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Agence de l'Environnement et de la Maîtrise de l'Energie ADEME (FR)
Trafikverket (SE)
Miljødirektoratet (NO)

HBEFA 4.2
Documentation of updates

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Content

Glossary

a	year
BEV	Battery-electric vehicle
CO_2**e**	CO_2 equivalent
EV	Electric vehicle (includes BEV, PHEV, FCEV)
CNG	Compressed natural gas
FCEV	Fuel-cell electric vehicle (fuel cell fuelled by hydrogen)
GHG	Greenhouse gas (CO_2, CH_4, N_2O)
GWP	Global warming potential
HDV	Heavy-duty vehicle (trucks and buses)
HGV	Heavy goods vehicle (truck/lorry)
kt	kilotonnes = 10^3 tonnes
ICCT	International Council on Clean Transportation
LCV	Light commercial vehicle
LDV	Light-duty vehicle (includes PC and LCV)
LNG	Liquefied natural gas
MC	Motorcycle
PC	Passenger car
PHEV	Plug-in hybrid electric vehicle
TT/AT	Truck/trailer combination or articulated truck (as opposed to rigid truck)
TTW	“Tank-to-wheel”: direct emissions from the use of road vehicles
UF	Utility factor (share of mileage of PHEV driven on electricity, i.e. in charge-depleting mode)
vehkm, vkm	vehicle kilometers
WLTP/WLTC	Worldwide harmonized Light vehicles Test Procedure/Cycle: Test procedure and corresponding driving cycle for type approval of LDV, in force in EU from 2017
WTT	“Well-to-tank”: emissions from the production of energy
WTW	“Well-to-wheel”: emissions from the use of road vehicles and from the production of the required energy (i.e. WTW emissions = TTW emissions + WTT emissions; see respective glossary entries above)

1. Overview of updates in HBEFA 4.2

1.1. Input updates

HBEFA 4.2 can be considered a “light update” of Version 4.1 (comparable e.g. to Version 3.3 relative to 3.2). Only the most urgent updates from the point of view of the funding national environment agencies have been implemented.

The inputs into HBEFA updated with Version 4.2 are listed as an overview in Table 1. The subsequent chapters of this documentation contain further details on each update.

Table 1: Overview of input updates in HBEFA Version 4.2

Update	Remarks
Hot EF for HDV Euro-VI	Differentiated by steps A-C vs. D-E
Deterioration functions HDV	Based on CONO$_x$ RS data; new speed-dependent input format due to SCR behaviour of HDV
Deterioration functions for NO_2/NO_x ratios	Accounting for lower NO_2 shares in NO_x for aged catalysts
Additional software updates of Diesel PC	Software-updated PC Diesel Euro-5 other than EA189 and Euro-6ab
Hot EF for PC BEV	Accounting for PHEM model updates
Well-to-tank GHG EF	Addition of production types lacking so far (for PtX, bioethanol, biodiesel)
Real-world energy consumption of electric vehicles	Integration of TA electricity consumption of BEV from EEA CO_2 monitoring DB, real-world electricity consumption of BEVs and fuel consumption of PHEVs from Spritmonitor, and PHEV utility factors based on ICCT White Paper (Plötz et al. 2020)
Update of cumulative mileage methodology	HGV: transformation of registered tractors to tractor-trailor combinations reflected in cumulative mileage; mileage-weighted averages by subsegment and reference year; cumulative mileage also calculated for fleet subscenarios that do not include vehicle stock
Country data	Comprehensive updates for Germany, France, Sweden, and Switzerland; partial updates for Norway and Austria
New information included in "Info" menu of Public Version	Mileage and temperature dependencies, energy/fuel properties and fuel mixes
Derived subsegments	Changes to the following subsegments (feedback from AVL): ▪ PC CNG/Petrol Euro 2-3 ▪ PC LPG/Petrol all Euro 2-6 ▪ PC FFV Euro 4-6 ▪ LCV CNG/Petrol and LNG/Petrol Euro 6 ▪ UBus CNG Euro II-IV ▪ UBus LNG Euro IV-VI ▪ UBus Ethanol Euro II-VI
CO_2e calculation	Bugfix: Now also fully calculated if CH_4 and N_2O not selected by user

1.2. Effects on emission factors

1.2.1. Types of effects

The effects on emission factors include:

- effects on base emission factors, i.e. at the most detailed level (subsegment/individual traffic situation at 50'000 km cumulative mileage and 20°C), independent of country-specific data such as fleet compositions, aging, climate etc.;
- effects on final emission factors including the effects of country-specific activity data, e.g. aging, climate, or utility factors, as well as all aggregations at higher levels (e.g. emission concept, technology, vehicle category) that are influenced by the fleet compositions and traffic situation distributions. Some countries (DE, FR, SE, CH) have updated their input data for HBEFA Version 4.2, while others (AT, NO) are using basically the same activity data as for HBEFA 4.1 (see also Chapter 4).
  However, the introduction of the newly differentiated HDV Euro-VI D-E and the newly considered additional Diesel PC software updates has been considered for all countries (including AT and NO).

1.2.2. Effects on base emission factors

The changes in base emission factors in HBEFA 4.2 compared to HBEFA 4.1 include (see Chapter 3 for details):

- The hot air pollutant emission factors of Euro-VI D-E HDV decrease significantly (as a result of the stricter type approval process for these steps). E.g NO_x emission factors decrease by 25% to 80% (generally more for trucks and coaches than for urban buses).
- For urban buses, emission factors have also been updated for Euro-VI A-C vehicles due to the availability of additional measurement data (for HBEFA 4.1, only one vehicle had been measured; recent RS data have shown that it was not representative for the whole fleet). The new EF are considerably higher.
- NO_2 decreases by varying rates for LDV and HDV as a result of the new deterioration/aging functions of the NO_2/NO_x ratio (see Chap. 3.3). The decrease rates are between 1% and 17%. Generally, the decrease is more pronounced in newer emission concepts, since the improved catalysts reduce NO_x more effectively for new vehicles, which leaves relatively more NO_2 in the exhaust; consequently, the share of NO_2 in NO_x decreases more strongly in the aging process.
- The NO_x emission factors of the additional software-updated Diesel PC (i.e. Euro-5 other than the VW EA189 engines, which were already covered in HBEFA 4.1, and Euro-6ab) are lower than their non-updated counterparts (however, they display a stronger temperature dependence, see Chap. 3.4).

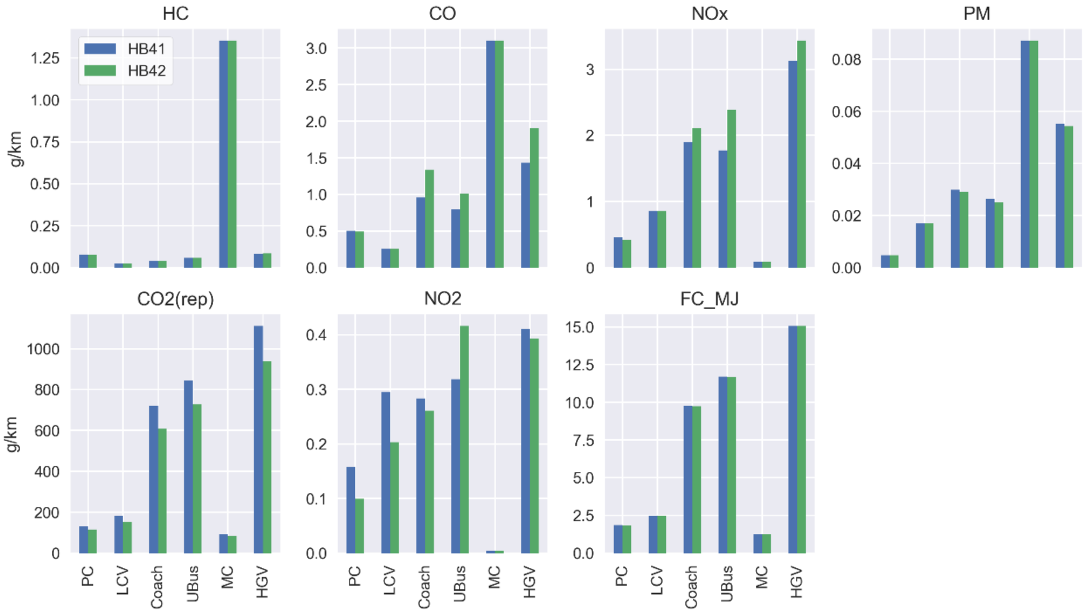
- The base energy consumption factors of PC BEV are slightly reduced, mainly for traffic situations with higher average speed (see Chapter 3.5).

1.2.3. Effects on final emission factors

For countries that have not significantly updated their activity data with the HBEFA light update 4.2, the average emission factors by vehicle category mostly reflect the changes to the base emission factors (see previous chapter). Figure 1 illustrates this with average EF by vehicle category for the year 2020 for Norway:

- NO_x and CO EF have increased for all HDV categories. The effect of the updated deterioration functions dominates over the lower emission factors of the Euro-VI D-E vehicles, which account for approximately 8% of total HDV mileage in 2020.
- The effect of the additional software updates (Euro-5 other than EA189 and Euro-6ab) results in a roughly <8% reduction of average NO_x PC EF. The affected vehicles account for about 6.5% of the passenger car fleet mileage in 2020.
- NO_2 EF have decreased for all vehicle categories except MC and urban buses. The decrease of the NO_2/NO_x ratios due to the consideration of catalyst aging overrides the NO_x aging effect for HGV and coaches. Fur urban buses, conversely, the increased NO_x EF due to additional measurements overrides the lowering effect of the NO_2/NO_x ratios.
- CO_2 (reported) has changed for Norway for all vehicle categories because a new fuel mix was added that now contains biofuels.
- The EF of other pollutants have not changed at all, or only slightly due to the above-mentioned updates.

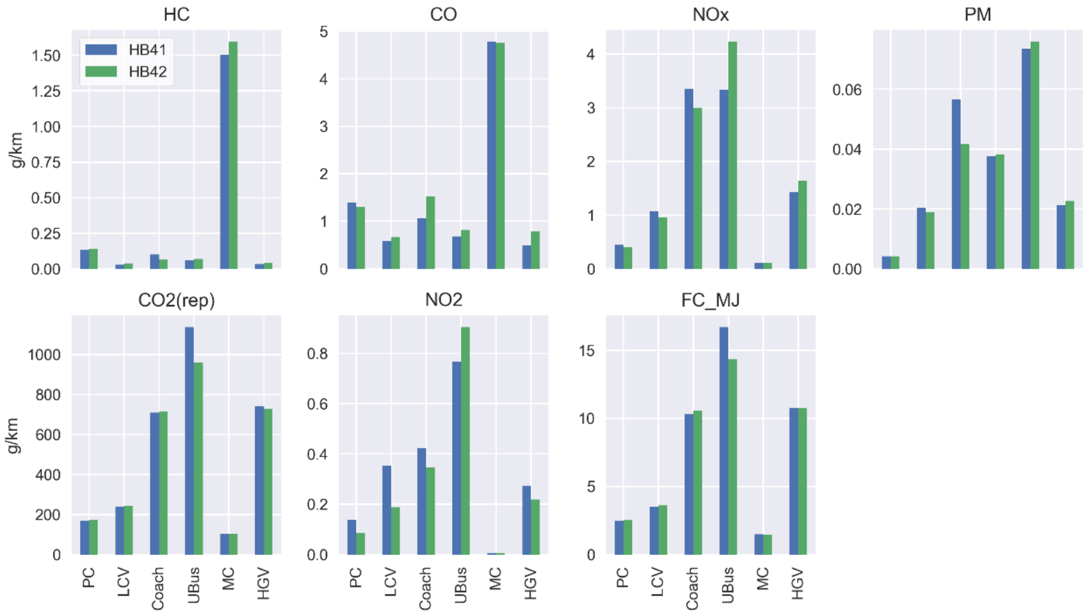
Figure 1: Average emission factors by vehicle category for the year 2020 for Norway (unchanged activity data from HBEFA 4.1 to 4.2)



Graphics by INFRAS. Source: HBEFA 4.1, HBEFA 4.2

For countries with updated activity data, there are additional considerable changes in the resulting average EF due to effects of changed fleet composition (e.g. different fleet compositions, different traffic situation distributions, different weights of hot/cold start emissions etc.). A comparison between emission factors from HBEFA 4.1 and HBEFA 4.2 for Germany is shown in Figure 2.

Figure 2: Average emission factors by vehicle category for the year 2020 for Germany

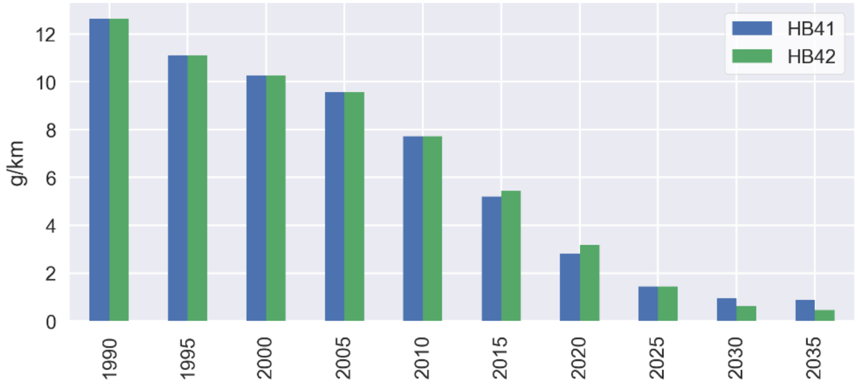


Graphics by INFRAS. Source: HBEFA 4.1, HBEFA 4.2

Over the whole timeseries, NO_x emissions for HDV increase or decrease depending on the reference year (Figure 3):

- For years before Euro VI vehicles enter the fleet there is no change in emission factor.
- For reference years in which Euro-VI A-C vehicles dominate in terms of total mileage (i.e. around the year 2023), an increase is observed due to the updated deterioration functions
- For reference years in which Euro-VI D-E vehicles dominate, the decrease of the D-E emission factors overrides the effect of aging.

