engines

5.3.2.1 Fuel consumption factor functions

The fuel consumption by mass for vehicles using E5 and E85 increase due to a lower LHV for ethanol compared with neat gasoline. This fuel consumption increase in percent, ΔM%(E%), is found as:

$$\Delta M\%(E\%) = \frac{LHV_{E0}}{LHV_{E\%}} \cdot 100 - 100 \quad (7)$$

ΔM%(E%) = fuel consumption change (% mass), due to LHV changes for E5/E85 compared to neat gasoline
LHV_{E0} = lower heating value for normal gasoline (MJ/kg)
$LHV_{E\%}$ = lower heating value for E5/E85 (MJ/kg)

Further, the function k_{fc}(E%) established by Winther (2010) predicts the percentage energy (joule) consumption change for E5 and E85, respectively, due to changes in engine thermal efficiency. The results from k_{fc}(E%) are transformed into fuel consumption change by mass, by multiplication with the LHV ratio between neat gasoline, and E5 and E85, respectively.

Hence, the mass based fuel consumption factor in g/km, fc_M, for E5/E85 is calculated by using the ΔM%(E%) and k_{fc}(E%) adjustment factors in combination with the fuel consumption factor for normal gasoline, $fc_{M,E0}$:

$$fc_M(E\%) = fc_{M,E0} \cdot (100 + \Delta M\%(E\%))/100 \cdot (100 + k_{fc}(E\%) \cdot \frac{LHV_{E0}}{LHV_{E\%}})/100 \quad (8)$$

Where:

fc_M(E%) = fuel consumption factor (g/km) for E5/E85
$fc_{M,E0}$ = fuel consumption factor (g/km) for normal gasoline
ΔM%(E%) = fuel consumption change (%) by mass, due to LHV changes for E5/E85 compared to normal gasoline
k_{fc}(E%) = fuel consumption change (%) for E5/E85 due to thermal efficiency changes compared to normal gasoline
LHV_{E0} = lower heating value for normal gasoline (MJ/kg)
$LHV_{E\%}$ = lower heating value for E5/E85 (MJ/kg)

The energy based fuel consumption factor in MJ/km, fc_E(E%), for E5/E85 is found from:

$$fc_E(E\%) = fc_M(E\%) \cdot LHV(E\%) \quad (9)$$

Where

fc_E(E%) = energy based fuel consumption factor (MJ/km) for E5/E85
fc_M(E%) = mass based fuel consumption factor (g/km) for E5/E85
$LHV_{E\%}$ = lower heating value for E5/E85 (MJ/kg)

5.3.2.2 Emission factor functions for CO, VOC, NO_x and PM

The km based emission factor, emf_{km}, in g/km for the emission component i (CO, VOC, NO_x, PM), is calculated by using the emission change ratio, k_i(E%) established by Winther (2010) for E5 and E85, respectively, in combination with the km based emission factor for normal gasoline, $emf_{km,B0}$:

$$emf_{km,i}(E\%) = emf_{km,i,B0} \cdot (100 + k_i(E\%))/100 \quad (10)$$

Where:

$emf_{km,i}(E\%)$ = emission factor (g/km) for the emission component i, for E5/E85
$emf_{km,i,B0}$ = emission factor (g/km) for the emission component i, for neat gasoline
i = emission component, i = CO, VOC, NO_x, PM

5.3.2.3 Emission factor functions for CO_2 and SO_2

Bioethanol is CO_2 and SO_2 neutral, and hence, as a function of $B\%_E$, the fuel related emission factors, emf_E, become:

$$emf_E(E\%) = emf_{E0} \cdot (100 - E\%) \quad (11)$$

Where

$emf_E(E\%)$ = fuel related emission factor (g/MJ) for E5/E85
emf_{E0} = fuel related emission factor (g/MJ) for normal gasoline

6. Calculation method

For each inventory year, fuel consumption and emissions results for operationally hot engines are calculated per layer and road type. The procedure is to combine fuel consumption/emission factors, number of vehicles, annual mileage levels and the relevant road-type shares from Table 1 in the following expression:

$$E_{i,j,k,y} = emf_{i,j,k,y} \cdot S_k \cdot N_{j,y} \cdot M_{j,y} \quad (12)$$

E = fuel consumption/emission
emf = fuel consumption/emission factor
i = fuel consumption, CO, VOC, NO_x and PM
y = inventory year
j = layer
S = road type share
k = road type

The fuel consumption factors from the equations 4 and 9 are inserted in (12) in order to calculate the fuel consumption for diesel and gasoline vehicles, respectively. The emissions of CO, VOC, NO_x and PM are estimated for diesel and gasoline vehicles, respectively, by inserting the emission factors from (5) and (10), into equation 12.

For CO_2 (and SO_2) the emissions are calculated in (13) as the product of the energy consumption calculated from (12), and the fuel related emission factors as a function of the biofuel percentage share, E%, from (11):

$$E_{j,k,y}(i) = E_{j,k,y} \cdot emf_E(E\%) \quad (13)$$

E (i) = Emissions
E = Fuel consumption by energy
$emf_E(E\%)$ = fuel related emission factor (g/MJ)
i = CO_2, SO_2
y = inventory year
j = layer
k = road type

For bioethanol special remarks must be made in order to fully explain the calculation procedure. As mentioned in Section 4, The REBECA scenario definition is to use a five percent v/v mix of bioethanol in gasoline fuels (E5) by all gasoline vehicles, and let the increasing surplus of ethanol available in the scenario years be used by FFV cars using E85.

In practical terms it is assumed that in 2010, FFV's belonging 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.

The VOC emissions from gasoline evaporation is also calculated, following the COPERT based calculation procedures explained e.g. in Winther (2008).

No attempts are made in REBECa to estimate the difference in evaporative hydrocarbon emissions from the use of E5 and E85 fuels instead of normal gasoline. However, it is well known that evaporative emissions from vehicles using fuels with small ethanol blends (<10%) increase, and this has been explained by a decrease in the canister efficiency due to ethanol absorption (e.g. Martini et al. 2009). Conversely, for high ethanol blends the evaporative hydrocarbon emissions tend to be smaller than those coming from vehicles running on low ethanol blends, or even tend to reach the same levels as those evaporative hydrocarbon emissions coming from the use of neat gasoline (Martini et al. 2009; pers. comm. L. Erlandsson, AVL/MTC 2009, pers. comm. B. Larsen, JRC 2010).

Two specific characteristics for the use of low ethanol blends in Denmark tend to minimise the increase in evaporative emissions from fuels with low ethanol blends compared to neat gasoline. As a starting point, the Danish fuel vapour pressures are already high for neat gasoline, and adding 5% ethanol to this fuel base will not change the fuel vapour pressure, since such changes are compensated for in the blending process by removing high volatility hydrocarbons from the fuel. Hence, the effect of elevated evaporative hydrocarbon emissions becomes smaller. Moreover, improved emission after treatment systems also reduce this particular emission problem in the future, due to the fact that for the future Euro 5 standards, vehicles must be equipped with larger carbon canisters and tanks made with low permeation materials.

