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Miljødirektoratet (NO)

HBEFA 5.1
Documentation of updates

Bern/Graz/Heidelberg/Lyon/Göteborg/Oslo/Dresden, 13 February 2026

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Editorial Information

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Commissioned by

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Umweltbundesamt UBA (DE)

Umweltbundesamt UBA (AT)

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Version history

Version	Date	Comment
1.0	22.10.2025	Version published with HBEFA application version 5.1
1.1	13.02.2025	Added Chapter 4.9 on HEV and PHEV methodology

Content

1. Introduction

1.1. Overview of updates in HBEFA 5.1

Version 5.1 represents a major update of the HBEFA (Handbook of Emission Factors for road transport). This means all contents of the Handbook have been reviewed and updated where necessary. A particular focus has been set on aspects that gain importance as road vehicle fleets evolve due to regulations and decarbonisation – such as non-exhaust emissions, cold start extra energy consumption and emissions, non-regulated pollutant emission, or tampering and malfunctioning vehicles.

Table 1 presents an overview of the **content updates**. All in all, the 5.1 update represents a substantial extension of contents compared to previous HBEFA versions, with new vehicle types, new pollutants and new processes. For example,

- The number of output "components" (which include energy consumption or positive engine work besides actual pollutants) has increased from 27 to 44;
- the number of subsegments (i.e. vehicle types at the finest level of detail) has increased from 833 to 1375;
- The number of hot base emission factors (at subsegment/driving cycle/gradient/load differentiation) has increased from about 20 million to almost 100 million.

Besides the content updates, two further new features are published with HBEFA 5.1:

- The **HBEFA application has been migrated** from Microsoft Access to a Python-based client-server solution: On one hand, the substantial addition of contents would have not been possible with the previous Access-based application; on the other hand, the new Python-based application is more user-friendly and allows for more efficiency in use – both when using the front-end and by offering automated API access.
  Chapter 2 contains additional information on the migrated application.
- **Guidelines for the use of the HBEFA Traffic Situations** (TS) have been elaborated in response to wide demand, in order to promote consistent application of the TS between users and use cases. The TS Guidelines can be accessed here: www.umweltbundesamt.de/publikationen/hbefa-traffic-situations

One feature has been discontinued in HBEFA 5.1: These are the CO2e WTT (well-to-tank) emission factors that were available in HBEFA 4.x. They have been removed from HBEFA 5.1 since they would have required continuous updates of energy production type emission factors and shares. This is not the main focus of HBEFA, there are better sources available (i.e. various LCA databases).

Table 1: Content updates in HBEFA Version 5.1

Update	Description
Hot EF update	General update of all hot base energy consumption and emission factors based on latest available measurement data. Besides lab and PEMS measurements (as up to HBEFA 4.x), also remote sensing (RS) data have been systematically analysed for validation of base emission factors and derivation of correction functions.
Non-exhaust EF	Non-exhaust emission factors based on new model, differentiated by processes (tire/brake/road wear, resuspension) and subsegments
Non-regulated EF	Additional non-regulated pollutants: CH3CHO (Acetaldehyde), HNCO (Isocyanic acid), HNO2 (Nitrous acid), HCHO (Formaldehyde); N2O and NH3 for new vehicles based on PHEM model at traffic situation resolution.
Cold start EF	Cold start excess emission factors based on new model, and available also for HDV and for BEVs.
Evaporation EF	Gasoline evaporation emission factors based on latest COPERT methodology
Euro-7 EF	Euro-7 emission factors based on known regulations/test conditions and PHEM simulation
Mileage correction factors	Updated functions for mileage correction: Additive instead of multiplicative factors allow for more realistic correction across all traffic situations
SCR tampering and malfunctions	Emission factors for tampered or malfunctioning SCR included; high emitters included in fleet scenarios.
New HGV size classes	HGV size classes for alternative drivetrains at same detail as for Diesel (HBEFA 4.x: simplified size classes for alternative HGV); In addition, size classes up to 90 t.
New L-cat. vehicle types	New segments/subsegments in the vehicle category "motorcycles" (which contains all L-category vehicles): 4-stroke mopeds, ATVs, minicars
Conditioning cycle updates	Conditioning cycles ("trip history", relevant for SCR temperature and hybrid vehicle battery SOC) updated based on driving behaviour data from Horizon Europe project "uCARe"
Country data	Update of all country-specific data (fleet data, fuel properties etc.) with time-series covering at least the period 1990-2050