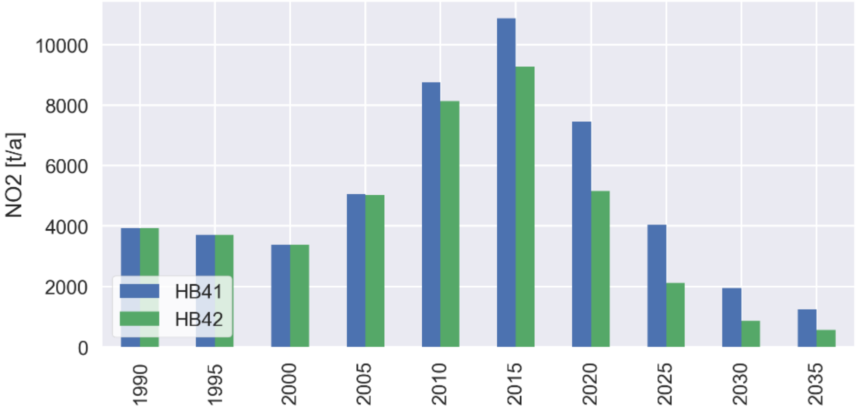
Figure 3: Average NO_x EF for HDV in Norway, 1990 – 2035, in HBEFA 4.1 and 4.2



Graphics by INFRAS. Source: HBEFA 4.1, HBEFA 4.2

Overall road transport related NO_2 emissions in Norway decrease by about 7% (around the year 2010) to over 55% (after 2030) due to the consideration of catalyst aging and the associated decrease of the NO_2 to NO_x ratio with age. The decrease of the base emission factors (see above) overcompensates the aging effect even for Euro-VI A-C HDV (Figure 4).

Figure 4: Total road transport NO_2 emissions for Norway, 1990 – 2035, using HBEFA 4.1 and 4.2



Graphics by INFRAS. Source: HBEFA 4.1, HBEFA 4.2

Average final energy consumption (FC_MJ) of BEV PC has not changed considerably with the update. Since a base correction factor has been derived on the basis of Spritmonitor real-world consumption for both HBEFA 4.1 and 4.2, which scaled the HBEFA 4.1 base EF down to the average level of the HBEFA 4.2 base EF, the differences are minimal. Since at the level of individual traffic situations, mainly the high-velocity situation EF have decreased, this results in an overall decrease by < 1% for a country like Germany with a high share of high-velocity motorway TS, and an overall increase by < 1% for most other countries.

PHEV PC have experienced rather large increase in energy consumption (and air pollutant emissions) due to the lower utility factors[1] (UF, i.e. electric driving shares) derived from the ICCT White Paper on PHEV (Plötz et al. 2020). Furthermore, an error in the base correction factors for PHEV in combustion mode for all countries was corrected that results in an additional increase in energy consumption in charge sustaining mode. The overall increase in final energy consumption of PHEV PC ranges from -5% (Norway) to approx. 30% (Germany), depending on the country. It must be stressed, however, that the uncertainty in PHEV utility factors for the HBEFA countries is subject to large uncertainty – on one hand due to the fact that the ICCT (2020) White Paper did not cover most HBEFA countries, and on the other hand due to the effect of company cars, which tend to display lower UF nowadays, which may rapidly change in the near future.

2. Remarks on the application

2.1. Memory limitations in MS Access

HBEFA sometimes reaches the limits of random-access memory available to MS Access. This problem has occurred more frequently with each new HBEFA version due to the increasing data amounts. Already in Version 4.1, it occurred more frequently than in the 3.x versions due to a significant increase in both the number of subsegments and traffic situations. In Version 4.2, the data amount has increased again, so this error is to be expected even more frequently. Since it is a limitation of MS Access, i.e. the software platform in which HBEFA is implemented, the solution for this problem will be migrating HBEFA to a different software platform. This is planned for the next major version 5.1.

For the current Version 4.2, however, users of HBEFA unfortunately still have to accept this inconvenience. In order to raise the awareness of HBEFA users of this problem, an “important information” box with a bold red outline has been added on the start screen of HBEFA 4.2. A button “memory limitations in MS Access” displays the most important pieces of advice to cope with the memory limitations (Figure 5).

The same information has already been available in the Help file for HBEFA 4.1 and it continues to be available there, but the new info box should make sure users do not overlook it.

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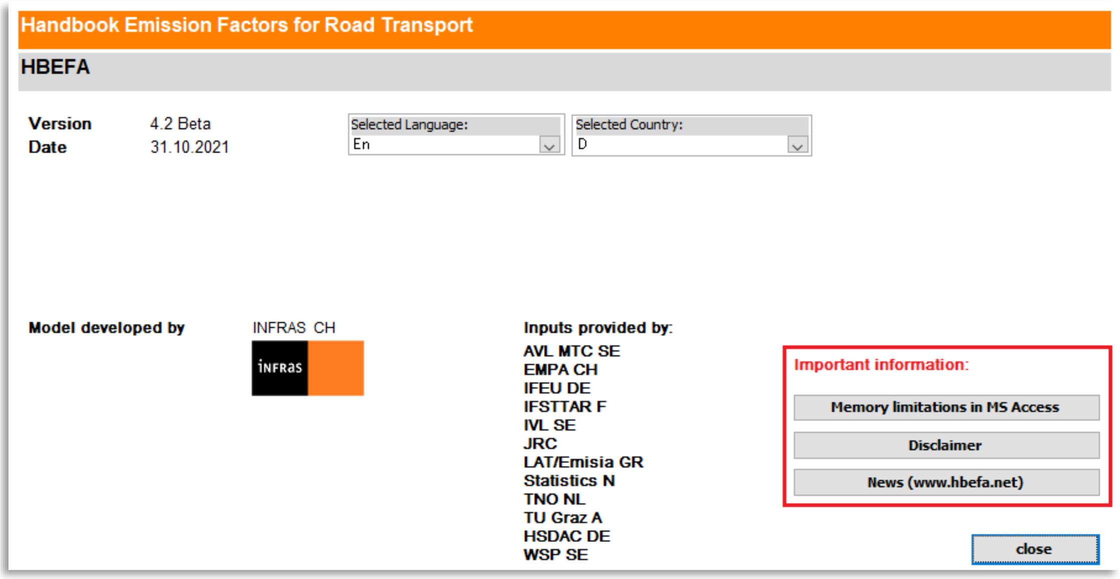
[1] With the exception of Norway and France, which had rather conservative UF for PHEV PC in HBEFA 4.1.

Figure 5: Start screen of HBEFA 4.2 with the “important information” box outlined in red.



Handbook Emission Factors for Road Transport

HBEFA

Version 4.2 Beta
Date 31.10.2021

Selected Language: En
Selected Country: D

Model developed by INFRAS CH

Inputs provided by:
AVL MTC SE
EMPA CH
IFEU DE
IFSTTAR F
IVL SE
JRC
LAT/Emisia GR
Statistics N
TNO NL
TU Graz A
HSDAC DE
WSP SE

Important information:

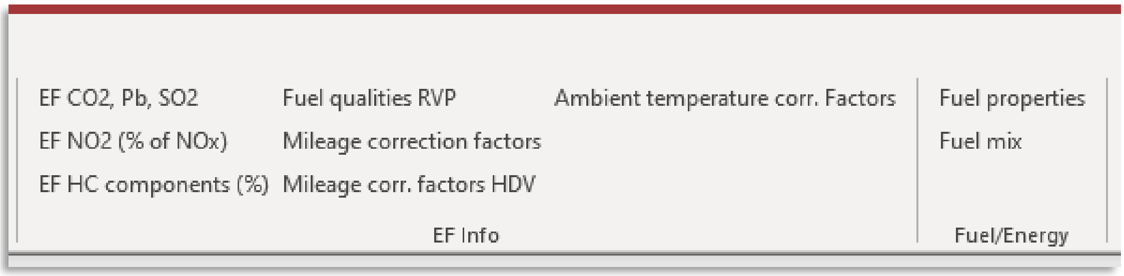
Graphics by INFRAS. Source: HBEFA 4.2

2.2. New “Info” menu items

We have included some additional background information under the menu “Info” (Figure 6):

- Energy properties
- Fuel mixes
- Deterioration functions
- Ambient temperature functions

Figure 6: Additional „Info“ menu items in HBEFA 4.2.



Graphics by INFRAS. Source: HBEFA 4.2

3. Country-independent contents

3.1. New hot EF for Euro-VI HDV

3.1.1. Introduction

The introduction of the emission standard Euro VI step D[2] extends the regulatory test conditions in in-service conformity (ISC) tests. The main challenge is the reduction of the average engine power for valid moving average windows (MAW) from 20 % to 10 %. Since the EURO VI emission limits have to be met from EURO VI D on also at lower loads, this leads to an improved real world emission behaviour of HDV especially regarding NO_x. This effect is proven by measurement results in the HBEFA 4.2 data set. This reduction in NO_x emissions was achieved by enhanced catalyst technologies and thermal management strategies.

Since the beginning of 2021 the first vehicles with emission standard Euro VI E are on European roads. Euro VI E includes the cold start phase[3] in the evaluation of ISC tests and requires on-board measurement of PN[4]. To evaluate the effect of these modifications on the real world emission behaviour measurement data is necessary, but until now no emission tests data of Euro VI E vehicles is available. However, it is not expected that Euro VI E comes along with a similar real word hot emission reduction like Euro VI D compared to Euro VI A, B and C. Consequently, Euro VI E hot emission level is assumed to be similar to the one of Euro VI D vehicles at this point.

To consider the improved real world emission behaviour of new HDVs, the category Euro VI is split in 2 groups:

- HDV with emission standard Euro VI A, B and C
- HDV with emission standard Euro VI D and E

3.1.2. Methodology - emission factors for Euro VI A, B and C HDVs

The HDV Euro VI database in HBEFA 4.1 consisted only of vehicles with emission standard Euro VI A, B and C. Since no relevant additional test data for EURO VI A, B and C was available in the meantime, the emission factors of Euro VI A, B and C HGVs and coaches in HBEFA 4.2 are equal to the Euro VI emission factors in HBEFA 4.1.

However, HBEFA 4.2 includes an update of the emission factors of Euro VI ABC city busses. The Euro VI emission factors in HBEFA 4.1 were based on measurement results of only 2 city busses from the same manufacturer and these vehicles seem not to represent the fleet

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[2] 9/2018 for new types, 9/2019 for all new registrations [(EC) 2019/1939]

[3] Evaluation starts after reaching 30°C coolant temperature. The final result is calculated by use of the 100 percentile MAW including cold start phase (weighted with 14 %) and the 90 percentile MAW for the hot phase after reaching a coolant temperature of 70°C (weighted with 86 %).

[4] Until Euro VI D PN was only measured on the test bed.

average as remote sensing results show[5]. Consequently, all Euro VI measurement data (HGVs, coaches and city busses) was pooled together to generate the updated city bus emission model in PHEM as input for HBEFA 4.2. This model was used to calculate the emission factors of city busses according to emission standard Euro VI A, B and C.

3.1.3. Methodology - emission factors for Euro VI D and E HDVs

The database for HBEFA 4.2 comprises 13 vehicles from different vehicle categories (tractor trailer and rigid trucks) with emission standard Euro VI D. The dataset covers vehicles from the OEMs[6] with the highest market shares in Europe and gives consequently a good overview on the current fleet. The different HDV measurement campaigns for HBEFA 4.2 were executed by TU Graz and AVL MTC and were funded by UBA Germany and the Swedish government.

Table 2: Overview on measurement data of Euro VI D vehicles for HBEFA 4.2

Laboratory	HGV	City bus	Total
TUG	10	2	12
AVL MTC	2	-	2
Total	12	2	14

The Euro VI dataset for HBEFA 4.1 has already shown that a sample of 2 city busses does rather not give representative emission factors for this vehicle category, although the 2 city busses are from different OEMS. Consequently, city busses were pooled together with HGVs to one comprehensive emission model.

The methodology for the creation of the emission models was exactly the same as already used for the emission model in HBEFA 4.1. This method is explained in detail in [Weller 2020]:

- Driving resistance parameters: Euro VI DE vehicles come along with improvements of the air drag resistance and the axle efficiency rates.
- All emission data was used to set up emission maps for CO, HC, PM and PN.
- NO_x: Detailed emission models[7] have been set up for 5 vehicles which provided the necessary data (NO_x engine out, temperatures up- and downstream SCR). In order to meet the NO_x emission behaviour of these single vehicles the emission model PHEM was extended and offers now the possibility to integrate special heating strategies for the exhaust gas after treatment system. The entire set of tested vehicles has been used for model calibration.

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[5] The emission levels in g/kg CO2 measured by remote sensing tests in Frankfurt were similar between buses and trucks (Diegmann, 2021)

[6] Mercedes Benz, MAN, Scania, Iveco, DAF and Volvo

[7] The detailed NO_x model in PHEM is using engine out emission maps and simulates the NO_x-conversion in the SCR as function of space velocity in the catalyst and the catalyst temperature.

3.1.4. Results - emission factors HBEFA 4.2

This section gives an overview of the final emission factors for HDVs in HBEFA 4.2. Table 3 shows a comparison of the emission factors for the most important rigid truck and tractor trailer groups in the average German traffic situation. The results show that Euro VI DE vehicles come along with a reduction in fuel consumption, CO emissions and NO_x. HC and PN emissions are increased, but they remain on a low level compared to the specific emission limits.

Table 3: Emission factors for RT and TT/AT, Euro VI ABC and Euro VI D, average German traffic mix

Vehicle category	Emission standard	FC [g/km]	CO [g/km]	HC [g/km]	NO_x [g/km]	PN [g/km]
RT 14-20t HL	Euro VI ABC	194.0	0.187	0.016	0.403	4.8 E10
	Euro VI DE	189.0	0.153	0.024	0.142	7.1 E10
TT/AT 34-40t HL	Euro VI ABC	290.7	0.215	0.022	0.491	6.8 E10
	Euro VI DE	287.3	0.062	0.032	0.213	1.0 E11

Figure 7 and Figure 8 show the emission factors for a typical tractor trailer combination in the German traffic mix from pre Euro (called Euro 0) to Euro VI DE. The first graph shows the improvement in NO_x emissions from Euro VI ABC to Euro VI DE, which is small regarding absolute values compared to the step from Euro V to Euro VI ABC. The second one illustrates the low level of PN emissions of Euro VI vehicles independent of Euro VI ABC or Euro VI DE compared to all former Euro classes. This can be related to the introduction of a PN limit with Euro VI and consequently the comprehensive installation of DPFs in the HDV fleet.