7. Fuel consumption and emission results

7.1 Fuel consumption and emissions for the baseline scenarios

The calculated totals for energy consumption, CO_2, NO_x, PM, CO and VOC are shown in Table 4 for the baseline scenario based on the 65$ and 100$ mileage forecasts, respectively.

The total mileage increase is higher for the 65$ forecast than for the 100$ forecast, c.f. Section 3, and this is reflected in the calculated results. The percentage differences between 2004 and 2030 for the 65$ and 100$ (results in brackets) scenarios are 43 %[23 %] for fuel consumption and CO_2 emissions, -81 %[-84 %] for NO_x, -89 %[-91 %] for PM, -82 %[-84 %] for CO, and -78 %[-79 %] for VOC.

Table 4 Calculated totals for energy consumption and emissions for the baseline scenario based on the 65$ and 100$ mileage forecasts

Mileage forecast: 65 $							Mileage forecast: 100 $						
Year	Energy	NO_x	VOC	CO	CO_2	TSP	Year	Energy	NO_x	VOC	CO	CO_2	TSP
	PJ	Tons	Tons	Tons	kTons	Tons		PJ	Tons	Tons	Tons	kTons	Tons
2004	164,8	75960	29470	200099	12114	2854	2004	164,8	75960	29470	200099	12114	2854
2005	170,1	74128	28120	198963	12506	2840	2005	170,1	74128	28120	198963	12506	2840
2006	171,8	70831	24986	177144	12633	2679	2006	171,5	70587	24973	177088	12609	2672
2007	173,3	70468	23811	165881	12747	2690	2007	168,2	68921	23214	160850	12379	2611
2008	174,5	66893	20976	145968	12846	2556	2008	161,3	63430	19559	133610	11871	2369
2009	176,5	63599	18707	129743	12992	2424	2009	160,3	59612	17215	116440	11805	2220
2010	178,8	60389	16824	116153	13170	2297	2010	161,1	56186	15431	103520	11868	2087
2011	180,8	57099	15220	104195	13318	2111	2011	162,1	52849	13968	92700	11945	1909
2012	183,0	54037	13863	93681	13482	1919	2012	163,6	49795	12748	83381	12053	1730
2013	185,4	51312	12756	85007	13658	1744	2013	165,3	47086	11755	75739	12180	1567
2014	187,8	48578	11786	77254	13838	1580	2014	167,0	44392	10887	68934	12312	1417
2015	190,4	44868	10957	70500	14035	1430	2015	169,0	40830	10142	63007	12460	1279
2016	193,0	41272	10252	64656	14227	1296	2016	171,0	37405	9507	57870	12604	1156
2017	195,9	37945	9673	59857	14440	1174	2017	173,2	34248	8982	53635	12767	1045
2018	198,7	34736	9165	55563	14649	1059	2018	175,3	31224	8521	49839	12925	941
2019	201,7	31707	8724	51889	14868	948	2019	177,5	28382	8117	46580	13091	841
2020	204,8	29011	8364	48727	15101	847	2020	180,0	25866	7785	43766	13268	750
2021	207,7	26512	8048	45981	15317	753	2021	182,1	23547	7492	41313	13431	667
2022	210,9	24337	7788	43926	15554	668	2022	184,6	21531	7247	39453	13610	590
2023	213,9	22351	7564	42174	15770	594	2023	186,7	19700	7034	37858	13771	525
2024	217,1	20574	7331	40671	16010	526	2024	189,2	18068	6808	36467	13952	464
2025	220,0	18959	7155	39462	16220	465	2025	191,3	16593	6638	35341	14105	410
2026	223,1	17592	7006	38521	16454	413	2026	193,6	15347	6491	34447	14279	364
2027	226,0	16429	6866	37708	16670	374	2027	195,8	14287	6353	33664	14436	329
2028	229,2	15540	6748	37082	16904	344	2028	198,1	13474	6233	33042	14608	303
2029	232,3	14798	6634	36530	17133	321	2029	200,3	12796	6117	32483	14774	282
2030	235,5	14197	6566	36135	17370	304	2030	202,7	12244	6046	32071	14946	267

For the 65$ mileage forecast the calculated results are shown per vehicle category in Figure 10.

The fuel consumption and CO_2 emissions increase by 43 % from 2004 to 2030. The emission increase is highest for heavy duty vehicles (trucks and buses) and vans, 51 % and 48 %, respectively, due to a larger traffic growth.

For NO_x and PM, the emissions decrease by 81 % and 89 %, respectively. The NO_x and PM emissions decrease of 72 % and 83 %, respectively, for cars, are smaller than the total emission decreases, due to a gradually larger share of diesel cars expected in the future vehicle fleet.

From 2004 to 2030 the CO and VOC emissions decrease by 82 and 78%, respectively. In the case of 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.