1.2. Effects on emission factors at subsegment level

Most uncorrected base EF[1] remain the same as in HBEFA 4.2. However, new measurements have become available for the different Euro 6/VI stages; therefore, the respective base EF have been adjusted (see e.g. Figure 1 for NOx, Figure 2 for PM10-exhaust of Diesel passenger

[1] “Uncorrected EF” are valid for “new” reference vehicles, i.e. with 50’000 km cumulative mileage, at 20°C. Corrections can include corrections for catalyst ageing (mileage-based, affects various air pollutants), ambient temperature (affects NOx in LDV), energy efficiency (affects energy consumption and pollutants derived thereof, e.g. CO2, Pb, SO2), or fuel quality (effect of different fuel standard than at the time of new registration of the vehicle; affects regulated air pollutants).

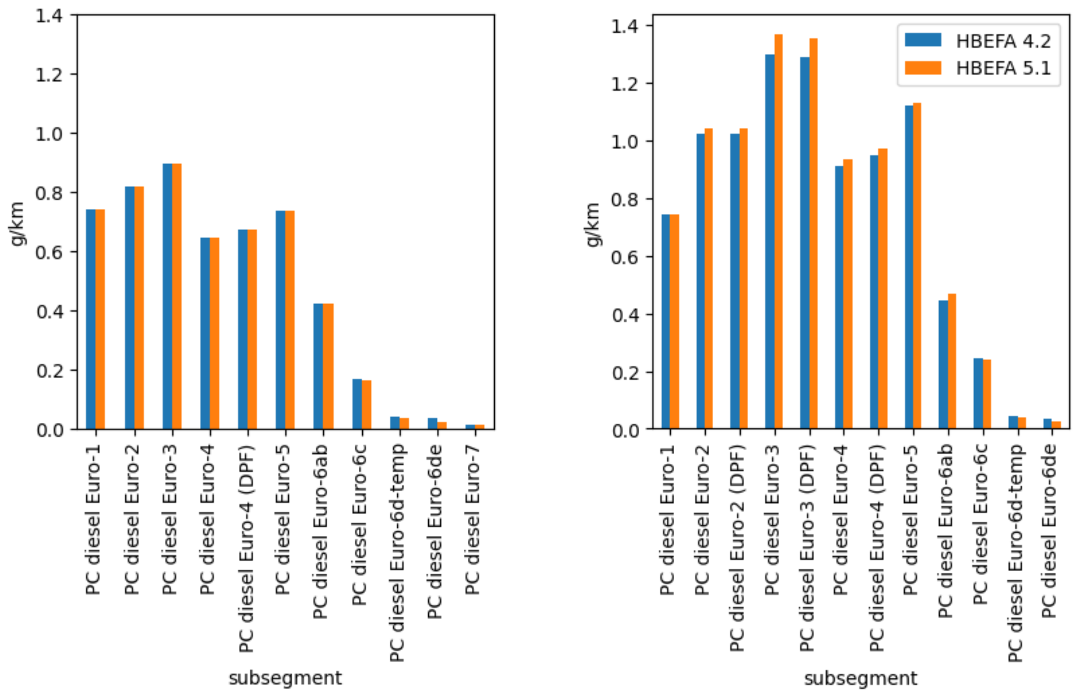
cars and LCV, respectively). In the majority of cases, the updated emission factors of the newer vehicles are lower than in HBEFA 4.2. In addition, estimated emission factors for Euro-7 vehicles are included in HBEFA 5.1.

The updated mileage correction factors (additive instead of multiplicative to better represent ageing for low absolute EF) lead to different values also for older vehicles for the affected pollutants (see e.g. the slightly higher corrected NOx EF of Diesel PC in Figure 1).

The non-exhaust emission factors, which are based on a new modelling method (see Chapter 4.10), are significantly higher in HBEFA 5.1 than in the previous version (Figure 2).