Figure 7: NO_x emission factors HBEFA 4.2, TT 34-40t HL, average German traffic mix

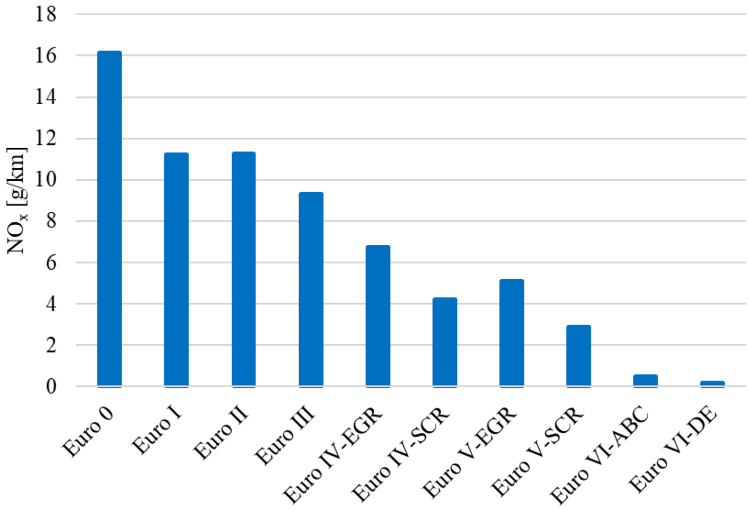


Figure 8: PN emission factors HBEFA 4.2, TT 34-40t HL, average German traffic mix

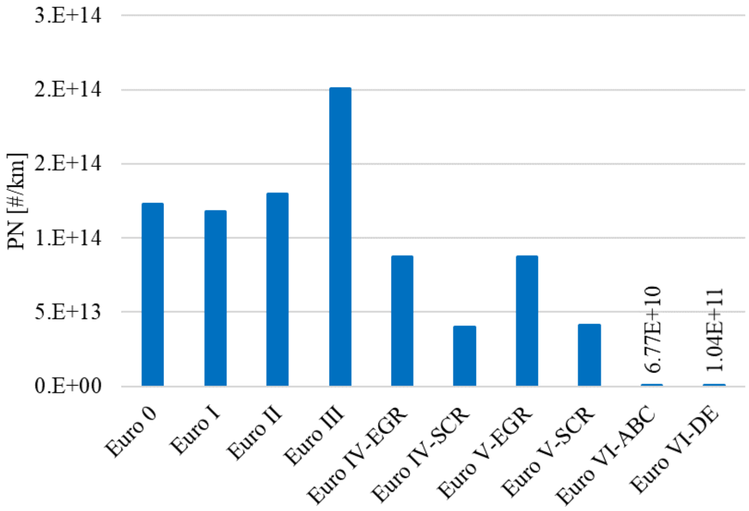
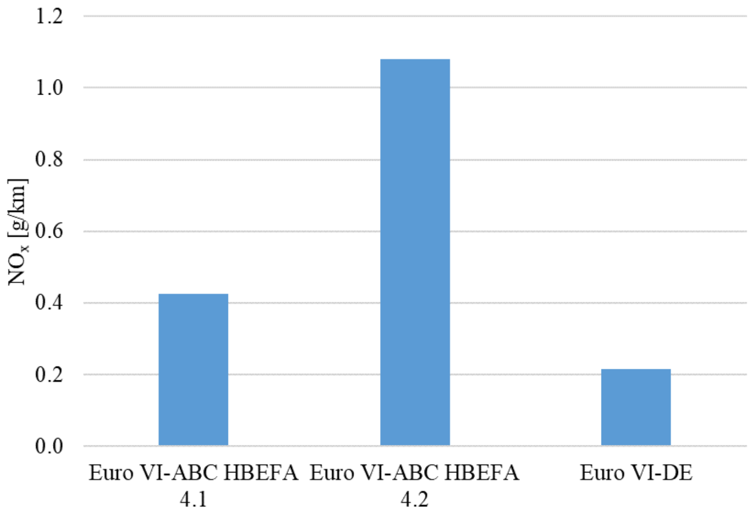


Figure 9 shows the NO$_x$ emission factors for city busses in the average German urban traffic. The updated Euro VI ABC emission model leads to higher emissions compared to the Euro VI ABC model used in HBEFA 4.1. This follows the update of the emission model triggered by the remote sensing measurement results.

The NO$_x$ results for the Euro VI D urban bus is on a lower NO$_x$ level than for EURO VI ABC. The level of the EURO VI D city buses is principally proven by measurement results of 2 urban busses (category CB > 18t) in real world traffic. The average NO$_x$ emissions of these 2 busses on standard urban bus routes was 0.207 g/kWh. For a reduction of the uncertainty related to the limited sample of measured buses measurement data of more different makes and models would be necessary.

Figure 9: NO$_x$ emission factors, CB 15-18t HL, average German urban traffic



3.1.5. Non-regulated emission components – HBEFA 4.2

In the past HBEFA versions, Emission factors for non-regulated emission components were based on EMEP/EEA 2019 data. These emission factors have been already used in HBEFA 4.1 and will also be used in HBEFA 4.2. These values do not divide the groups Euro VI ABC and Euro VI DE, consequently the emission factors are equal.

More accurate data however, could be based on recent measurement activities. The use of FTIR measurement systems in the last years enables a detailed look on the emission situation of non-regulated pollutants in real world traffic scenarios. TUG set up emission maps for the main non-regulated emission components based on these measurement data and calculated the emission factors. The results are split in the 2 groups Euro VI ABC and Euro VI DE.

Table 4 compares the emission factors based on measurement data and on the EMEP/EEA 2019 data for a tractor trailer combination with emission standard Euro VI ABC and DE. The FTIR measurement based N_2O emission factor is nearly twice as high as the one from EMEP/EEA data used in HBEFA. The measured N_2O emission factor increases the total CO_2 equivalent exhaust emissions[8] by 2.7 % while the HBEFA emission factor raises the value only by 1.5 %. This difference is remarkable regarding the effect of CO_2 on the climate change. The ammonia emission factors are both on a low level. However, the measurement-based value is 35 % higher than the HBEFA value. The CH_4 emission factors are on a very low level independent of using HBEFA results or measurement-based ones.

Table 4: Emission factors for TT/AT 34-40t HL Euro VI/Euro VI DE, average German traffic mix

	N2O [g/km]	NH3 [g/km]	CH4 [g/km]
HBEFA 4.1/4.2 – Euro VI ABC/DE from EMEP/EEA 2019	0.054	0.014	0.001
Measurement based simulation results for Euro VI DE	0.095	0.020	0.000

For HBEFA 5 we suggest using the emission factors based on the model PHEM using existing measurement data. We assume that EMEP/EEA has not updated these emission factors. The rather high N_2O emissions measured at modern HDVs are mainly a result of optimising the SCR substrates for better low temperature NO_x conversion for EURO VI. This topic can be discussed with the developers of the EMEP/EEA emission guidebook (Emisia).

3.2. Deterioration functions for HDV

3.2.1. Database

For the assessment of deterioration factors for HDVs individual vehicle measurements by TUG and AVL MTC and most recently also remote sensing data are available. The remote sensing data come from various European countries and have already been published in individual reports (Hooftman 2020, Schmidt 2021, Sjödin 2021, Grange 2021, Sintermann 2020). The individual vehicle measurements give us detailed emission values per vehicle in different driving situations and for all exhaust gas components, but only for a relatively small number of different vehicles. The individual results of remote sensing data, on the other hand, only represent a

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[8] The CO2 equivalent emissions of N2O are based on 5th IPCC report 100years GWP values (EMEP/EEA 2019).

single driving situation of ca 1 second duration per vehicle, namely exactly at the measurement position, and the method also entails certain uncertainties. However, due to the large number of vehicles, remote sensing data provide a good overview of the actual fleet on the road.

Table 5 gives an overview on the available Euro VI measurement data for the elaboration of deterioration functions for HDVs.

Table 5: measurement database in number of vehicles for the elaboration of deterioration functions

Emission standard	TUG	AVL-MTC	Remote Sensing
Euro VI A, B und C	28	48	-
Euro VI D	12	2	-
Euro VI	40	50	20’425

The deterioration functions for all Euro VI sub-categories (ABC and DE) are elaborated on data of Euro VI ABC vehicles, because no Euro VI DE measurement data of vehicles with high mileage is available until now due to the short time since the introduction of Euro VI DE 2/3 years ago. The exhaust aftertreatment hardware of Euro VI DE vehicles is in principal the same as of Euro VI ABC vehicles, consequently this assumption is reasonable.

In addition to EURO VI, ageing functions for Euro V vehicles have also been elaborated from the remote sensing data.

3.2.2. Results

This section illustrates the final deterioration functions for the different emission components of HDV.

HC: Both the results of the remote sensing data and the individual vehicle measurements show no significant influence of mileage on the emission level of Euro V and Euro VI vehicles.

PN: According to the measurement data, the particle number also does not change over the mileage of the vehicles.

- Euro V: The remote sensing data does not show a deterioration of the PN emissions for Euro V trucks. Although combustion may get worse over vehicle life time, the impact seems to be not significant enough to be detected by remote sensing analysers.
- Euro VI: On the one hand the ash load in the filter increases, which leads to a higher filtration efficiency, but on the other hand this ash load becomes so high after approx. 400’000 km that the filter has to be changed or emptied. As a result, the filtration efficiency starts again at the level of a new filter and increases again with increasing ash loading. In addition, the filtration efficiency can be significantly reduced by mechanical damage to the filter.

These various effects result obviously in a PN emission level that is independent of mileage when considering the fleet average.

CO: The CO emissions of Euro V and Euro VI vehicles increase with mileage for both distribution and long-distance vehicles. For Euro V vehicles there is no difference in ageing between rigid and long-haul trucks. In contrary Euro VI shows a higher ageing over the mileage for rigid trucks compared to long-haul vehicles. It should be noted, however, that distribution trucks cover fewer kilometres per year on average than long-distance vehicles. This means that not only the mileage, but also the vehicle age, i.e. the operating hours, has an influence on age-related emission increases. For HBEFA 5.1 we should consider basing the HDV deterioration functions on vehicle age instead of vehicle mileage[9].

The age-related increase in CO emissions can mainly be attributed to the deterioration in the conversion efficiency of the oxidation catalyst due to chemical and thermal ageing.

Figure 5 shows the CO ageing functions versus mileage in motorway driving for Euro VI vehicles. Distribution trucks (dotted) and long-distance vehicles (dashed) are shown separately.

Figure 10: Deterioration function CO, motorway driving, Euro VI

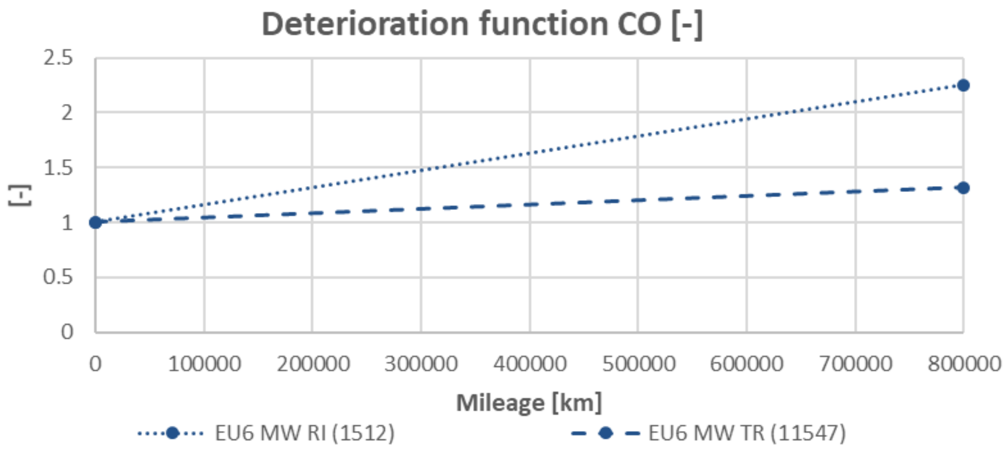

Table 6 shows the different results of the Euro VI CO ageing function versus mileage for both urban and motorway traffic for distribution and long-haul trucks. Between the individual grid points, the values can be calculated by linear interpolation.

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[9] A city bus drives more than 8 hours for approx. 250 days per year at ca. 25 km/h, leading to 50.000 to 60.000 km p.a. while a 40t articulated truck drives in the same operation hours more than 60 km/h and thus ca. 120.000 km p.a. obviously the operation time is more relevant for the aging effects than the distance driven in this time. Furthermore, remote sensing data provides always the age of the vehicles but often not their mileage.

For the distribution truck it can be seen that the ageing is capped at a factor of two. This assumption was made because the highest measurement points are in the range of 500’000 to 600’000 km (ageing factor just below two) and no more measured data are available for higher mileages. Since there is no clear evidence of further degradation, the values were capped at two.