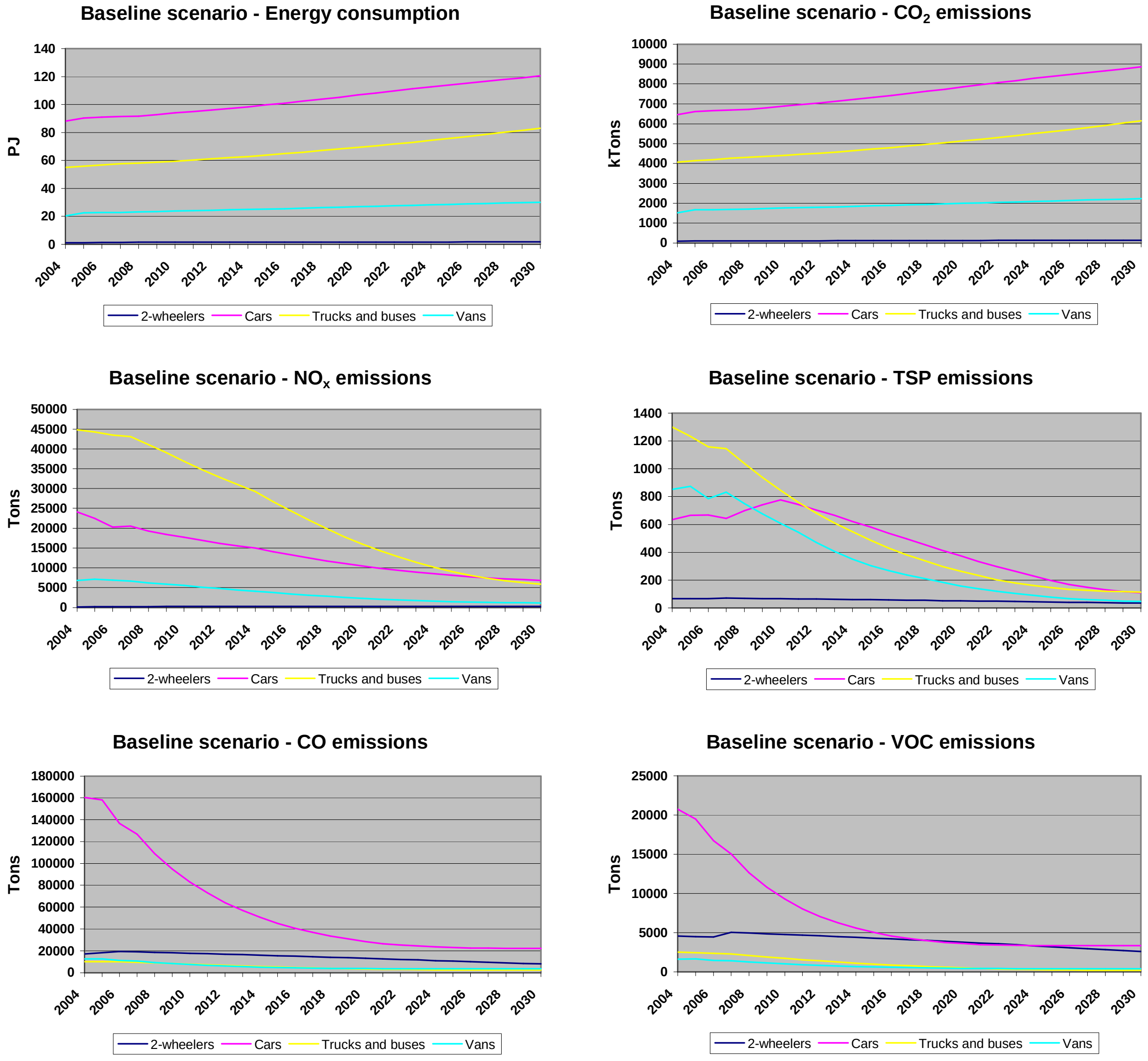


Figure 10 Total energy consumption and emission results per vehicle type for the baseline scenario 2004-2030

The non exhaust emissions from brake, tyre and road wear are shown in Table 5. 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 5 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

7.3 Spatial mapping of baseline fuel consumption and emissions

The road transport emissions of NO_x, PM (exhaust only), CO and VOC are shown on GIS maps in the Figures 11-14, for the 65$ baseline scenario. The step wise emission reductions from 2004, 2010, 2020 and 2030 are clearly visible from the maps.