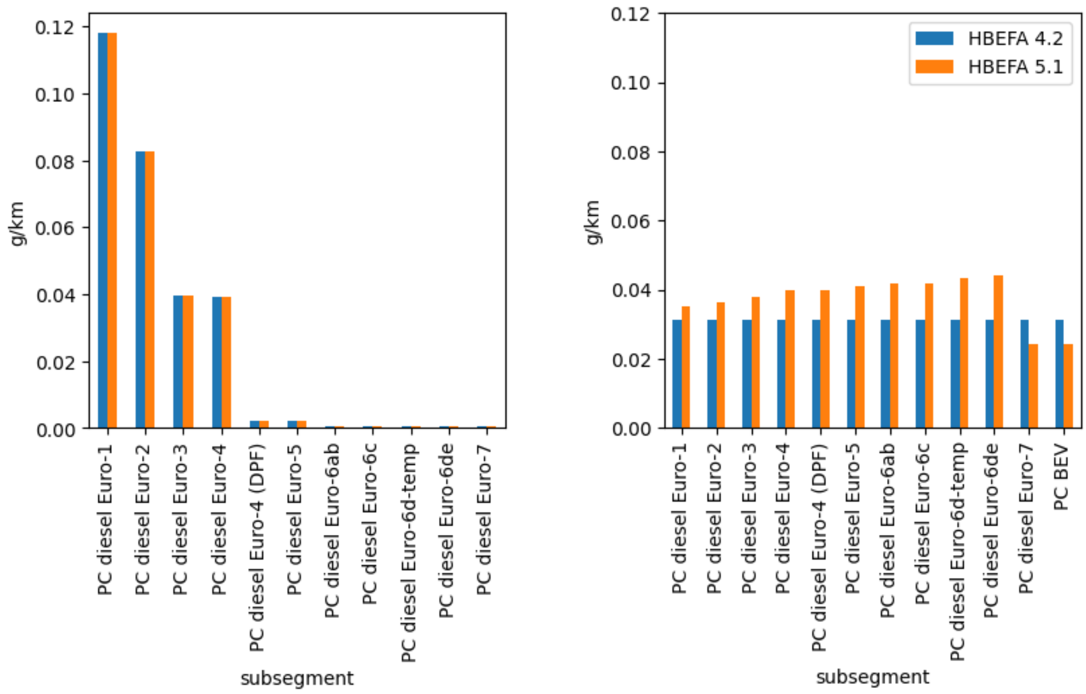
Cold start extra emission factors are newly available for HDV in HBEFA 5.1 (see Table 1). For the vehicle types that already had cold start EF in HBEFA 4.2, the version comparison shows generally higher values for HBEFA 5.1.

Figure 1: Hot uncorrected (left) and corrected (for year 2025, right) NOx EF of Diesel PC, HBEFA 5.1 vs. 4.2 (Swiss overall aggregate TS).



The uncorrected EF at the left are the mileage-weighted average for the Swiss aggregate traffic situation distribution (2017) and they include Euro-7 PC, since the uncorrected query does not need to consider a reference year. The corrected EF at the right have been corrected for mileage (catalyst aging) and ambient temperature effects. They do not include Euro-7 since the fleet data used for corrections are for the year 2025.
Graphics by INFRAS. Source: HBEFA 4.2, 5.1

Figure 2: Hot PM10 exhaust (left) and non-exhaust (right) EF of Diesel passenger cars, HBEFA 5.1 vs. 4.2 (Swiss overall aggregate TS).



The PM10 EF are not affected by any corrections; results include Euro-7 as the query is year-independent.
Graphics by INFRAS. Source: HBEFA 4.2, 5.1

1.3. Effects on total emissions

Besides the changes in base emission factors, total road transport emission factors are also affected by changes in activity data, i.e. mileages, stock, starts, stops, fleet composition, aging and temperature effects, energy efficiency, and special effects such as tampering and malfunctions. The latter have for the first time been integrated into fleet data in HBEFA 5.1 for HGV and NOx[2] (see also Chapter 5.3.1).

Figure 3 shows total emissions from road transport in Switzerland of fossil CO2, NOx, PM10 exhaust and PM10 non-exhaust, differentiated by hot and cold start emissions, comparing HBEFA 5.1 to 4.2.