Table 6: Deterioration function, CO, Euro VI

Mileage [km]				Traffic situation
		Urban driving		Motorway driving
	Rigid truck	Long-haul truck	Rigid truck	Long-haul truck
50’000	1.00	1.00	1.00	1.00
300’000	1.20	1.10	1.44	1.11
700’000	1.52	1.26	2.00	1.28
800’000	1.60	1.30	2.00	1.32

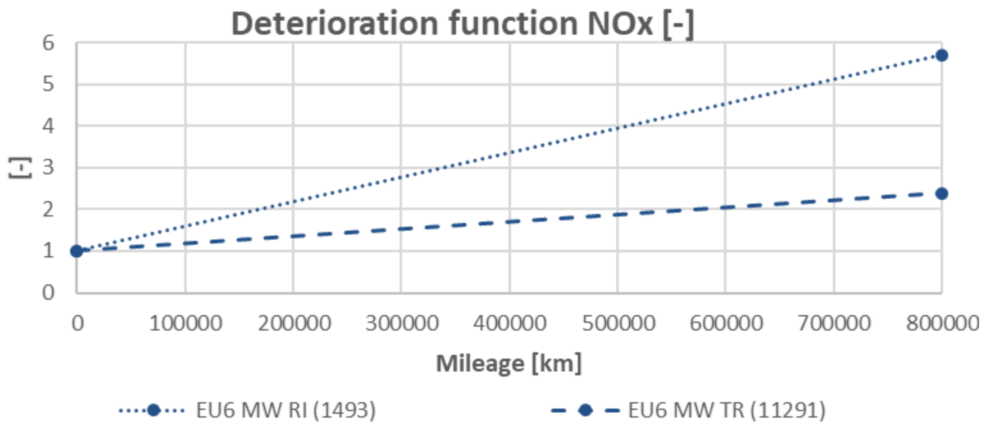
NO$_x$: NO$_x$ emissions also increase with mileage. Euro VI trucks show a stronger deterioration for distribution trucks compared to long-haul vehicles. For Euro V no difference between distribution and long-haul trucks is visible.

Regarding Euro VI, the age-related increase in NO$_x$ emissions is mainly due to the deterioration in the effectiveness of the diesel oxidation catalyst and of the SCR catalyst. If the oxidation capacity of the DOC decreases, the ratio of NO$_2$ to NO at the downstream SCR catalyst drops and thus the so-called "fast SCR reaction", which requires equal proportions of NO and NO$_2$, can only take place to a limited extent. This reduces the SCR efficiency. In addition, the SCR itself also ages (chemically and thermally), which reduces its effectiveness, too.

The individual Euro VI vehicle measurements have not shown any significant influence of mileage on the raw emissions due to e.g. deterioration of the exhaust gas recirculation system. The raw emissions can therefore be considered to be equal over the vehicle age and the ageing is mainly due to the exhaust gas aftertreatment.

Figure 11 shows the ageing functions for NO$_x$ versus mileage for Euro VI vehicles on the motorway.

Figure 11: Deterioration function NO_x, motorway driving, Euro VI



The ageing for Euro VI ABC and Euro VI D vehicles is assumed to be the same, since, as already described, no measurement data from aged vehicles are yet available for Euro VI D vehicles. Nevertheless, these two categories are differentiated in the following due to different OBD limits for NO_x. These different OBD limits have an influence on the upper limit above which no further degradation is to be expected.

- Vehicles in the Euro VI ABC category have an OBD limit of 1.5 g/kWh in the WHTC [(EC) 582/2011]. However, since vehicles in real traffic do not drive in the WHTC, it is assumed that the OBD comes up with a fault message at 1.75 g/kWh [Weller 2020]. Due to the resulting repairs, this level can be assumed as the upper limit. This results in a maximum ageing of 2.6.
- For Euro VI D, the OBD limit was reduced to 1.2 g/kWh [(EC) 582/2011]. The assumption that the limit is exceeded in the same proportion as the 1.5 g/kWh limit for Euro VI ABC, but that the base emission level is lower, results in a maximum ageing factor of 4.8[10].

Table 7 shows the final ageing functions for Euro VI ABC vehicles in urban and motorway traffic based on remote sensing data.

Distribution vehicles age faster than long-distance vehicles, which again indicates the dependence of the ageing on the operating hours. Distribution vehicles reach the OBD limit on the motorway after less than 300’000 km, while long-distance vehicles have not yet reached the limit at 800’000 km. This can also be attributed to the legislation in which vehicles in the N2 and N3 < 16 tonne category (distribution transport) can be subjected to ISC tests for a maximum of 6 years or a mileage of 300’000 km. Vehicles of the category N3 > 16 tons (long-

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[10] The average absolute emission values at the maximum deterioration rate are still lower for EURO VI d than for EURO VI ABC. How to organise this prerequisite on single emission factor level needs to be discussed during the beta version test phase.

distance traffic), on the other hand, can be subjected to ISC tests up to a maximum service life of seven years or a mileage of 700’000 km. These vehicles must therefore comply with the Euro VI emission limits for longer mileages [(EC) 595/2009]. The measured data of the distribution vehicles with a mileage of more than 300’000 km do not show a significant increase in emissions after this limit, but the number of available measured data in this range is quite limited.

Table 8 shows the results of the single vehicle measurements in ISC on-board emission tests for Euro VI. The ageing functions are not shown separately for urban and motorway traffic, but for typical driving of the different vehicle categories. When comparing these values with the motorway ageing functions from the remote sensing data, it can be seen that distribution trucks age even faster according to the individual on-board vehicle measurements than in the remote sensing data. Without limitation, the ageing factor of the remote sensing data at approx. 308’000 km would be just under 3 (see Figure 11) compared to 4.14 for the single vehicle measurements. Long-distance vehicles also age somewhat faster according to single vehicle PEMS measurements. At approx. 600’000 km the ageing factor is 2.58 and with remote sensing 2.08. In any case, the results of the single vehicle measurements confirm the trends of the remote sensing results. However, due to the higher visual sample, the remote sensing results are considered to be the final ageing functions.

Table 7: Deterioration function based on remote sensing data, NO_x, Euro VI ABC

Mileage [km]	Traffic situation			
		Urban driving		**Motorway driving**
	Rigid truck	**Long-haul truck**	**Rigid truck**	**Long-haul truck**
50’000	1.00	1.00	1.00	1.00
300’000	1.74	1.22	2.60	1.49
700’000	2.60	1.49	2.60	2.08
800’000	2.60	1.67	2.60	2.48

Table 8: Deterioration function based on single vehicle PEMS measurements, NO_x, Euro VI ABC

Mileage [km]	Traffic situation	
	ISC tests, urban bus routes	
	Rigid truck	**Long-haul truck**
15’114	1.00	-
33’871	-	1.00
308’250	4.14	-
615’583	-	2.58

For Euro VI D vehicles, the same ageing function is used as for Euro VI ABC, but the upper limit are higher despite the lower OBD limit due to the lower base emission level. The results are shown in Table 9.

Table 9: Deterioration function based on remote sensing data, NO_x, Euro VI DE

Mileage [km]	Traffic situation			
		Urban driving		Motorway driving
	Rigid truck	Long-haul truck	Rigid truck	Long-haul truck
50’000	1.00	1.00	1.00	1.00
300’000	1.74	1.22	2.66	1.49
700’000	2.93	1.58	4.80	2.28
800’000	3.23	1.67	4.80	2.48

3.3. Deterioration functions for NO_2/NO_x ratio

3.3.1. LDVs

The share of NO_2/NO_x drops over lifetime for passenger cars and light commercial vehicles (LCVs). The reduction of NO_2 shares is mainly caused by the loss in conversion efficiency of the diesel oxidation catalysts (DOCs) over vehicle lifetime resulting from thermal and chemical ageing processes. Similar to HDVs the ageing effect has an impact on NO_2/NO_x ratios only in driving situations, where the DOC is operating close to and above light-off temperature (typically, at ca. 180°C, depending on catalytic material). Below the light-off, i.e. mainly during the cold start phase, low NO_2/NO_x ratios are expected, since the engine out NO_x consist mainly of NO due to the high combustion temperatures[11]. The DOCs from LDVs are typically located close to the engine. Thus, in normal hot running conditions DOC converts NO to NO_2 efficiently and so far no significant impact of the traffic situation on the NO_2/NO_x ratio was found from vehicle and from remote sensing tests analysed for HBEFA 4.1[12]. The data newly available from literature also does not indicate impacts of the traffic situation on the NO_2/NO_x ratio. However, in contrary to the HDVs analysis, a collection and analysis of all available remote sensing data was not part of the quick update for HBEFA 4.2.

For the quick update, we used the analysis of NO_x and NO_2 emission levels from remote sensing data from York and London given in (Carslaw, 2019). No other literature was identified which analysed NO_2 and NO_x emission levels per EURO class and per year of registration[13].

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[11] The thermodynamic equilibrium is at almost 100% NO2/NOx at ambient temperatures while it is below ca. 5% NO2/NOx at the high engine out temperatures.

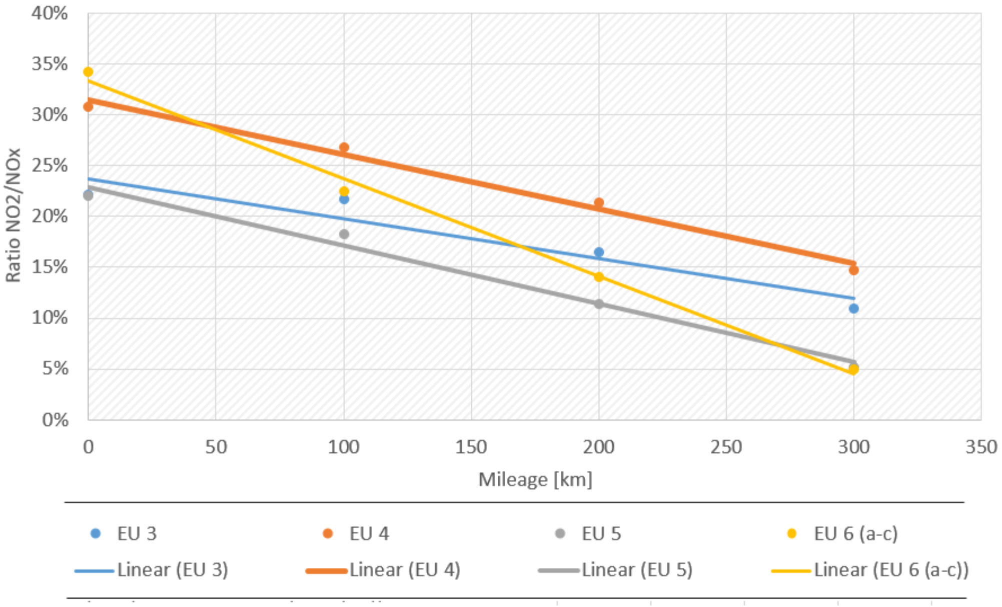
[12] Since NO2 produced in the DOC is used to oxidise soot in the DPF (C + 2 NO2 → CO2 + 2 NO) above ca. 250°C, the NO2/NOx ratio at tailpipe is expected to drop above ca. 250°C exhaust gas temperature. However, from the test data available, we did not see significantly lower NO2/NOx shares e.g. in highway cycles compared to urban driving.

[13] Since a lot of new remote sensing data is available but yet not analysed for NO2/NOx effects, we suggest to include an updated analysis in the HBEFA 5.1, if made available from any parallel project.

The resulting trends for the NO_2/NO_x ratio of diesel cars over the vehicles cumulated mileage are shown in Figure 12. The highest reduction rates of the NO_2/NO_x ratio are found for EURO 6abc. The reason for the quite massive drop in NO_2 shares for the new cars compared to former EURO classes is unclear yet. It may be a due to e.g. ageing of NO_x storage catalysts, a technology rather not applied on former EURO classes, but also uncertainties in remote sensing measurements (lower absolute concentrations for EURO 6 compared to former EURO classes). Since the mileages of the vehicles passing the remote sensing area were gained from the vehicles licence plate using a link to the data base from the yearly inspection, the mileage data seems to be robust.

Before EURO 3 almost no DOCs were used in cars, thus no significant deterioration effects on the NO_2/NO_x ratio exist for these old technologies.

Figure 12: NO_2/NO_x ratios for diesel passenger cars elaborated from remote sensing data with average 10°C ambient temperature; base data from (Carslaw, 2019)



Beside the mileage effects we also analysed possible effects from different ambient temperatures. The data available (remote sensing and vehicle chassis dyno tests) did not show a significant impact of the ambient temperature on the NO_2/NO_x ratio. For vehicles with SI engine (gasoline engines) neither a mileage not a temperature effects was identified in the analysis. However, due to the low NO_2 shares of SI engines possibly existing effects would be in the range of measurement accuracy.

The correction factors applied in HBEFA 4.2 for the NO_2/NO_x ratio of diesel cars are shown in Table 10. For gasoline driven vehicles no correction is used. In HBEFA 4.1 the NO_2/NO_x ratio did not drop with increasing mileage, thus the NO_2 emissions from older vehicles are overestimated while NO emissions are underestimated in HBEFA 4.1.

Table 10: Reduction rates of the NO_2/NO_x ratio from diesel cars as function of the cumulated vehicle mileage implemented in HBEFA 4.2

Mileage [km]	EU 3	EU 4	EU 5	EU 6 (a-c)	EU 6d-temp
0	100%	100%	100%	100%	100%
100’000	98%	87%	83%	66%	65%
200’000	74%	69%	52%	41%	41%
300’000	49%	48%	24%	15%	12%

3.3.2. HDVs

HDVs show similar effects as passenger cars and LCVs. The NO_2/NO_x ratio decreases over lifetime also mainly caused by the ageing of the DOC.

The functions for HDVs are elaborated based on remote sensing data from various European countries already published in individual reports (Hooftman 2020, Schmidt 2021, Sjödin 2021, Grange 2021, Sintermann 2020).

Table 11 shows the reduction rates of the NO_2/NO_x ration from HDVs as function of the cumulated vehicle mileage implemented in HBEFA 4.2 for the different Euro V and Euro VI HDVs. The data illustrates the same deterioration of the NO_2/NO_x ratio for rigid and long- haul trucks. Consequently, these categories are not split in this case for the HBEFA 4.2. The remote sensing data are not detailed enough for a distribution in the different Euro V groups. Consequently, the deterioration ratio is the same for all Euro V sub categories.

The NO_2/NO_x ratios at 50’000 km have not changed from HBEFA 4.1 to HBEFA 4.2.