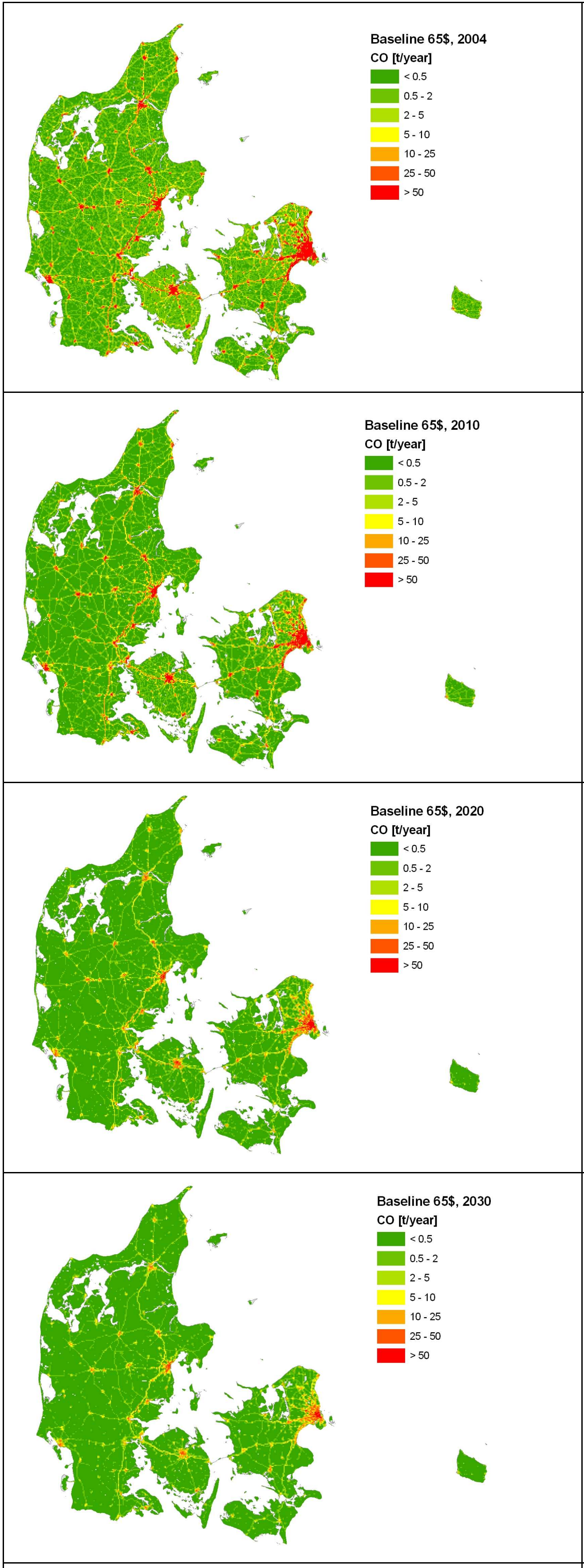


Figure 11 Baseline CO emissions for road transport

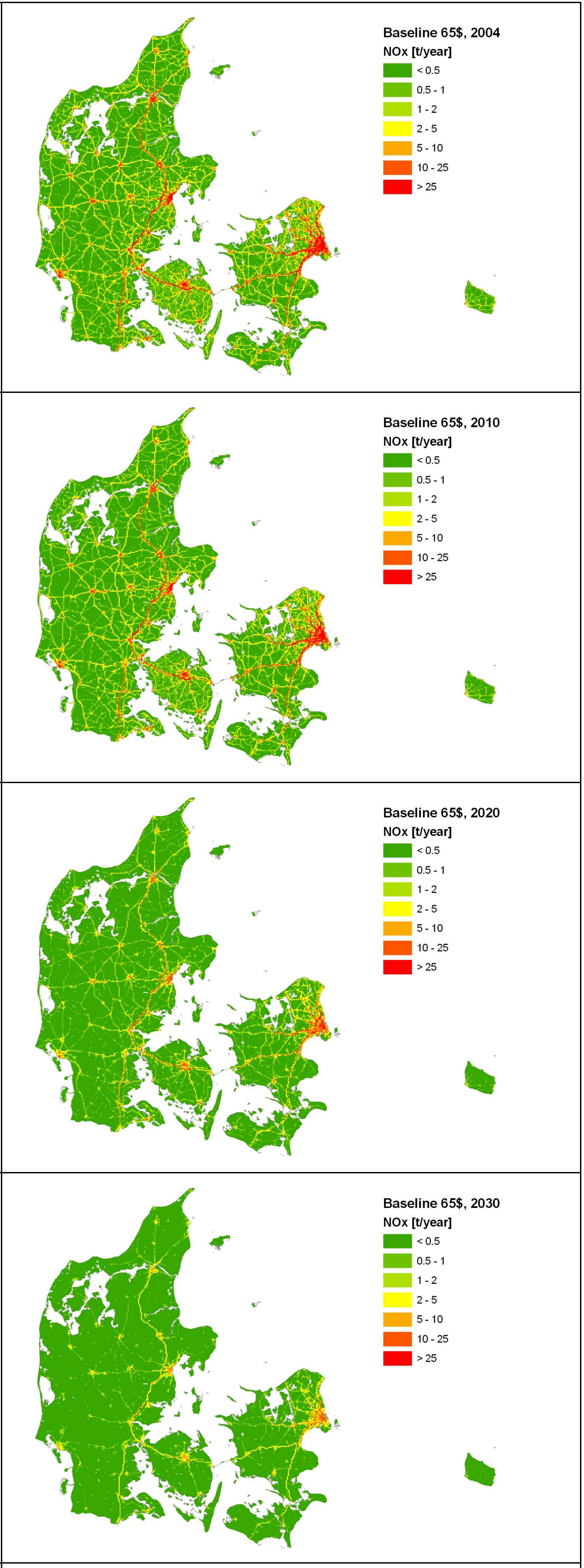


Figure 12 Baseline NO_x emissions for road transport

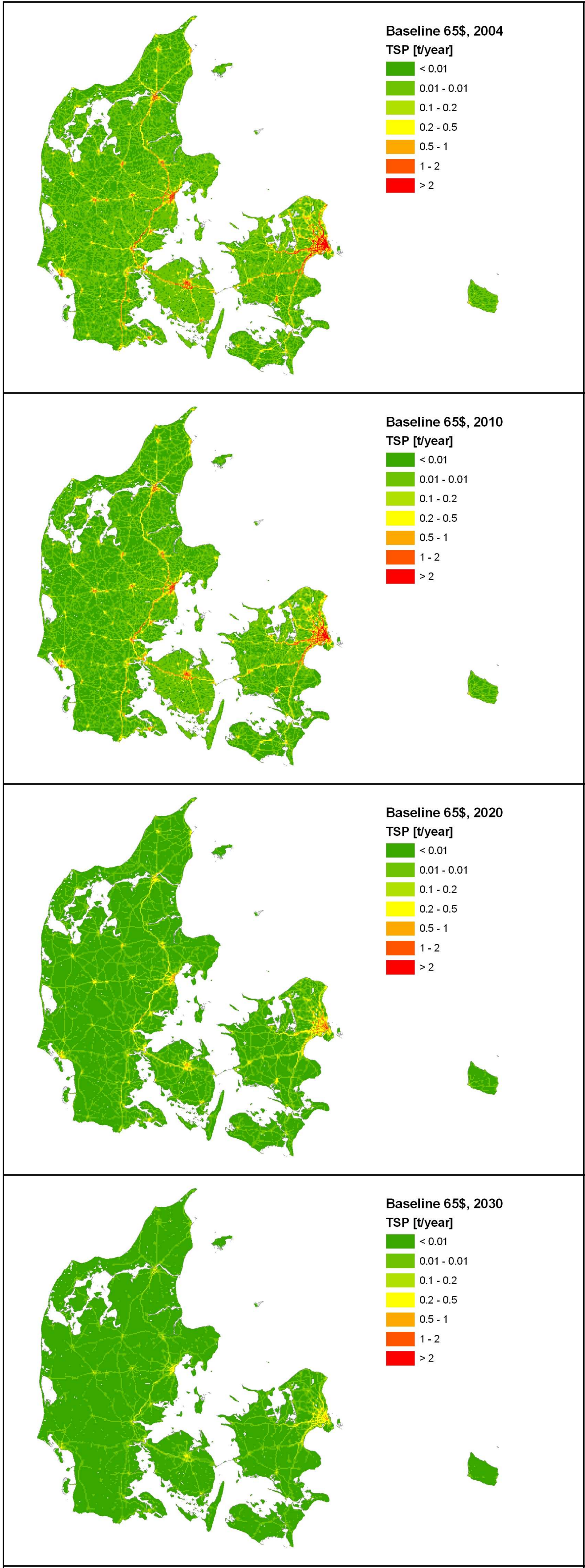


Figure 13 Baseline TSP emissions for road transport

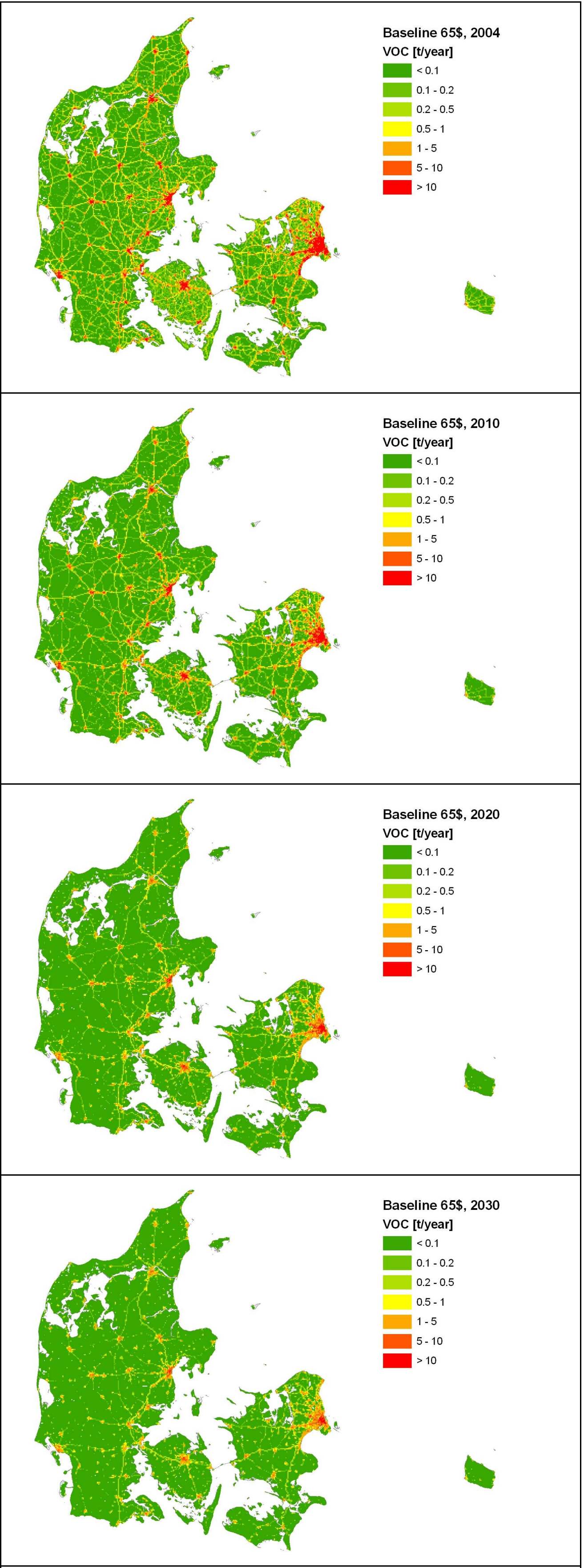


Figure 14 Baseline VOC emissions for road transport

7.4 Fuel consumption and emissions differences between baseline and biofuel scenarios

The fuel consumption and emission results for the baseline and biofuel scenarios are shown in Table 6, for the 65$ and 100$ mileage scenarios, respectively.

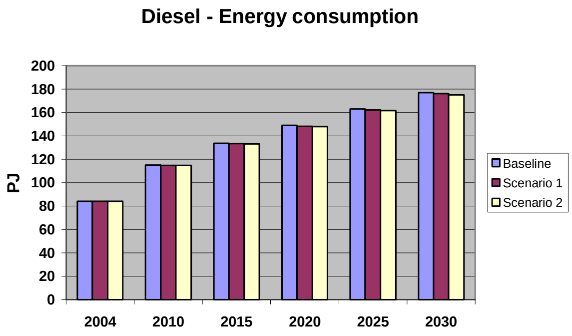
For the 65$ scenario, the percentage differences between 2004 and 2030 for the baseline and biofuel (Scenario 1, Scenario 2; results in brackets) scenarios are 43 %[42 %, 41 %] for fuel consumption, 43 %[28 %, 6 %] for CO_2 emissions, -81 %[-81 %, -81 %] for NO_x, -89 %[-90 %,-91 %] for PM, -82 %[-81 %, -80 %] for CO, and -78 %[-78 %, -77 %] for VOC.

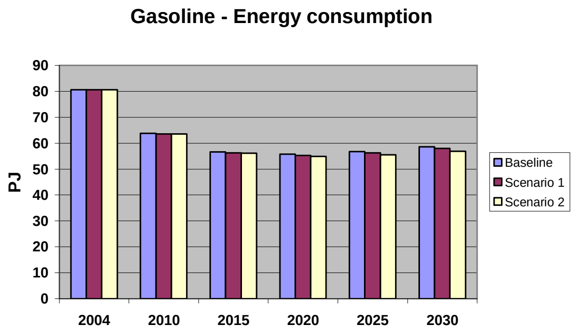
For the 100$ scenario, the percentage differences between 2004 and 2030 for the baseline and biofuel (Scenario 1, Scenario 2; results in brackets) scenarios are 23 %[22 %, 21 %] for fuel consumption, 23 %[10 %, -9 %] for CO_2 emissions, -84 %[-84 %, -84 %] for NO_x, -91 %[-91 %,-92 %] for PM, -84 %[-84 %, -83 %] for CO, and -79 %[-79 %, -79 %] for VOC.

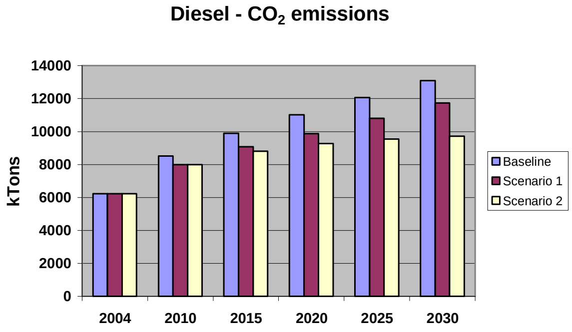
Table 6 Fuel consumption and emission results for the baseline and biofuel scenarios calculated in the present study

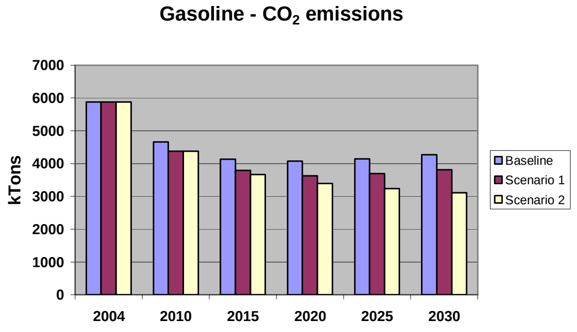
Mileage forecast: 65 $								Mileage forecast: 100 $							