Compared to HBEFA 4.2, in Version 5.1 the emissions of almost all pollutants decrease faster and are consequently lower in the projected period from 2030 onwards. This is due to higher shares of electric vehicles in the projected fleet, the Euro-7 regulation, and the lower

[2] Please note tampering and malfunctions of LDV is not accounted for separately, but included in the mileage (ageing) correction factors.

base emission factors of Euro-6de/VI DE vehicles compared to HBEFA 4.2 (see previous Chapter).

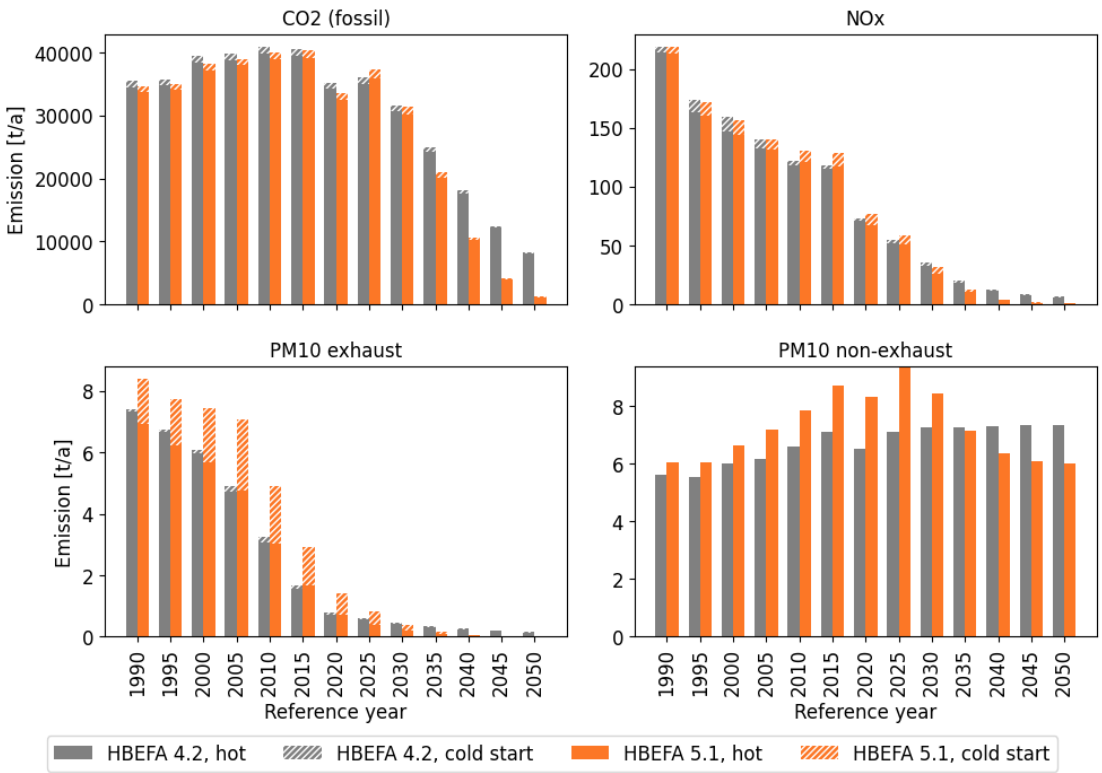
In the period up to 2025, whether emissions are higher in HBEFA 5.1 or 4.2 varies by pollutant and year. While the base emission factors of reference vehicles older than Euro 6de/VI DE have mostly not changed between the two HBEFA versions (see previous chapter), CO, HC and NOx are affected by the updated mileage correction functions. For NOx, SCR malfunctions and tampering add to higher emissions between 2010 and 2025.

Cold start excess emissions, considered for HDV for the first time in HBEFA 5.1, most visibly add to PM10 emissions over the entire time series, and to all pollutant emissions in the later years, when hot exhaust emissions are lower.