Table 11: Reduction rates of the NO_2/NO_x ratio from HDVs as function of the cumulated vehicle mileage implemented in HBEFA 4.2

Traffic situation	Mileage [km]	EU V EGR	EU V EGR (DPF)	EU V SCR	EU V SCR (DPF)	EU VI
Urban driving	50’000	100%	100%	100%	100%	100%
	800’000	90%	88%	86%	88%	29%
Rural driving	50’000	100%	100%	100%	100%	100%
	800’000	71%	72%	71%	72%	46%

3.4. Additional software updates of Diesel PC

3.4.1. Data model

Software updates for Diesel PC have been implemented already in HBEFA 4.1 in such a way that not only emission factors for the updated PC are available in addition to the “normal” emission factors, but also the effect of vehicles being updated on the non-updated rest of the fleet is accounted for (see also INFRAS et al. 2019).

This is achieved by differentiating three subsegments for every source subsegment in which software updates take place:

- The vehicles not affected by the update (i.e. subsegments “PC diesel Euro-5”, “PC diesel Euro-6ab”)
- The affected vehicles before the update (i.e. the subsegment “PC diesel Euro-5 EA189 before software update” – already available in HBEFA 4.1 – and the new subsegments “PC diesel Euro-5 other SU before software update” and “PC diesel Euro-6ab SU before software update”)
- The affected vehicles after the update (i.e. the subsegment “PC diesel Euro-5 EA189 after software update” – already available in HBEFA 4.1 – and the new subsegments “PC diesel Euro-5 other SU after software update” and “PC diesel Euro-6ab SU after software update”)

This way, when querying HBEFA at subsegment levels, EF for all three subsegments are produced. When HBEFA is queried at more aggregated levels (e.g. emission concept, Diesel Euro-5), the effect of the software updates becomes visible by changing average emission factors over time.

3.4.2. Emission factors

For the update of the SU vehicles in the HBEFA, KBA, DUH und TU Dresden performed measurements on Euro 5 (9 vehicles) and 6 (23 vehicles) cars with mandatory and voluntary software updates. The measurements included on-road measurements (RDE measurements) with portable measurement technology (PEMS) at different temperatures as well as measurements on the chassis dynamometer in the WLTC driving cycle at temperatures 5 °C, 10 °C and 15 °C. With the RDE data from KBA and TU-Dresden, engine emission maps for the emission model PHEM were generated for each measured vehicle using the HBEFA method (9 data sets for Euro 5 and 23 data sets for Euro 6). In order to use all RDE tests, including those that have been run below 15 °C and are usually not used directly in the HBEFA basic method, the HBEFA approach has been slightly modified here. With this new approach, all measurement data were weighted according to fleet shares of the SUs to an average map (separated before / after SU as well as Euro 5 and Euro 6). The weighted temperatures of the RDE measurements were determined analogously. This resulted in mean temperatures of approx. 19 °C for Euro 5 vehicles before / after SU and approx. 10 °C for Euro 6 vehicles before / after SU. By applying the temperature correction functions explained later, the hot emission maps were then transformed into the standard 20°C maps.

As part of this work, it was checked whether vehicles with a particularly large number of software updates had a particularly strong influence on the results. This was not the case.

Table 12: HBEFA4.1 German fleet mix weighted emissions at 20°C

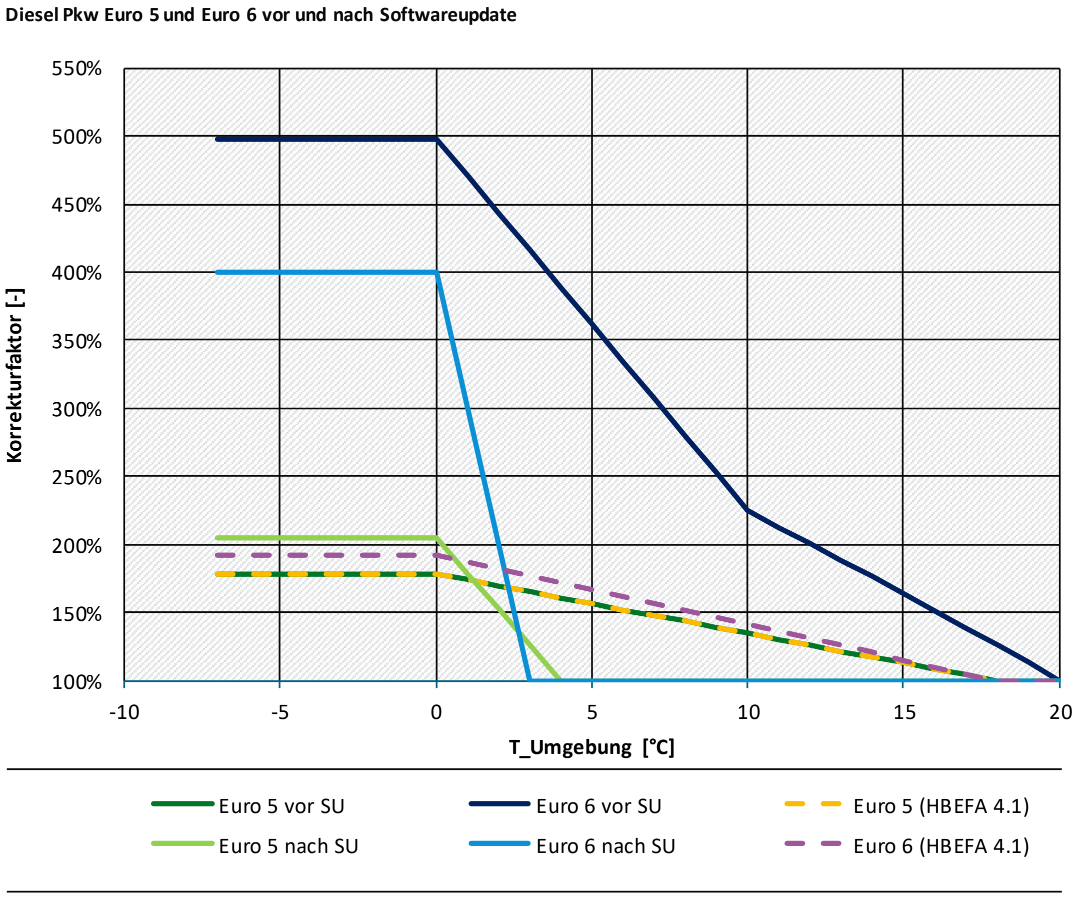
Fahrzeug	Weighted CO2 in g/km	Weighted CO in g/km	Weighted NOx in g/km
Euro 5 (HBEFA 4.1)	175.3	0.032	0.812
Euro 5 after SU	177.1	0.039	0.503
Euro 5 (HBEFA 4.1 EA189 SW-update)	181.5	0.007	0.583
Euro 6ab (HBEFA 4.1)	175.3	0.078	0.461
Euro 6 after SU	176.1	0.058	0.447

3.4.3. Temperature dependencies

To create the temperature correction functions, WLTC data were available for a total of 8 Euro 5 vehicles and 6 Euro 6 vehicles. From these measurements, the emission values of phases 2 to 3 of the WLTC were used for the three measured temperature ranges (5 °C, 10 °C and 15 °C). The measurement data of the individual vehicles were then weighted according to the fleet shares of the individual vehicle models in the SUs to an average measured value per temperature and emission standard. The temperature correction functions were derived from these average values per temperature.

For Euro 5 before SU, we found no major differences compared to the temperature correction function currently used in the HBEFA for Euro 5 diesel cars. Therefore the same correction function was used for Euro 5 before SU than for the average Euro 5. The Euro 5 vehicles after SU showed no temperature dependence down to 5°C. Because there are no measurement data available below 5° C an estimate of the course below 5°C was made due to the reduced usability of EGR. In the case of the Euro 6 before SU, a very strong temperature dependency was determined and a separate correction curve was created from the measurement results, while the Euro 6 after SU showed no significant temperature dependence. The same correction curve was therefore assumed for them as for the Euro 6d-Temp of HBEFA 4.1.

Figure 13: NO$_x$- Temperature functions



ohne Pkw mit Motor EA-189

Quelle: eigene Darstellung, TU Graz

3.5. BEV base energy consumption factors

The technical data of the average German BEV for HBEFA 4.2 was determined by weighting the technical data of each electric passenger car model according to its share in the German fleet. The fleet shares of BEV models was obtained from the KBA, which provides the monthly new registrations broken down by car make and model. All new registrations of 50 different car models between 2014 and June 2021 were considered (nearly 480 000). The car's empty weight, drag coefficient, cross sectional area, rated engine power and speed were compiled from various sources. When available, manufacturers' product catalogues were used, if not, the data was obtained from different sources[14] where such data is collected. For the loading a value of 110 kg (about 1.5 persons) was set. The rolling resistance factors were taken from the

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[14] Mainly: https://www.automobile-catalog.com/, https://automobil-guru.de/cw-werte-tabelle-stirnflaeche/ and https://www.adac.de/rund-ums-fahrzeug/autokatalog/

HBEFA 4.2 Euro 6d-Gasoline car and reduced by about 20 %, corresponding to tyres with very low rolling resistance.

The battery of the average German BEV, which was calculated together with the other technical data, has a capacity of 47.1 kWh. The state of charge at the start of each driving cycle was set to 90 %.

The motor efficiency map was taken over unchanged from HBEFA 4.1, since the efficiency map of the motor is normalized (values are divided by the rated engine power or speed respectively) and is thus independent of the rated engine power set in the vehicle data. Furthermore, the full load curve of the electric motor was needed, which was also taken over from HBEFA 4.1.

In addition to the technical specifications, the real energy consumptions of the battery electric vehicles in the German fleet were determined based on entries in Spritmonitor and a weighted average of 174 Wh/km was calculated. On the one hand, this result is very useful as it is based on the values of real drivers, but on the other hand it is subject to many uncertainties, e.g. charging losses might be included if some people measured the energy via a wattmeter, and questions like “What was the driving behaviour like?” or “What kind of roads did they drive on?” cannot be answered. Comparing the simulated and the real energy consumption shows that the value of the simulation is about 10 % higher (195 Wh/km for the German traffic mix).

Real world tests by TU Graz showed that some battery electric have an energy consumption of about 170 Wh/km when the speed limit on motorways is 100 km/h and that some cars have a consumption in the range of 200 Wh/km when there is no speed limit (130 km/h). Therefore, both the results from the simulation and those of Spritmonitor are plausible since we may assume that current BEV drivers, who fill in their data into spritmonitor.de are rather eco- than aggressive drivers. Since HBEFA does not use different shares of traffic situations for BEVs than for conventional cars, the average weighted HBEFA result may overestimate real BEV energy consumption, as long as (or if) BEVs are driven more ecological than the conventional cars.

The specifications of the average German BEV for HBEFA 4.2 are shown in Table 13 and are compared with those of HBEFA 4.1.

Table 13: Technical data of the average German battery electric vehicles from 2019 and 2021

Parameter		Unit	HBEFA 4.1	HBEFA 4.2
Empty weight (without a driver)		[kg]	1503	1556
Loading		[kg]	94	110
Drag coefficient		[-]	0.321	0.298
Cross sectional area		[m2]	2.34	2.29
Rolling resistance factors	Fr0	[-]	0.00537	0.00761
	Fr1	[s/m]	4.00E-05	6.02E-05
Rated engine power		[kW]	99	133
Rated engine speed		[min-1]	2865	4165
Empty weight (without a driver)		[kg]	1503	1556

3.6. Well-to-tank GHG EF

Factors for fuel and energy types that were missing in HBEFA 4.1 have been included HBEFA 4.2. Furthermore, existing factors have been updated based on new versions of previously used data sources (See Table 14). Table 16 in the annex describes which datasets are new, updated and unchanged as well as the data sources used in more detail. In general, the WtT emission factors are based where possible on a cradle-to-grave life cycle perspective (new in HBEFA 4.2) also include upstream impacts for renewable electricity production technologies. As with HBEFA 4.1, we use the method of GWP100 to convert non-CO_2 climate pollutants to CO_2- eq.

WtT emission factors taken from the Renewable Energy Directive (2018) are the default values and include cultivation, processing, transport and distribution only. Where multiple production pathways from the RED 2018 are available for a fuel type, an unweighted average of all matching production types is used to determine the WtT EF used in HBEFA 4.2.

WtT emission factors from ecoinvent 3.8 (2021) are calculated using the cut-off system model. The exact datasets used are listed in Table 16 in the annex.

Table 14: Overview of updated well-to-tank GHG emission factors

Energy	Production Type	Source / Comment
Petrol, Petrol 2s, Diesel, CNG, Kerosene, LPG, Propane, LNG	Average	Updated from Ecoinvent 2021
Ethanol (bio)	Maize-to-liquid, rye, sugar beet, wheat straw, wood Fischer-Tropsch	Renewable Energy Directive 2018
Ethanol (bio)	what-by-gas, wheat-by-waste, lignocellulose	Unchanged from HBEFA 4.1
Biodiesel	FAME rapeseed oil, FAME soya oil, FAME palm oil, HVO palm oil, HVO waste, wood Fischer-Tropsch	Renewable Energy Directive 2018
Biokerosene	HVO palm oil, HVO waste, wood Fischer-Tropsch	Assume same as Biodiesel
Biogas	Maize-to-gas, Waste-to-gas	Unchanged from HBEFA 4.1
Electricity	All types except Biomass-waste	Updated from Ecoinvent 2021
Electricity	Biomass-waste	Pfadt-Trilling et al. 2021
Hydrogen	Electrolysis (from all electricity types)	Conversion efficiency and infrastructure emissions from Romain Sacchi, Paul Scherrer Institute (PSI)
Hydrogen	SMR, SMR with CCS	Antonini et al. 2020
Petrol PtX, Diesel PtX, Gas PtX, Kerosene PtX	Electrolysis (from all electricity types)	Conversion efficiency and infrastructure emissions from Romain Sacchi, Paul Scherrer Institute (PSI)

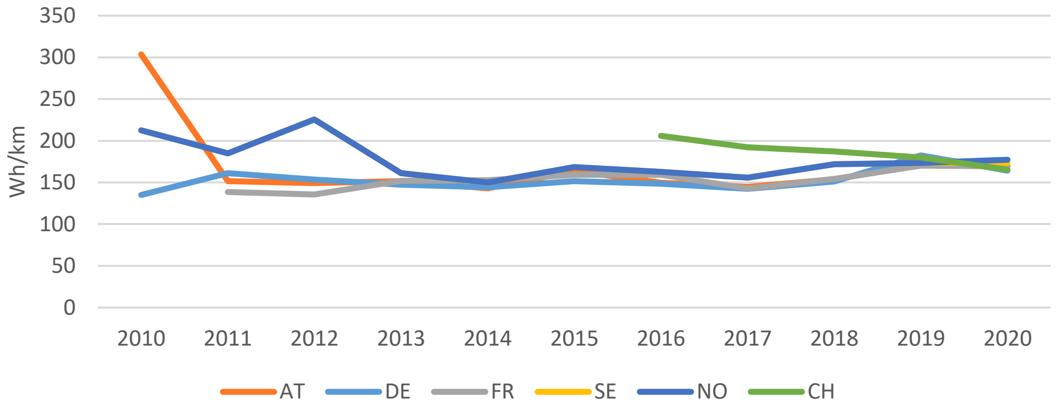
4. Country-specific contents

4.1. Real-world energy consumption of electric vehicles

4.1.1. BEV

In this task the real-world energy consumption of electric passenger cars was analysed. In the first step, the average type approval energy consumption values for new BEV for each year was calculated based on the CO_2 Monitoring datasets provided by the EEA (2020) and Swiss statistical data (www.ivz-opendata.ch). These are shown Figure 14. Note that energy consumption for Norwegian BEV was incomplete so values for Sweden were used, which show similar shares of new models and average weights.