Scenario	Year	Energy	NO_x	VOC	CO	CO_2	TSP	Scenario	Year	Energy	NO_x	VOC	CO	CO_2	TSP
		PJ	Tons	Tons	Tons	kTons	Tons			PJ	Tons	Tons	Tons	kTons	Tons
Baseline	2004	165	75960	29470	200099	12114	2854	Baseline	2004	165	75960	29470	200099	12114	2854
Baseline	2010	179	60389	16824	116153	13170	2297	Baseline	2010	161	56186	15431	103520	11868	2087
Baseline	2015	190	44868	10957	70500	14035	1430	Baseline	2015	169	40830	10142	63007	12460	1279
Baseline	2020	205	29011	8364	48727	15101	847	Baseline	2020	180	25866	7785	43766	13268	750
Baseline	2025	220	18959	7155	39462	16220	465	Baseline	2025	191	16593	6638	35341	14105	410
Baseline	2030	236	14197	6566	36135	17370	304	Baseline	2030	203	12244	6046	32071	14946	267
Scenario 1	2010	178	61284	16400	116795	12378	2215	Scenario 1	2010	161	56991	15053	104045	11154	2013
Scenario 1	2015	190	45523	10774	71218	12873	1361	Scenario 1	2015	168	41424	9979	63602	11431	1217
Scenario 1	2020	204	29474	8305	49692	13511	796	Scenario 1	2020	179	26282	7732	44582	11874	706
Scenario 1	2025	219	19244	7147	40492	14515	439	Scenario 1	2025	190	16844	6631	36220	12624	387
Scenario 1	2030	234	14370	6575	37212	15544	288	Scenario 1	2030	202	12393	6054	32993	13377	253
Scenario 2	2010	178	61284	16400	116795	12378	2215	Scenario 2	2010	161	56991	15053	104045	11154	2013
Scenario 2	2015	189	45659	10774	71491	12474	1337	Scenario 2	2015	168	41553	9977	63830	11077	1196
Scenario 2	2020	203	29651	8333	50296	12658	770	Scenario 2	2020	178	26444	7755	45094	11125	682
Scenario 2	2025	217	19429	7231	41744	12780	413	Scenario 2	2025	189	17009	6703	37287	11118	365
Scenario 2	2030	232	14484	6717	39133	12823	266	Scenario 2	2030	200	12493	6176	34634	11039	234