Effects of the HBEFA 5.1 update on fossil CO2 vary by country, since CO2 is largely dependent on fuel consumption, which in turn may be calibrated to national fuel sales. It is slightly lower in HBEFA 5.1 than 4.2 in the example of Switzerland shown in Figure 3 due to an updated fleet composition: On one hand, the diesel mileage shares are slightly higher up to about 2015. This is due to the fact that up to HBEFA 4.2, mileage ratios between petrol and diesel PC were fixed in the fleet model, which artificially kept petrol mileages too high (since increasing numbers of new diesel PC were introduced mainly in that period, the diesel fleet was on average newer, and newer vehicles are driven more than older ones; this effect was cancelled out by the fixed share). On the other hand, newer data on the heavy-duty levy in Switzerland (LSVA), which are used to calibrate fleet shares for trucks, differentiate rigid trucks from truck/trailer and articulated trucks, which led to a higher rigid truck (RT) share.

PM10 non-exhaust is based on a new model in HBEFA 5.1 (see Chapter 4.10). It generally increases with vehicle weight (and thus with newer ICE vehicles), but is lower for BEV due to their higher share of motor braking, which reduces brake wear.

Figure 3: Emissions of selected GHG and air pollutants from road transport in Switzerland, HBEFA 5.1 and HBEFA 4.2, differentiated by hot and cold start emissions.



1.4. Project contributions

As all HBEFA versions so far, the 5.1 update is the result of a common funding by the national environment or transport agencies of the six countries represented in HBEFA. All countries have contributed (more or less) equally in terms of funding. Some countries have funded certain specific tasks, while others have contributed to the overall effort. The tasks specifically funded by single countries include:

- Germany: Traffic Situation guidelines (Notter et al. 2025[3]), correction factors for mileage and temperature, Euro-7 emission factors, new non-regulated pollutants (Weller et al. [Forthcoming]);
- France: Remote sensing data analysis, conditioning cycle update, moped and additional L-category vehicles emission factors, update of emission factors from EMEP/EEA Guidebook;
- Switzerland: Cold start emission factors, non-exhaust emission factors (Hausberger et al. 2024), additional options for emission factor queries in HBEFA application;

[3] https://www.umweltbundesamt.de/publikationen/hbefa-traffic-situations

2. Remarks on the application

2.1. New Python-based client-server solution

HBEFA 5.1 is the first version published after the migration of HBEFA from Microsoft Access to Python. The new Python-based HBEFA implements a **client-server architecture**:

- The **server application**, run on a central server, is built using the Flask framework[4]. It carries out most calculations and offers an API (Application Programming Interface) to communicate with client applications;
- The **main front-end** is a desktop client application developed in PySide6[5]. It is compiled as a Windows executable (.exe). It can be downloaded and run by double-clicking on it. It does not require installation, but login credentials (e-mail + password). The main front-end is basically free to use, but without license only enables the emission factor queries also available in the "Online Version"[6]. Users with an HBEFA license receive an initial password by e-mail after registration and can change it afterwards.
- The HBEFA API can also be accessed third-party scripts and clients. We request interested users to contact INFRAS directly for this option, and we reserve the right to charge for additional resources or support efforts necessary due to the use of third-party clients.

The interaction with the main front-end application is similar as with the previous MS Access application. Useful hints are available within the Help document, available from within the main front-end (menu *Settings > Open Help file*) and at https://download.hbefa.net/help-files/HBEFA51_help_en.pdf.

2.2. Additional emission factor query options

2.2.1. Filtering by subsets of vehicle categories

- An emission factor query can be filtered by single or multiple sub-vehicle category vehicle types at all fleet aggregation levels (technology, (aggregated) size class, segment, (aggregated) emission concept, subsegment)

[4] https://flask.palletsprojects.com/
[5] https://pypi.org/project/PySide6/
[6] https://www.hbefa.net/en/software#online-version

2.2.2. Fleet aggregation levels

Emission factors can be queried at the following fleet aggregation levels:

- Vehicle category
- Technology
- Aggregated size class (differentiates only MC, mopeds, and other L-category vehicles within vehicle category "motorcycles", and RT (rigid trucks) vs. TT/AT (truck+trailer combinations or articulated trucks) within vehicle category "HGV")
- Size class
- Segment (=combination of all above aggregation levels)
- Aggregated emission concept
- Emission concept
- Subsegment (=combination of all above aggregation levels)

Multiple fleet aggregation levels can be selected and freely combined in an emission factor request.