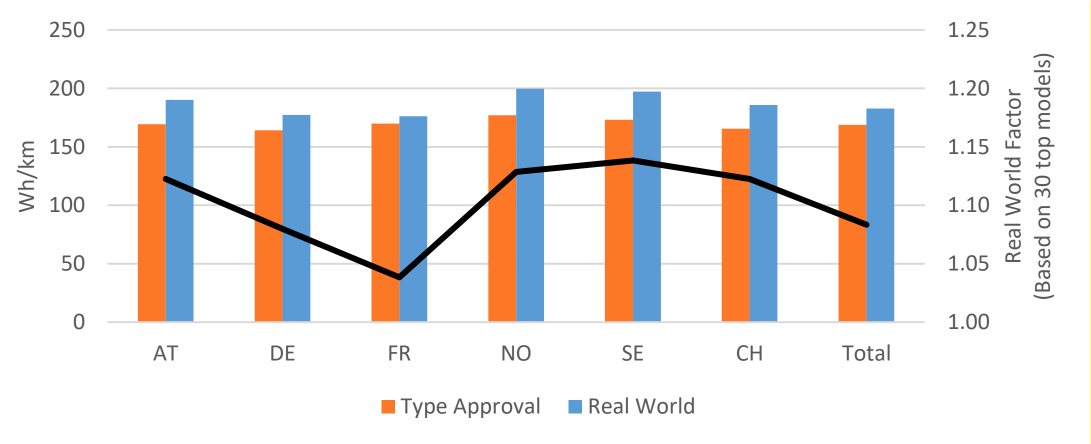
Figure 14: Type approval energy consumption (WLTP) for new electric passenger cars



Graphics by INFRAS. Source: CO_2 Monitoring datasets by the EEA (2020) and Swiss statistical data (www.ivz-opendata.ch).

The next step was to calculate the "real-world" energy consumption for electric vehicles, which was done using data from www.spritmonitor.de, which contains measured energy consumption data by vehicle model and year for German drivers. Energy consumption data were gathered from SpritMonitor for the 30 BEV with the highest sales share in Europe in 2020. Using these energy consumption values and the type approval and new registration data described above, the average real-world energy consumption and real-world factor for all six HBEFA countries could be calculated using a weighted average based on new registrations (see Figure 15).

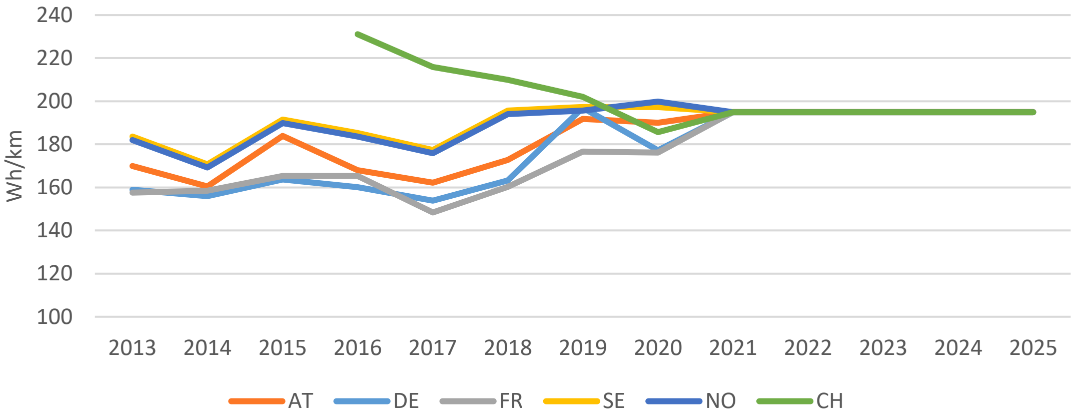
Figure 15: Real world and type approval energy consumption of new battery electric passenger cars in 2020



Graphics by INFRAS. Source: Own calculation.

Finally, the time series data real-world energy consumption for new battery electric cars could be calculated by multiplying the type approval energy consumption shown in Figure 14 with the European average real-world factor of 1.083 shown in Figure 15. Energy consumption for electric cars for all countries starting in the year 2021 is assumed to be 195[15] Wh/km (see section 3.5). See Figure 16.

Figure 16: Real world energy consumption of new battery electric passenger cars in HBEFA 4.2



Graphics INFRAS. Source: Own calculation

4.1.2. PHEV

Utility factors for plug-in hybrid (PHEV) passenger cars were updated for all countries based on a white paper published by the ICCT (2020) (See Table 15). The current utility factor for German plug-in hybrids is quite poor because of the very high share of company owned vehicles. The ICCT study finds company owned PHEV in Germany to be charged too infrequently, leading to low average utility factors. We assume that German PHEV utility factors will improve in the future and approach the values for other countries as a) a larger share of PHEV reach the private market, and b) companies become more aware of this problem and promote regular charging of their PHEV.

Table 15: Plug-in hybrid passenger car electric driving shares (utility factors) for HBEFA 4.2

Road Category	All countries except Germany	Germany before 2021	Germany from 2025
MW	17%	11%	17%
Rural	56%	36%	56%
Urban	67%	44%	67%

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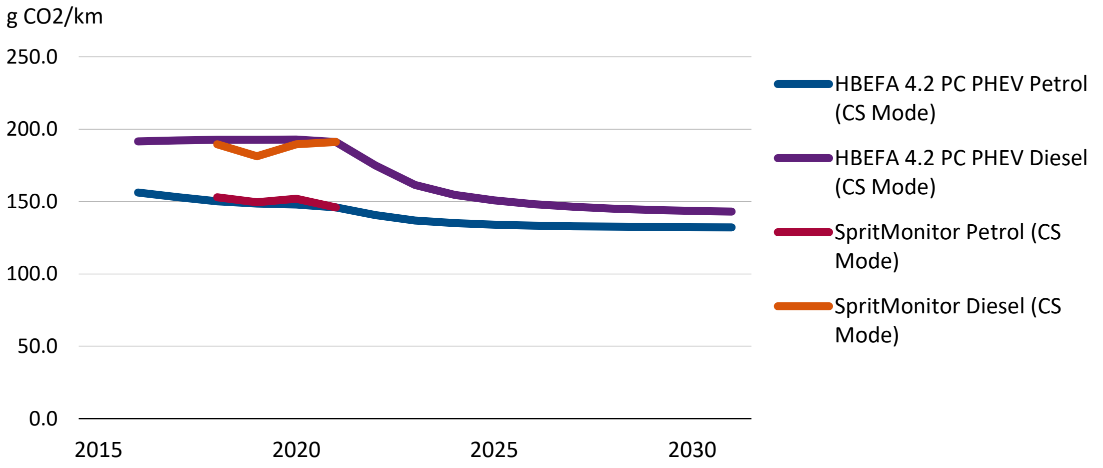
[15] The base correction factor for all countries was modified accordingly.

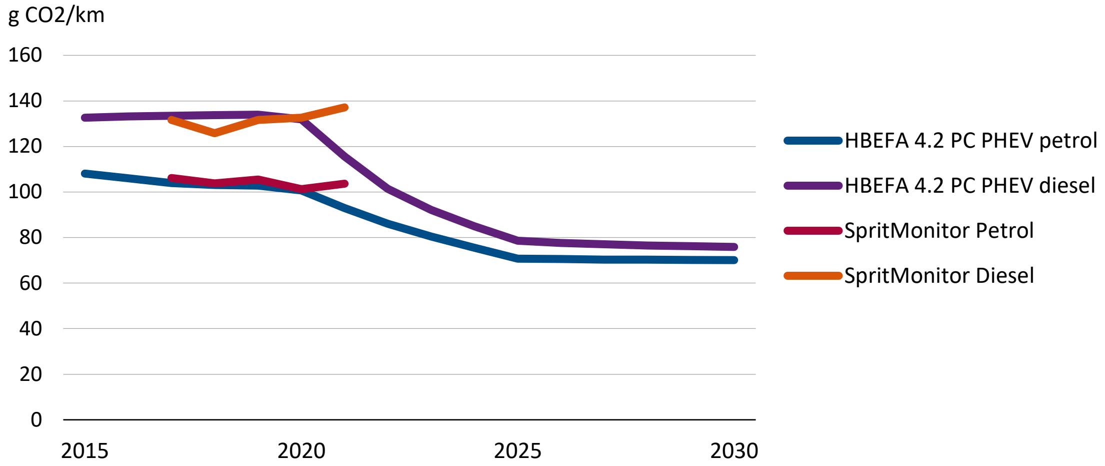
Furthermore, the energy consumption of passenger car PHEV were calibrated based on “real-world” data from www.spritmonitor.de. Data were taken from SpritMonitor for German PHEV with the production years 2017-2021 seperately for each year. Only data for vehicles with more than 1500 km of registered data were used. The calibration was done by using the above German average UF for German PHEVs to back-calculate the CO_2 emissions of the vehicles from the SpritMonitor data in charge sustaining mode. These values were then compared to the HBEFA values for German average PHEV in charge sustaining mode to yield a correction factor for both petrol and diesel fuelled PHEV in charge sustaining mode. Figure 17 shows the results of this calibration for German PC PHEV in charge sustaining mode compared to the calculated charge sustaining mode CO_2 emissions from the SpritMonitor dataset. The improvements in the HBEFA energy consumption starting in 2021 are due to the assumed fuel reduction rates assumed in the German country input data. Figure 18 shows the overall average CO_2 emissions from German PC PHEV, considering the new electric utility factors. The improvement in the CO_2 emissions in the HBEFA 4.2 datasets starting in 2021 are due to the compounding of the above mentioned fuel reduction rates for PHEV and also the improved Utility Factors for Germany described in Table 15 above.

Figure 17: CO_2 emissions of average German plug-in hybrid passenger cars in charge sustaining mode in HBEFA 4.2 compared to data from SpritMonitor



Graphics INFRAS. Source: Own calculation

Figure 18 CO_2 emissions of average German plug-in hybrid passenger cars in HBEFA 4.2 compared to data from SpritMonitor (average operation)



Graphics INFRAS. Source: Own calculation

4.2. Cumulative mileage

4.2.1. Overview

Cumulative mileage – i.e. the mileage performed by a vehicle in its lifetime up to a given age, which can usually be read on its odometer – is an important input for all pollutants and vehicle types affected by catalyst deterioration (compare Chapters 3.2 or 3.3). The fleet model behind HBEFA calculates an average cumulative mileage for every subsegment and reference year based on annual mileage inputs and associated age dependencies.

A review of the cumulative mileage calculation in the context of the updates of the deterioration functions (see Chapters 3.2 and 3.3) led to the adaption of two aspects of the methodology, which are described in the following two subchapters.

4.2.2. Consideration of HGV transformation

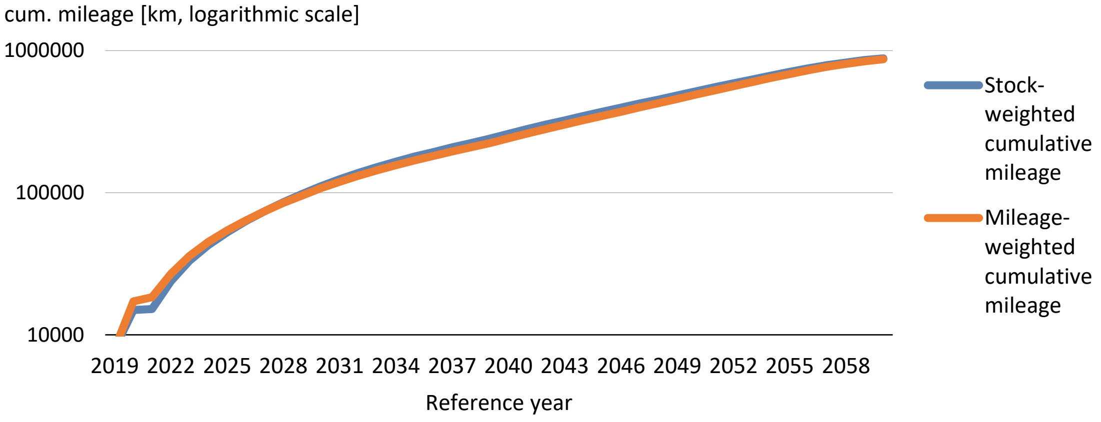
The HBEFA fleet model includes an optional “transformation” step for HGV, which can be used depending on the input fleet data available: HGV tractors often circulate, combined with trailers, in a different size class than the one they are registered as. E.g. a 28t rigid truck can also be used together with a trailer as a 40t TT/AT. The HBEFA fleet model offers the possibility to enter the 28t stock and individual annual mileage as obtained from registration data, plus the mileage shares driven by these vehicles as different size classes. The latter are then used for the “transformation” from registered stock/mileage by size classes into the mileage shares on the road.