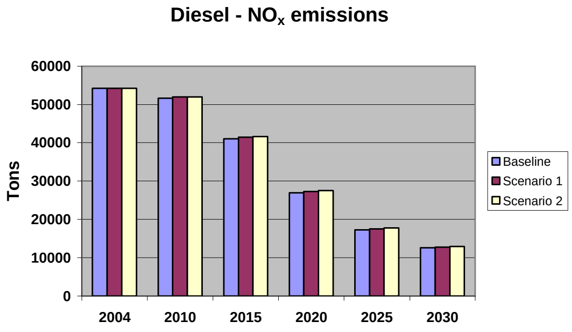
The fuel consumption and emission results for the baseline and biofuel scenarios are shown in Figure 15, split into fuel type for the 65$ mileage forecast. The following trend and emission difference explanations given for the 65$ mileage forecast results, are valid for the 100$ scenario also.

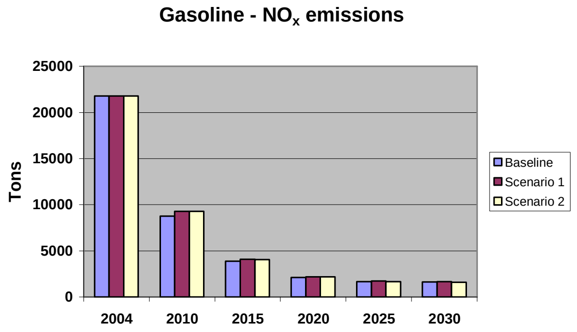

Diesel - Energy consumption
PJ
0
20
40
60
80
100
120
140
160
180
200
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2

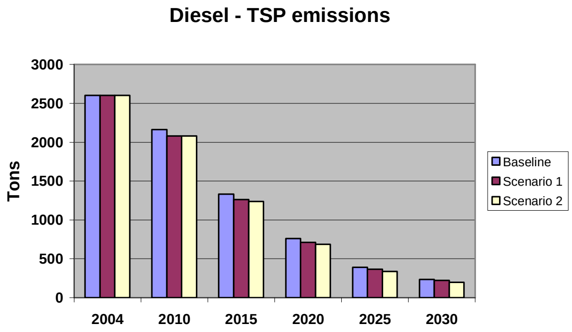

Gasoline - Energy consumption
PJ
0
10
20
30
40
50
60
70
80
90
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2

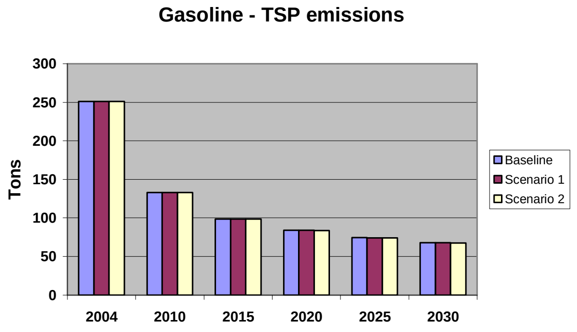

Diesel - CO_2 emissions
kTons
0
2000
4000
6000
8000
10000
12000
14000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2

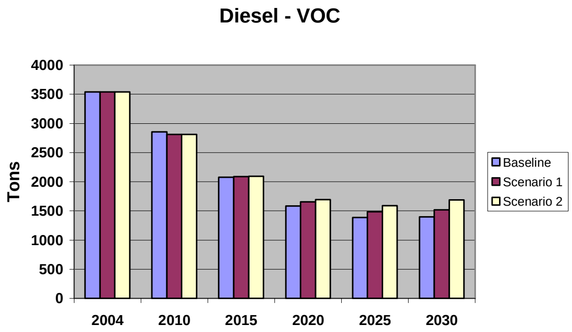

Gasoline - CO_2 emissions
kTons
0
1000
2000
3000
4000
5000
6000
7000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2

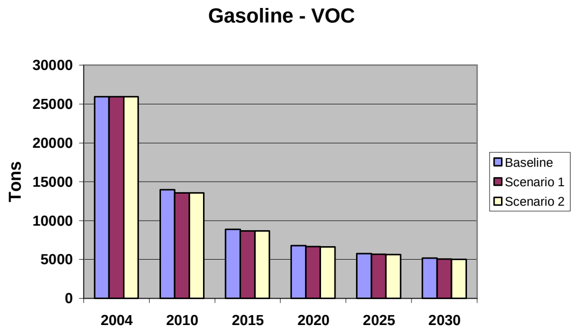

Diesel - NO_x emissions
Tons
0
10000
20000
30000
40000
50000
60000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2


Gasoline - NO_x emissions
Tons
0
5000
10000
15000
20000
25000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2


Diesel - TSP emissions
Tons
0
500
1000
1500
2000
2500
3000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2


Gasoline - TSP emissions
Tons
0
50
100
150
200
250
300
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2


Diesel - VOC
Tons
0
500
1000
1500
2000
2500
3000
3500
4000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2


Gasoline - VOC
Tons
0
5000
10000
15000
20000
25000
30000
2004
2010
2015
2020
2025
2030
Baseline
Scenario 1
Scenario 2

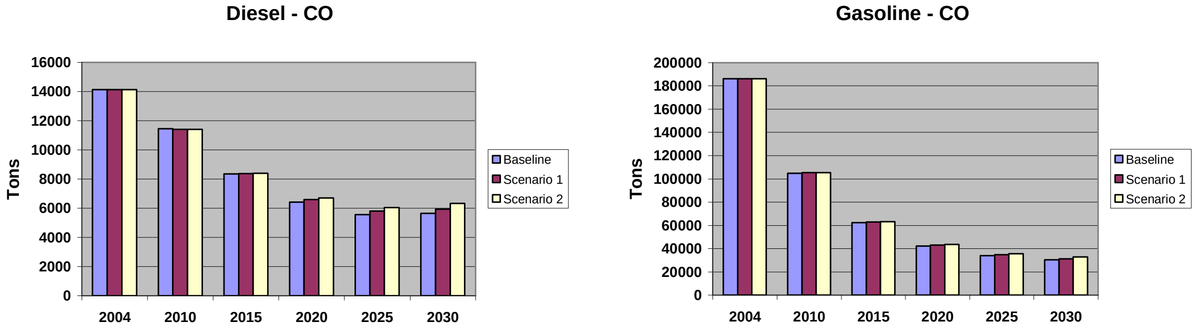


Figure 15 Baseline, and scenario 1 and 2 energy consumption and emission results per fuel type in the scenario years

As shown in Figure 15, 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 7 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 Biofuel scenario 2 during the forecast period. The reason is that the biodiesel and bioethanol is regarded as CO_2 neutral for exhaust emissions. The well to wheel emission consequences of introducing biofuels in the road transport sector, including the entire chain from agricultural production to manufacturing, distribution and engine combustion of the biofuel is treated in a different part of the present project (Slentø et al., 2010).