2.2.3. Energy aggregation levels

The Python-based HBEFA app enables the selection of energy aggregation levels (which was not possible in the MS Access based app):

- "None" (default): Emission factors are not differentiated by energy or fuel type, other than the the differentiation implicit in the selected fleet aggregation level (see above);
- "Main": Emission factors are differentiated by "main" energies (e.g. petrol, diesel, electricity)
- "Base": Emission factors are differentiated by all energies in fuel mixes, i.e. by the fossil, biogenic, and synthetic shares of fuel (e.g. petrol/bioethanol/synthetic petrol)

2.2.4. Traffic situation aggregation levels

In previous HBEFA versions, it has been possible to select between individual traffic situations and aggregate (or "average") traffic situations. In the Python-based HBEFA app, an additional option "static traffic situations" is available.

This new option differentiates the static traffic parameters (area type, road type, and speed limit) of individual traffic situation, but not the dynamic parameter Level of Service (LOS). The emission factors for the different LOS are averaged using the mileage weights for the given country, area and road type, and speed limit (which is contained in an "aggregate traffic situation"; therefore, users can optionally select a specific "aggregate traffic situation").

This option is useful for users who want to calculate emissions by road segments in a network, but don't know the concrete or typical LOS shares of mileage.

2.2.5. Disaggregation by age class

The Python-based HBEFA app enables the differentiation of emission factors by vehicle age class (which was not possible in the MS Access based app). The following age classes are available:

- <1 year (=new registrations)
- 1-4 years
- 5-9 years
- 10-19 years
- >=20 years

2.2.6. Additional output units

By default, HBEFA outputs emission factors in grams (for most pollutants), MJ (for energy consumption) or # (particle number PN) per traffic unit related to the respective emission category. This means:

- For hot and evap-running losses EF, the default output unit is .../vehkm;
- For cold start EF, the default output unit is .../start;
- For evap-soak EF, the default output unit is .../stop;
- For evap-diurnal EF, the default output unit is .../veh*day;

In HBEFA 5.1, the option to select additional output units has been added:

- EF per vehicle km for emission catories with other original activity units (cold start, evaporation)
- EF per MJ of final energy consumption (EC)
- EF per kg fuel consumption (FC)
- EF per kWh of positive engine work (WE-pos)
- Fuel consumption (FC) in l/100 km (for liquid fuels) or Nm3/100 km (for gaseous fuels)

If one of these options is selected, rows with the additional selected output units are added to the result. The rows with the original (default) units (see above) are always included as well. For requested output units that do not make sense or no input data is available, the unit conversion is skipped and a warning is issued This is the case e.g.

- if EC (energy consumption) is requested in combination with the output unit "…/MJ" – because MJ/MJ does not make sense, the EF value would always be 1 in this case;

- or if the output unit "…/kWh" is requested for cold start EF. This would theoretically be possible, but cold start extra positive engine work (WE-pos), which would be required to calculate this unit, is not available.

2.3. Adaptations of calculation algorithms for HBEFA 5.1

Mostly due to the much larger data amount in HBEFA 5.1 than previous versions (compare Chapter 1.1), but also due to new methodological features, the following adaptations of the calculation algorithms were necessary for HBEFA Version 5.1, compared to the first (only internally available) Version 4.2 migrated to Python:

- Query speed/memory usage optimizations due to significantly higher input data amounts:
  - In EF requests for aggregate traffic situations, traffic situation aggregation is carried out as early as possible in hot EF calculation to minimize involved data amounts in subsequent steps. In particular, a partial aggregation of traffic situations is performed after the correction steps requiring traffic situation differentiation, but before before adding pollutants of which calculation inputs are differentiated by "idrc_ef" (the average speed-based road category class used in COPERT). These pollutants include e.g. N2O, NH3, and NO2. This first aggregation step leaves "idrc_ef" still disaggregated; after adding the pollutants requiring "idrc_ef", the rest of the traffic situation aggregation is performed.
  - Dynamic iterations: The peak number of rows during an emission factor request is estimated at the beginning of the calculation. If it exceeds certain thresholds, the request is broken up into smaller chunks: by vehicle category, aggregate traffic situation pattern, gradient class, or ambient condition pattern. This increases calculation time, but ensures server memory will be sufficient for the request.
  - If emission factor requests are issued the result of which is so large that it would consume too much memory, the server does not carry out the query, but tells the user to break it up into several smaller queries.
  - Hot EF: Already in the Python version of HBEFA 4.2, querying all hot base emission factors has been programmed to take place only once after server start, in the first larger emission factor query (therefore, the first larger emission factor query after server start takes longer – which most users will not notice, since the server is usually not restarted often) – with the benefit that subsequent requests can be performed much faster). In HBEFA 5.1, also the calculation of base EF for derived subsegments has been set to take place only once for all derived subsegments and pollutants during the first larger request after server start – for all subsequent request, the derived emission factors are already ready, which reduces calculation time.