This option has been available already in the previous versions of HBEFA – however, the transformation has been neglected when calculating the cumulative mileage. Up to HBEFA 3.3, this was not relevant, since no deterioration was considered for HGV. In HBEFA 4.1, NO_x deterioration was included shortly before publication for Euro-VI HDV, but the calculation method of cumulative mileage was not reviewed. This has been corrected for HBEFA 4.2 – the transformation is now also reflected in cumulative mileage. However, since most countries do not use the "transformation" feature in the fleet model, this update only affects SE and CH.

4.2.3. Mileage-weighted averaging

Within the HBEFA fleet model, all parameters are differentiated by vehicle age in 1-year intervals during calculation; only in the last step, age classes are aggregated to subsegments (which usually include several construction years within the same emission concept). In this aggregation step, cumulative mileage was averaged using stock (number of vehicles) as weights up to HBEFA 4.1. This has now been corrected so that annual mileage is used as weight parameter. In general, the effects of this change are not large: It leads to a faster increase of cumulative mileage shortly after the introduction of a subsegment, when vehicles are new on average and driven a lot; however, when the average age of vehicles within a subsegment increases and annual milage decreases, the cumulative mileage increase per reference year is lower (see Figure 19).

Figure 19: Effect of mileage- vs. stock-weighted averages of cumulative mileage, using the example of Diesel PC Euro-6ab.



Graphics by INFRAS. Source: HBEFA 4.2

4.2.4. Calculation of cumulative mileage for “foreign fleet” subscenarios

Up to HBEFA 4.1, cumulative mileage was not calculated for subscenarios of the fleet model for which the option “no vehicle stock composition” was selected. This option is meant for subscenarios representing foreign vehicles, which contribute to traffic activity (mileage) within a country but which as vehicles do not reside within the current country.

However, cumulative mileage is relevant for these parts of the fleet; therefore the calculation of cumulative mileage has been extended to include these subscenarios in HBEFA 4.2.

This change only affects Switzerland, since it is the only country that has differentiated foreign fleets so far in separate subscenarios of the fleet model.

4.3. Fuel and energy mix updates

4.3.1. EU and Swiss energy mix

New energy mix scenarios for the EU and Switzerland have been created based on the mixes available in HBEFA 4.1. The only changes to these mixes are that production shares for sythentic fuels are added and are assumed to be the same as the production shares for the relevant electricity production scenario and year. For example, if for a given year 20% of the electricity in that scenario is produced via hydropower, also 20% of the PtX in the corresponding scenario is produced via electrolysis from hydropower.

This updated EU Energy mix scenario is defined as the default for all HBEFA countries (except Switzerland).

4.3.2. Germany

The fuel mix scenario was updated to the real biofuel shares from 2018 to 2020. For the period after 2020 (scenario) the values have not been changed.

4.3.3. France

The characteristics of fuels have been updated from the public database of emission factors Base Carbone® (https://bilans-ges.ademe.fr/).

Biofuel contents in liquid fuels from 1990 to 2019 have been updated from CITEPA (https://www.citepa.org/fr/secten/) and SDES data (https://www.statistiques.developpement-durable.gouv.fr). Biomethane content in CNG from 1990 to 2020 has been updated based on data from the CNG observatory of the AFGNV - Association française du gaz naturel véhicule (https://gnv-grtgaz.opendatasoft.com/pages/observatoire/).

The prospective biofuel contents of petrol, diesel and CNG have been constructed by ADEME to achieve carbon neutrality in 2050.

4.3.4. Sweden

Fuel-Mix tables have been updated with biofuels shares for all used fuels and for all vehicle categories up to 2020 based on national fuel delivery statistics. Fuel shares from 2021 and onwards have been set to equal the shares used for 2020.

4.3.5. Switzerland

The biofuel shares in petrol, diesel and gas have been updated based on fuel sales statistics up to the year 2020. From 2021 to 2060, the fuel mix of the "Zero Basis" scenario of the recently published Swiss Energy Perspectives (Prognos et al. 2020) is assumed. This includes increasing PtX (Power-to-X, i.e. synthetic fuel) shares from 2045 onwards in order to reach carbon neutrality at national level.

4.3.6. Norway

Fuel mixes for Norway, including biofuels, were included in HBEFA 4.2 based on the most recent statistical data.

4.4. Fleet data

4.4.1. All countries

For all countries, the following updates to the fleet data have been implemented:

- The differentiation of HDV EU-VI by steps A-C and D-E (see Chapter 3.1), has been implemented by including the introduction schemes of the D-E vehicles. This has been done based on country-specific registration data where available. For countries where the information on the steps A-E is not available in registration data, average values (i.e. shares of D-E vehicles in new registrations per year) from Germany were used.
- The differentiation of Euro-5 and Euro-6ab Diesel PC vehicles affected by the newly considered software updates (see Chapter 3.4) has been implemented. For most countries, country-specific data on software updates are not available; therefore, the same relative shares of affected and updated vehicles as in Germany have been used. For France only the share of updated vehicles was taken over from German data; the share of affected vehicles for each update is taken from French registration data.

4.4.2. Germany

The real vehicle stock was updated for the years 2018-2020. Those year were scenario years before. The total vehicle stocks and the technology shares were adapted for the scenario (2021-2050). This includes higher shares of electric vehicles due to the increasing market since HBEFA 4.1. The introduction scheme for Euro 6d and Euro 6d temp was changed slightly. From

2021 all new PC registrations are Euro 6d. In 2021 10 % of new LCV are Euro 6d temp and from 2022 only Euro 6d are registered.

For the HDV, the estimation of cumulative mileage was adapted: In HBEFA 4.1 and earlier, the cumulative mileage in Germany was determined by correlating the domestic mileage to the domestic vehicle stock and calculating average annual mileage per vehicle. This procedure is sufficiently accurate for passenger cars and light commercial vehicles (LDV), as the domestic mileage corresponds well with the mileage of the vehicles registered in Germany.

Since HBEFA 4.1, the cumulative mileage has also been included in the emissions calculation for heavy goods vehicles. Since a high proportion of the mileage of freight transport in Germany is provided by foreign vehicles, which significantly exceeds the mileage of German vehicles abroad (Bäumer et al. 2016), this procedure leads to an overestimation of the average mileage of heavy goods vehicles and thus also to an excessively high cumulative mileage, which only became apparent during the processing of the emissions reporting. Therefore, in HBEFA 4.2 the mileage per vehicle was derived using the mileage survey of the Federal Highway Research Institute 2014 (Bäumer et al. 2016) with the appropriate allocation of mileage to the stock. By excluding the mileage of foreign vehicles, the mileage per vehicle is 30% lower than before.

4.4.3. France

The French fleet dataset is built on vehicle registration data from the 1940s up to and including 2020, and is based on the use of survival and usage assumptions (annual mileage) derived from mobility surveys.

The years 2021 to 2050 are constructed under the assumptions of the French scenario for a national low-carbon strategy (SNBC), known as the "existing measures" scenario (SNBC-AME scenario, 2021 report): traffic evolution, evolution of the total fleet and registrations per vehicle categories, distribution according to engines, with however adjustments for plausibility. To give the user greater flexibility, the engines that are in strong decline are however preserved at low rates by 2050, which should make it possible to recompose the prospective assumptions to 2030 or 2050 in order to elaborate and estimate different scenarios.

A detailed note explains the assumptions of this scenario and is available from the French representatives in the HBEFA Working Group.

The scenario with additional measures (AMS) has not been considered, as the assumptions are much more uncertain and under revision.

4.4.4. Sweden

All fleet data have been updated based on Ex-post statistical data up to the year 2020. From 2021 and onwards data based on a scenario prepared by the Swedish Transport Administration (2021) has been implemented.

4.4.5. Switzerland

All fleet data (stock, new registrations, mileages etc.) have been updated based on Ex-post statistical data up to the year 2020 (see e.g. BFE 2021). From 2021 to 2060, the assumptions of the “Zero Basis” scenario of the recently published Swiss Energy Perspectives (Prognos et al. 2020) have been adopted.

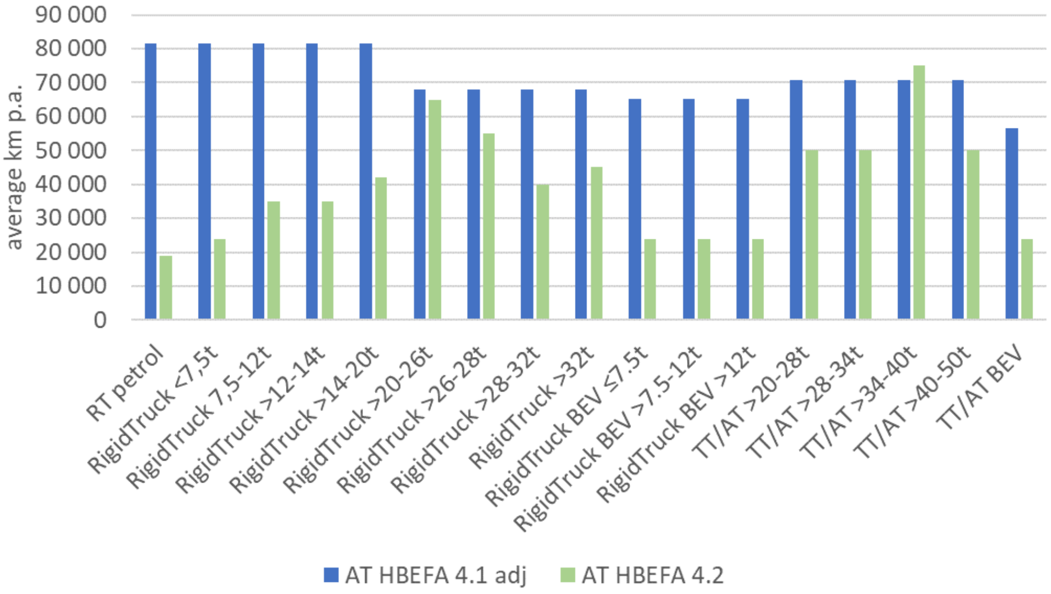
In addition, the following adaptions have been made:

- The annual mileages of the foreign (non-Swiss) truck fleet have been updated based on the updated German data (see Chapter 4.4.2);
- The age dependencies of annual mileage for all vehicle categories have been revised based on the registration data of the Swiss Federal Roads Office;
- HGV introduction schemes and transformation patterns have been recalibrated to fit the distribution of mileage by size class and emission standard to LSVA data (i.e. mileage data collected via the Swiss heavy traffic levy) again after the above-mentioned adaptations.

4.4.6. Austria

Changes to Austrian HGV and Coach fleet data and traffic activity were made in HBEFA 4.2. The main adjustments concerned the specific HDV vehicle kilometres driven per year (Figure 20). The new data is based on the evaluation of the “Zentrale Datenbank (ZDB)” which compiles the registration data and the odometer readings from the regular vehicle inspection. Since the weight classes are yet not separated in HBEFA formats in the ZDB, the differentiation between weight classes includes still uncertainties. We suggest to run a more detailed analysis and a follow up update for HBEFA 5.1. The adjustments we made, result in lower shares of the smaller HDV classes in HBEFA 4.2 compared to HBEFA 4.1. This tends to increase the weighted emission factor of the average HDV on the road. In contrary, lower km/year lead to slower increases of the total accumulated mileage and thus to lower deterioration effects on the NO_x emissions from the HDV fleet.

Figure 20: Specific annual vehicle km for the HDV classes for Austria in HBEFA 4.1 and for HBEFA 4.2



In addition, the payload of HGV, coach and urban busses has been updated according to measurement data. Up to HBEFA 4.1 the payload of all HDV categories was set to “default” means 33 % driving with 0 % payload, 33 % driving with 50 % payload and 33 % driving with 100 % payload.

4.5. Aggregate traffic situations

4.5.1. Germany

For Germany, new distributions of traffic situations were determined on the basis of floating car data in the project FKZ_3719581020 of the Federal Environment Agency (UBA). On the one hand, this results in new distributions with regard to the proportions of road types travelled and associated localities as well as speed classes. On the other hand, the corresponding shares of the Level of Service were also newly determined.

The number of 1480 different traffic situations identified, differentiated by road category (two spatial types, up to eight road types and 12 speed classes), gradient class (four classes) as well as traffic state (five states) exceeds the current limit of the implementation of HBEFA in MS Access for the determination of nationwide emissions. Tests have shown that more frequent out-of-memory errors result if aggregate traffic situations contain more than 225 individual traffic situations (see also Chapter 2.1). Therefore, the number of individual traffic situations per aggregate traffic situation for each road category (Average, Urban, Rural, and MW) was reduced to about 225 records. To achieve this reduction, the traffic situations with emission factors as similar as possible were grouped per road category while maintaining the gradient class shares, separately for each vehicle category.

4.5.2. Sweden

TSGrad-Patterns to be used from the year 2019 an onwards have been added. All TSGrad-Patterns used from year 1990 and onwards have been updated to now include a distribution on different road gradients.

4.6. Other country data

4.6.1. Sweden

- The base corrections for passenger cars (petrol and diesel) have been updated.
- CO_2/energy consumption for passenger cars (petrol, diesel, FFV, CNG/petrol) has been updated by using data on real-world consumption reported by ICCT and TNO (2019).
- Sulphur content tables for petrol and diesel up to 2020 have been updated from data reported in accordance with the Fuel Quality Monitoring System. From 2021 and onwards the sulphur content is assumed to equal the average for the years 2015 to 2020.

5. Online Version

The “online version” of HBEFA, available on www.hbefa.net > HBEFA > ONLINE VERSION, is updated to the current contents of Version 4.2.

One change should be noted: The pollutant “CO2” in the online version does not correspond to “CO2 (total)” from the installable version anymore, which includes fossil and biogenic CO2 emissions, but to the pollutant “CO2 (rep.)”, which includes ONLY FOSSIL CO2. The latter is more informative (since it includes information on the fuelmix of the respective country and year) and corresponds better to what users expect.