For NO_x, VOC, CO and PM, large emission reductions for gasoline vehicles are noted due to the combination of strengthened emission standards for future engine technologies in general, and fuel consumption declines in the first part of the forecast period. For diesel vehicles the emission limits are also gradually lowered in the future, the increase in fuel consumption however, tends to outbalance the positive environmental effects of cleaner engine emission technologies.

For gasoline vehicles, the small difference in NO_x emissions between the baseline scenario and the two biofuel scenarios, is the weighted result of the small increase in NO_x emissions for vehicles using E5 and the somewhat reduced NO_x emissions related to E85 usage by modern cars (c.f. Figure 9) for which the absolute emission levels are already low. The generally low CO, VOC and PM emission levels for modern cars, and the E85 share of total fuel consumption by gasoline vehicles, also explain why the impact of using bioethanol is somewhat smaller than the direct emission differences between neat gasoline and E85 shown in Figure 9.

For diesel vehicles, the emission differences between the baseline scenario and the two biofuel scenarios for NO_x, CO, VOC and PM shown in Figure 15, results from the combination of the emission differences between neat diesel and different diesel-biodiesel blends for cars/vans and heavy duty vehicles shown in the Figures 7 and 8. Due to the increasing number of diesel cars in the forecast period, the weight of the diesel-biodiesel emission differences from this vehicle type become more and more important in the calculated totals.

The following summary Table 7 shows the percentage differences between baseline and biofuel scenario 1 and 2 for fuel consumption and emissions calculated in the REBECa project (c.f. Table 6).

The emission consequences of using biofuel in road transport even at blend ratios up to 25 % are small. For NO_x and VOC the absolute differences between the baseline and biofuel scenarios are less than 3 %. For CO and exhaust PM the largest emission differences, 8 % and -13 %, respectively, occur between the baseline and biofuel scenario 2 in 2030, related to a biofuel share of 25 %. CO is however of less environmental concern, and if for PM the emission contribution coming from non exhaust is included in a total PM assessment, the emission differences between baseline and biofuel scenarios become considerably smaller (c.f. Section 7.1).

Table 7 Fuel consumption and emission percentage differences between baseline and biofuel scenario 1 and 2

		Mileage forecast: 65 $									Mileage forecast: 100 $								
Scen.	Year	En	NO_x	VOC	CO	CO_2	PM	TSP	PM_{10}	$PM_{2.5}$	En	NO_x	VOC	CO	CO_2	PM	TSP	PM_{10}	$PM_{2.5}$
							Exh.	Exh. + Non exh.								Exh.	Exh. + Non exh.		
S. 1	2010	-0,3	1,5	-2,5	0,6	-6,0	-3,6	-1,6	-2,0	-2,5	-0,3	1,4	-2,4	0,5	-6,0	-3,6	-1,6	-2,0	-2,5
	2015	-0,4	1,5	-1,7	1,0	-8,3	-4,9	-1,5	-2,0	-2,8	-0,4	1,5	-1,6	0,9	-8,3	-4,8	-1,5	-2,0	-2,8
	2020	-0,6	1,6	-0,7	2,0	-10,5	-6,0	-1,2	-1,7	-2,5	-0,6	1,6	-0,7	1,9	-10,5	-6,0	-1,2	-1,7	-2,5
	2025	-0,6	1,5	-0,1	2,6	-10,5	-5,6	-0,7	-1,0	-1,5	-0,6	1,5	-0,1	2,5	-10,5	-5,6	-0,7	-0,9	-1,5
	2030	-0,6	1,2	0,1	3,0	-10,5	-5,2	-0,4	-0,6	-1,0	-0,6	1,2	0,1	2,9	-10,5	-5,1	-0,4	-0,6	-1,0
S. 2	2010	-0,3	1,5	-2,5	0,6	-6,0	-3,6	-1,6	-2,0	-2,5	-0,3	1,4	-2,4	0,5	-6,0	-3,6	-1,6	-2,0	-2,5
	2015	-0,6	1,8	-1,7	1,4	-11,1	-6,5	-2,1	-2,7	-3,7	-0,6	1,8	-1,6	1,3	-11,1	-6,5	-2,1	-2,7	-3,7
	2020	-0,9	2,2	-0,4	3,2	-16,2	-9,1	-1,9	-2,6	-3,9	-0,9	2,2	-0,4	3,0	-16,2	-9,1	-1,9	-2,6	-3,8
	2025	-1,3	2,5	1,1	5,8	-21,2	-11,2	-1,3	-1,9	-3,0	-1,3	2,5	1,0	5,5	-21,2	-11,1	-1,3	-1,9	-3,0
	2030	-1,6	2,0	2,3	8,3	-26,2	-12,7	-0,9	-1,4	-2,3	-1,6	2,0	2,2	8,0	-26,1	-12,4	-0,9	-1,4	-2,3

The emission difference functions established in this project are a key fundament for the calculations made in REBECa to assess the emission consequences of using biofuel in the Danish road transport. As discussed by Winther (2009 & 2010) mainly due to the limited emission data available from the literature, such emission difference functions are associated with some uncertainties, and consequently, caution must be applied to their use for emission calculation purposes.

For heavy-duty vehicles with Euro 3 and earlier engines, the fuel consumption/emission differences between neat diesel and different diesel-biodiesel blend ratios are well examined, whereas for Euro 4 and 5 heavy-duty engines, the average emission difference functions rely on a small number of measurements. The experimental data are even sparser for diesel passenger cars and vans for which the average functions are based on four experimental studies mainly testing Euro 3 cars. For gasoline vehicles using E5 and E85, the number of tested vehicles behind the emission difference functions are also small, 9 and 5, respectively, and large standard deviations are calculated for most of the emission species

It is straightforward to conclude that further emission measurements are needed in order to establish more precise expressions of the emission differences between fossil fuel and biofuel blends for Euro 4 and 5 heavy-duty diesel engines, as well as for cars and vans in general. For the two latter vehicle categories, most importantly measurements are required from the modern Euro 4 and 5 technologies, so that the majority of vehicle mileage driven today can be covered from a traffic composition point of view, and in order to take into account the gradual technology turnover in the future vehicle fleet.