- Cold start EF: The loop over reference years has been optimized so EF already calculated for a previous reference year in a request are cached and do not have to be calculated again. For this reason, cold start EF calculation always takes longest for the first reference year and is much quicker for subsequent reference year in a request.
  (Note: The same approach cannot be used for hot and evaporation emission factors, since these partially depend on cumulative mileage, which is different in every reference year).
- The fact that cold start extra emission factors also became available for HDV with HBEFA 5.1 necessitated a change in the data model of “ambient condition patterns”, and corresponding changes in the calculation algorithms for cold start and evaporation emissions. See Chapter 5.2 for more information.

2.4. Discontinuation of WTT CO2e emission factors

HBEFA versions 4.x contained CO2e emission factors for energy provision (Well-to-Tank, WTT). This option has been removed in HBEFA 5.1, since it would have required continuous updates of production type-specific emission factors and shares of production types of energy (energy mixes). This would have required relevant continuous effort and is not within the focus of HBEFA, while there are better, dedicated sources for such information (such as various LCA databases).

3. Driving behaviour

3.1. Conditioning cycle update

3.1.1. Background

The “operation history” of the drivetrain system of a vehicle may have an impact on emission behaviour in a given traffic situation. In HBEFA, this affects vehicle types with **diesel engines with SCR catalysts**[7]: Longer consecutive durations in low-load TS (i.e. traffic jam, streets with very low speed limits, or longer downhill stretches) may lead to a decrease in SCR temperature below the required temperature of 200 °C for the NOx reduction to work, with a sharp rise in NOx emissions as a consequence.

[7] The operation history also influences the battery SOC (state of charge) of BEVs or PHEVs at the entry into a given traffic situation or driving cycle. This affects energy recuperation and thus energy consumption. However, this effect is not considered in HBEFA so far.

The so-called „conditioning cycles“ were introduced in HBEFA 4.1 as a solution for this problem. When producing the HBEFA base emission factors in PHEM, they are simulated before the main driving profile of the respective traffic situation in order to "condition" the model parameters to likely initial values at the start of the actual TS. They are intended to represent a statistically likely "history" of the drivetrain system (i.e. resulting in assumedly representative average EF values).

For HBEFA 4.1, the conditioning cycles were based on a very simple methodology and a limited data base (Ericsson et al. 2019), because the effect was new, and no resources had previously been allocated to deal with it.

Therefore, the conditioning cycles were improved for HBEFA 5.1 based on the analysis of second-by-second driving profiles from the Horizon Europe project "uCARe" (Grant Nr. 815002), which provided 1200 hours of driving data for passenger cars from different locations across Europe classified by HBEFA traffic situations.

3.1.2. Driving data analysis

From the "uCARe" driving data, the percentage of time spent by traffic situation within time periods of

- 0 to 10 minutes before entry into each road segment,
- and 10 to 40 minutes before entry into each road segment

was analysed. The analysis of the driving data yielded the following observations:

- Often, vehicles have traversed similar traffic situations in the last 10 minutes as the current traffic situation;
- Very dense traffic situations (Levels of Service 4-5, i.e. "Stop+Go" and "Stop+Go2") do not seem to last too long on average. Therefore, a dense, but less congested Level of Service (3, "Saturated") is the most frequent in the last 10 minutes before a "Stop+Go" or "Stop+Go2" traffic situation.
- Looking at the somewhat longer term, i.e. 10-40 minutes before entry into the current traffic situation, the most frequent previous traffic situation is one that is dominant anyway in the current road category (motorway, rural, or urban).
- Gradients: Within 10 or also within the 40 last minutes before entry into the current traffic situation, the most frequent gradient was usually flat. The percentage of time spent in higher gradients (steeper terrain) rises with the gradient of the current traffic situation, but even in the steepest gradients, the majority of time spent in the last 10 or 40 minutes was on flat road segments.