Annex

Table 16: Detailed information about WtT GHG emission factors for HBEFA 4.2

Energy	ProductionType	WtT EF (gCO_2eq/MJ)	Source	HBEFA 4.2 update	Comment
petrol	Ø	13.5	ecoinvent 3.8	Update	Dataset: petrol production, unleaded, petroleum refinery operation, Europe without Switzerland
diesel	Ø	12.5	ecoinvent 3.8	Update	Dataset: diesel production, low-sulfur, petroleum refinery operation, Europe without Switzerland
CNG	Ø	10.8	ecoinvent 3.8	Update	Dataset: natural gas production, medium pressure, vehicle grade, CH
kerosene	Ø	10.53	ecoinvent 3.8	New	Dataset: kerosene production, petroleum refinery operation - Europe without Switzerland
electricity	Nuclear energy	1.8	ecoinvent 3.8	Update	Average of datasets: electricity production, nuclear, boiling water reactor, DE and electricity production, nuclear, pressure water reactor, DE
electricity	Solids	315.9	ecoinvent 3.8	Update	Average of datasets: electricity production, hard coal, DE and electricity production, lignite, DE
electricity	Oil	235.9	ecoinvent 3.8	Update	Dataset: electricity production, oil, DE
electricity	Gas	157.2	ecoinvent 3.8	Update	Average of datasets: electricity production, natural gas, combined cycle power plant, DE and electricity production, natural gas, conventional power plant, DE
electricity	Biomass-waste	22.9	Pfadt-Trilling et al 2021	Update	
electricity	Hydro	7.6	ecoinvent 3.8	Update	Average of datasets: electricity production, hydro, reservoir, non-alpine region, DE and electricity production, hydro, run-of-river, DE
electricity	Wind	4.9	ecoinvent 3.8	Update	Average of datasets: electricity production, wind, 1-3MW turbine, onshore, DE and electricity production, wind, 1-3MW turbine, offshore, DE
electricity	Solar	28.7	ecoinvent 3.8	Update	Average of datasets: electricity production, photovoltaic, 570kWp open ground installation, multi-Si, DE and electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted, DE
electricity	Geothermal	18.9	ecoinvent 3.8	Update	Dataset: electricity production, deep geothermal, DE
LPG	Ø	10.76		Update	Assume same as CNG
hydrogen	Nuclear energy	4.1	Romain Sacchi, PSI, 2021	New	
hydrogen	Solids	566.6	Romain Sacchi, PSI, 2021	New	
hydrogen	Oil	423.3	Romain Sacchi, PSI, 2021	New	
hydrogen	Gas	282.3	Romain Sacchi, PSI, 2021	New	

Energy	**ProductionType**	**WtT EF (gCO_2eq/MJ)**	**Source**	**HBEFA 4.2 update**	**Comment**
hydrogen	Biomass-waste	41.8	Romain Sacchi, PSI, 2021	New	
hydrogen	Hydro	14.4	Romain Sacchi, PSI, 2021	New	
hydrogen	Wind	9.6	Romain Sacchi, PSI, 2021	New	
hydrogen	Solar	52.3	Romain Sacchi, PSI, 2021	New	
hydrogen	Geothermal	34.6	Romain Sacchi, PSI, 2022	New	
hydrogen	SMR with CCS	40.0	Antonini et al 2020	New	
hydrogen	SMR without CCS	88.0	Antonini et al 2020	New	
petrol 2S	Ø	14.5	ecoinvent 3.8	Update	Dataset: petrol blending for two-stroke engines, Europe without Switzerland
extra light heating oil	Ø	10.52	ecoinvent 3.8	New	Dataset: light fuel oil production, petroleum refinery operation, Europe without Switzerland
ethanol (bio)	maize-to-liquid	50.9	RED 2018	Update	Average of 4 production variants for corn ethanol
ethanol (bio)	rye	53.0	RED 2018	Update	Average of 4 production variants for "other cereals"
ethanol (bio)	wheat-by-gas	48.2	HBEFA 4.1	Unchanged	Unchanged from HBEFA 4.1
ethanol (bio)	wheat-by-waste	34.9	HBEFA 4.1	Unchanged	Unchanged from HBEFA 4.1
ethanol (bio)	sugar beet	33.5	RED 2018	Update	Average of 6 production variants for sugar beet ethanol
ethanol (bio)	sugar cane	28.6	RED 2018	Update	
ethanol (bio)	ligno cellulose	31.3	HBEFA 4.1	Unchanged	Unchanged from HBEFA 4.1
ethanol (bio)	wheat straw	15.7	RED 2018	New	
ethanol (bio)	wood Fischer-Tropsch	15.2	RED 2018	New	Average of 2 production variants for ethanol from wood Fischer-Tropsch
biodiesel	wood Fischer-Tropsch	15.2	RED 2018	New	Average of 2 production variants for biodiesel from wood Fischer-Tropsch
biodiesel	FAME rapeseed oil	50.1	RED 2018	Update	
biodiesel	FAME soya oil	47.0	RED 2018	Update	
biodiesel	FAME palm oil	63.7	RED 2018	Update	Average of 2 production variants for FAME palm oil biodiesel
biodiesel	HVO palm oil	60.7	RED 2018	Update	Average of 2 production variants for HVO palm oil biodiesel
biodiesel	HVO waste	16.0	RED 2018	Update	
petrol PtX	Nuclear energy	12.3	Romain Sacchi, PSI, 2021	New	
petrol PtX	Solids	687.7	Romain Sacchi, PSI, 2021	New	
petrol PtX	Oil	515.6	Romain Sacchi, PSI, 2021	New	
petrol PtX	Gas	346.4	Romain Sacchi, PSI, 2021	New	
petrol PtX	Biomass-waste	57.6	Romain Sacchi, PSI, 2021	New	
petrol PtX	Hydro	24.8	Romain Sacchi, PSI, 2021	New	

Energy	ProductionType	WtT EF (gCO_2eq/MJ)	Source	HBEFA 4.2 update	Comment
petrol PtX	Wind	18.9	Romain Sacchi, PSI, 2021	New	
petrol PtX	Solar	70.2	Romain Sacchi, PSI, 2021	New	
petrol PtX	Geothermal	49.0	Romain Sacchi, PSI, 2022	New	
diesel PtX	Nuclear energy	6.9	Romain Sacchi, PSI, 2021	New	
diesel PtX	Solids	710.5	Romain Sacchi, PSI, 2021	New	
diesel PtX	Oil	531.2	Romain Sacchi, PSI, 2021	New	
diesel PtX	Gas	354.9	Romain Sacchi, PSI, 2021	New	
diesel PtX	Biomass-waste	54.1	Romain Sacchi, PSI, 2021	New	
diesel PtX	Hydro	19.8	Romain Sacchi, PSI, 2021	New	
diesel PtX	Wind	13.8	Romain Sacchi, PSI, 2021	New	
diesel PtX	Solar	67.2	Romain Sacchi, PSI, 2021	New	
diesel PtX	Geothermal	45.1	Romain Sacchi, PSI, 2022	New	
Gas PtX	Nuclear energy	6.7	Romain Sacchi, PSI, 2021	New	
Gas PtX	Solids	710.3	Romain Sacchi, PSI, 2021	New	
Gas PtX	Oil	531.0	Romain Sacchi, PSI, 2021	New	
Gas PtX	Gas	354.7	Romain Sacchi, PSI, 2021	New	
Gas PtX	Biomass-waste	53.9	Romain Sacchi, PSI, 2021	New	
Gas PtX	Hydro	19.6	Romain Sacchi, PSI, 2021	New	
Gas PtX	Wind	13.6	Romain Sacchi, PSI, 2021	New	
Gas PtX	Solar	67.0	Romain Sacchi, PSI, 2021	New	
Gas PtX	Geothermal	44.9	Romain Sacchi, PSI, 2022	New	
kerosene PtX	Nuclear energy	9.4	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Solids	785.2	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Oil	587.6	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Gas	393.2	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Biomass-waste	61.4	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Hydro	23.7	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Wind	17.0	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Solar	75.9	Romain Sacchi, PSI, 2021	New	
kerosene PtX	Geothermal	51.6	Romain Sacchi, PSI, 2022	New	
biogas	maize-to-gas	27.8	HBEFA 4.1	Unchanged	Unchanged from HBEFA 4.1
biogas	Waste-to-gas	14.0	HBEFA 4.1	Unchanged	Unchanged from HBEFA 4.1
propan	Ø	14.27	ecoinvent 3.8	New	Dataset: market for liquefied petroleum gas, Europe without Switzerland
LNG	Ø	19.4	ecoinvent 3.8	Update	Dataset: market for natural gas, liquefied - GLO

Energy	ProductionType	WtT EF (gCO_2eq/MJ)	Source	HBEFA 4.2 update	Comment
biokerosene	wood Fischer-Tropsch	15.2		New	Assume same as biodiesel
biokerosene	HVO palm oil	60.65		New	Assume same as biodiesel
biokerosene	HVO waste	16		New	Assume same as biodiesel

Literature

Antonini, C., Treyer, K., Streb, A., Spek, M. van der, Bauer, C., Mazzotti, M. 2020: Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis. Sustainable Energy & Fuels 4(6), 2967–2986.

Bäumer, M., Hautzinger, H., Pfeiffer, M., Stock, W., Lenz, B., Kuhnimhof, T., Köhler, K. 2016: Fahrleistungserhebung 2014: Begleitung und Auswertung - Schlussbericht zur Inlandsfahrleistung. Bundesanstalt für Straßenwesen (BASt), Mannheim.

BFE 2021: Ex-Post-Analyse des Energieverbrauchs der schweizerischen Haushalte 2000 bis 2020 nach Verwendungszwecken und Ursachen der Veränderungen. Bundesamt für Energie (BFE), Ittigen. https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/energieverbrauch-nach-verwendungszweck.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVib-GljYX/Rpb24vZG93bmxvYWQvMTA2OTM=.html [Accessed 17. January 2022].

Diegmann 2021: Diegmann V., Neunhäuser L., Kleefeld J.B. et.al.: Remote Sensing zur Emissionsmessung von im Verkehr befindlichen Kfz sowie Erarbeitung von Vorschlägen zur Weiterentwicklung des Handbuchs für Emissionsfaktoren des Straßenverkehrs; Forschungskennzahl 3718 52 100 0, UBA-FB I 2.2, draft final report for UBA Germany; 12/2021

EC 2009 : (EC) 595/2009: Commission Regulation (EU) 582/2011.

EC 2011 : (EC) 582/2011: Commission Regulation (EU) 582/2011.

EC 2018: Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. European Commission (EC), Brussels.

EC 2019: (EC) 2019/1939: Commission Regulation (EU) 2019/1939.

Ecoinvent 2021: Ecoinvent Database v3.8. Swiss Centre for Life Cycle Inventories, Dübendorf. www.ecoinvent.ch.

EEA 2020: Monitoring CO_2 emissions from passenger cars - Regulation (EU) 2019/631. https://www.eea.europa.eu/data-and-maps/data/CO2-cars-emission-18 [Accessed 11. December 2020].

EMEP/EEA 2019: European Environmental Agency: EMEP/EEA air pollutant emission inventory guidebook 2019, Technical guidance to prepare national emission inventories, Luxembourg 2019, ISBN 978-92-9480-098-5

Grange 2021: S. K. Grange et al.: Strong Temperature Dependence for Light-Duty Diesel Vehicle NO_x Emissions, University of York, 2021

Hooftman 2020: Hooftman N., Ligterink N., Bhoraskar, A., (2020) Analysis of the 2019 Flemish remote sensing campaign. Commissioned by the Flemish Government - Flanders Environment Agency - Team Air quality policy

ICCT 2019: FROM LABORATORY TO ROAD A 2018 UPDATE OF OFFICIAL AND "REAL-WORLD" FUEL CONSUMPTION AND CO_2 VALUES FOR PASSENGER CARS IN EUROPE. International Council on Clean Transportation (ICCT). https://theicct.org/sites/default/files/publications/Lab_to_Road_2018_fv_20190110.pdf.

INFRAS, ifeu, MKC 2019: HBEFA 4.1 Development Report. Update of the Handbook of Emission Factors for Road Transport to Version 4.1. INFRAS, ifeu, MK Consulting, Bern, Heidelberg. https://www.hbefa.net/e/documents/HBEFA41_Development_Report.pdf [Accessed 19. September 2019].

Pfadt-Trilling, A. R., Volk, T. A., Fortier, M.-O. P. 2021: Climate Change Impacts of Electricity Generated at a Waste-to-Energy Facility. Environmental Science & Technology 55(3), 1436–1445.

Plötz, P., Moll, C., Bieker, G., Mock, P., Li, Y. 2020: Real-world useage of plug-in hybrid electric vehicles. Fuel consumption, electric driving, and CO_2 emissions. International Council on Clean Transportation (ICCT) and Fraunhofer ISI. https://theicct.org/sites/default/files/publications/PHEV-white%20paper-sept2020-0.pdf [Accessed 15. April 2021].

Prognos, INFRAS, TEP Energy 2020: Energieperspektiven 2050+ Kurzbericht. Bundesamt für Energie (BFE). https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVib-GljYX/Rpb24vZG93bmxvYWQvMTAzMjM=.html [Accessed 22. November 2021].

Schmidt 2021: W. Schmidt, I. Düring: Ermittlung der Emissionen von Kraftfahrzeugen im fließenden Verkehr mit Remote Sensing Detection (EMI-RSD), Schlussbericht, Dresden, 2021

Sintermann 2020: J. Sintermann, G.-M. Alt, M. Götsch, F. Baum, V. Delb: Langjährige Abgasmessungen im realen Fahrbetrieb mittels Remote Sensing, Zürich, 2020

Sjödin 2021: Å. Sjödin et al.: Real Driving Diesel Vehicle Emissions as Measured by Novel Remote Sensing (RSD) Technology, Stockholm, 2021

Weller 2020: Emission Models for Heavy Duty Vehicles Based on On-road Measurements, Dissertation, Graz University of Technology, 2021.