8. References

Dalbro, S. 2007: Unpublished data material from Statistics Denmark.

Danish Energy Authority (2008): Energy Statistics 2007, 56 pp. available at: http://www.ens.dk/graphics/Publikationer/Statistik/Energistatistik%202007_Web.pdf

Delgado, R. (2003): "Comparison of vehicle emissions at European Union annual average temperatures from E0 and E5 petrol", Report LM030411, IDIADA AUTOMOTIVE TECHNOLOGY, 22 pp.

de Serves C., (2005): "Emissions from Flexible Fuel Vehicles with different ethanol bends", Report Nr. AVL MTC 5509, ISSN 1103-0240, 46 pp.

Durbin, T.D., Cocker, D.R., Sawant, A.A, Johnson, K., Miller, J.W., Holden, B.B., Helgeson, N.L., Jack, J.A. (2007): Regulated emissions from biodiesel fuels from on/off-road applications, Atmospheric Environment 41 (2007) 5647–5658

Ekman, B. 2005: Historical traffic data. Unpublished data material from the Danish Road Directorate.

EMEP/EEA, 2009: Air Pollutant Emission Inventory Guidebook, prepared by the UNECE/EMEP Task Force on Emissions Inventories and Projections (TFEIP). Available at http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009 (02-02-2010).

EPA (2002): A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions Draft Technical Report Environmental Protection, EPA420-P-02-001, United States Environmental Protection Agency, October 2002

Fontaras, G., Samaras, Z., Miltsios, G. (2007): Experimental Evaluation of Cottonseed Oil-Diesel Blends as Automotive Fuels via Vehicle and Engine Measurements, , SAE paper 2007-24-0126.

Fontaras, G., Tzamkiozis, T., Pistikopoulos, P., Samaras, Z. (2008): Experimental evaluation of biodiesel impact on vehicle regulated and non-regulated exhaust emissions over legislated and real world driving cycles, Transport and Air Pollution, 17th Symposium, 16th-17th June 2008.

Foldager, I. 2007: Unpublished data material from the Danish Road Directorate.

Fosgerau et al. (2007): Langsigtet fremskrivning af vejtrafik. Indikation af fremtidige problemområder - Baggrundsrapport. Danmarks Transportforskning. Rapport 2: 50 pp. (elektronisk). Findes på http://www.transport.dtu.dk/upload/institutter/dtu%20transport/pdf_dtf/rapporter/rapporter%202007/fremskrivning%20af%20trafikken_baggrund.pdf.

Hull A., Golubkov I., Kronberg B., Marandzheva T., van Stam J. (2005): "An alternative fuel for spark ignition engines", International Journal of Engine Research, vol. 7, 203-214.

Jensen, T.C., Winther, M. 2009: Fremskrivning af vejtransportens energiforbrug til REBECa-projektet, internal research note, 16 pp.

Markamp 2007: Personal communication, Henrik Markamp, The National Motorcycle Association.

Martini, G., Astorga, C., Farfaletti, A. (2007a): Effect of Biodiesel Fuels on Pollutant Emissions from EURO 3 LD Diesel Vehicles (1), report EUR 22745 EN, Institute for Environment and Sustainability, Joint Research Centre.

Martini G., Manfredi U., Mellios G., Mahieu V., Larsen B., Farfaletti A., Krasenbrink A., De Santi G., (2007b), "Joint EUCAR/JRC/CONCAWE study on: Effects of gasoline vapour pressure and ethanol content on evaporative emissions from modern cars", EUR 22713 EN.

McCormick, R.L., Tennant, C.J., Hayes, R.R., Black, S., Ireland, J., McDaniel, T., Williams, A., Frailey, M., Sharp, C.A. (2005): Regulated Emissions from Biodiesel Tested in Heavy-Duty Engines Meeting 2004 Emission Standards; SAE paper 2005-01-2200.

Martini, G., Astorga, C., Adam, T., Farfaletti, A. Manfredi, U., Montero, L., Krasenbrink, A., Larsen, B., De Santi, G. (2009): Effect of Fuel Ethanol Content on Exhaust Emissions of a Flexible Fuel Vehicle, EUR 24011 EN – 2009.

Nielsen, O.K., Winther, M., Mikkelsen, M.H., Lyck, E., Nielsen, M., Hoffmann, L., Gyldenkærne, S. & Thomsen, M. 2009: Projection of Greenhouse Gas Emissions. 2007 to 2025. National Environmental Research Institute, University of Aarhus. 211 s. NERI Technical Report 703.

Slentø, E., Møller, F., Winther, M. 2010: Integreret well-to-wheel-analyse af biobrændstoffer - scenarieberegninger for produktion og brug af raps-diesel og 1. og 2. generations bioethanol, mht. energi-forbrug, emissioner og velfærdsøkonomiske konsekvenser *(NERI Technical report to be published).*

Teknologirådet 2006: Energikatalog - Morgendagens Transportbrændstoffer. Danske perspektiver. Rapport 2006/15, ISSN 13959372/ISBN 87-91614-29-5, 68 sider (in Danish).
The Danish Infrastructure Commission (2008): The Danish Infrastructure Commission: The Danish Transport Infrastructure 2030 (Summary in English)

Trafikministeriet 2002: Vejsektorens emissioner. Dokumentationsnotat, ISBN: 87-91013-28-3, Trafikministeriet, november 2002.

Westerholm, R., Ahlvik, P., Karlsson H.L. (2008): An exhaust characterisation study based on regulated and unregulated tailpipe and evaporative emissions from bi-fuel and flexi-fuel light duty passenger cars fuelled by petrol (E5), bioethanol (E70, E85) and biogas tested at ambient temperatures of +22 °C and -7 °C, Final report, March 2008, 182 pp.

Winther, M. 2008: Danish emission inventories for road transport and other mobile sources. Inventories until year 2006. National Environmental Research Institute, University of Aarhus. 219 pp. – NERI Technical Report No. 686. (http://www.dmu.dk/Pub/FR686.pdf.)

Winther, M. 2009: Emission Differences between Petroleum based Diesel and different Biodiesel Blend Ratios for Road Transport Vehicles. / Winther, Morten. 2009. Transport and Air Pollution Symposium - 3rd Environment and Transport Symposium, nr. 17, Toulouse, Frankrig, 2. juni 2009 - 4. juni 2009.

Winther, 2010: Emission Differences between Neat Gasoline and E5 and E85 Gasoline-bioethanol fuel blends for Passenger Cars, internal research note 7 pp.