Note that given a typical average trip length of 10 to 15 km, many trips started within one of the time periods analysed; this means that also a relevant share of these time periods was spent NOT driving, and then a cold or warm start took place. The non-driving times were excluded from the analysis because a cold or warm start is already taken into account by the cold start emission factors.

3.1.3. Derivation of conditioning cycles

Conditioning cycles are constructed from the existing HBEFA driving cycles. From the Based on the observations described above, conditioning cycles were derived based on the following rules:

- LDV and MC need about 10 minutes of conditioning
- HDV need about 40 minutes of conditioning
- The first, or "short-term" conditioning cycle that is simulated right before the main cycle (i.e. the cycle assigned to the target traffic situation) is
  - For main cycles in LOS (Level of Service) 1-3 (i.e. "Freeflow", "Heavy" or "Saturated"): The same cycle as the main cycle
  - For main cycles in LOS 4-5 ("Stop+Go" or "Stop+Go2"): the corresponding cycle in LOS 3 (i.e. same area/road type/speed limit but LOS "Saturated")
  - This first cycle is repeated if necessary, so that total conditioning with this cycle lasts approximately 10 minutes.
- A second, or "long-term" conditioning cycle is simulated for HDV before the first (or "short-term") cycle to cover the 10-40 minutes before entry into the current traffic situation. This cycle is selected based on the road category of the main cycle:
  - For a motorway main cycle: The cycle for the traffic situation "Rural / Motorway / 120 km/h / Heavy" (the cycle for this traffic situation varies by vehicle category)
  - For a rural main cycle: The cycle for "Rural / Trunk/ 100 km/h / Freeflow"
  - For an urban main cycle: The cycle for "Urban / Trunk-city / 50 km/h / Heavy"
- Differing start/end speeds of two merged cycles are smoothened by artificially added "ramps", during which the vehicle accelerates or decelerates by 4 km/h per second (1,1 m/s^2). This prevents artificial engine heating (for SCR vehicles) or excess braking energy recuperation (for hybrid vehicles) that would influence conditioning.
- The gradient class during conditioning is 0%, regardless of the gradient class used within the main cycle.

3.1.4. Discussion

The possible variation in real emissions due to variable trip history before entry into any traffic situation cannot be captured with the traffic situation approach in HBEFA – this would only be possible if entire trips were simulated for individual vehicles. The conditioning cycles methodology aims to minimize potential errors by considering the statistically most frequent (typical) trip history. But obviously there will be certain situations that deviate from the statistically most frequent trip history. For example, on a flat or uphill segment after a longer downhill stretch, SCR catalysts may be cold, and NOx emissions may be higher than in the “typical” traffic situation assigned to this real-world situation.

The fact that the driving data analysed to determine the rules for conditioning cycle derivation is another limitation. Appropriate real-world driving datasets were not available for other vehicle categories. However, the conditioning cycle derivation rules derived from the PC data are very general and can plausibly assumed to be valid for HGV and MC also.

3.2. Traffic situation guidelines

Guidelines for the use of the HBEFA Traffic Situations (TS) have been elaborated in response to wide demand, in order to promote consistent application of the TS between users and use cases (see also Chapter 1.1). The TS Guidelines can be accessed here: https://www.umweltbundesamt.de/publikationen/hbefa-traffic-situations

4. Emission factors

Most cold and hot emission factors for exhaust and non-exhaust emissions in HBEFA 5.1 have been produced using the vehicle emission model PHEM (Passenger car and Heavy duty Emission Model) from TUG. The results are summarized in the following chapters.

For evaporation emissions, HBEFA implements the Tier 3 methodology described in the EMEP/EEA Emission Inventory Guidebook (Mellios et al. 2024).

Finally, some hot and cold start emission factors (mainly for older vehicles) are based on further sources such as the EMEP/EEA Emission Inventory Guidebook.

4.1. DBEFA

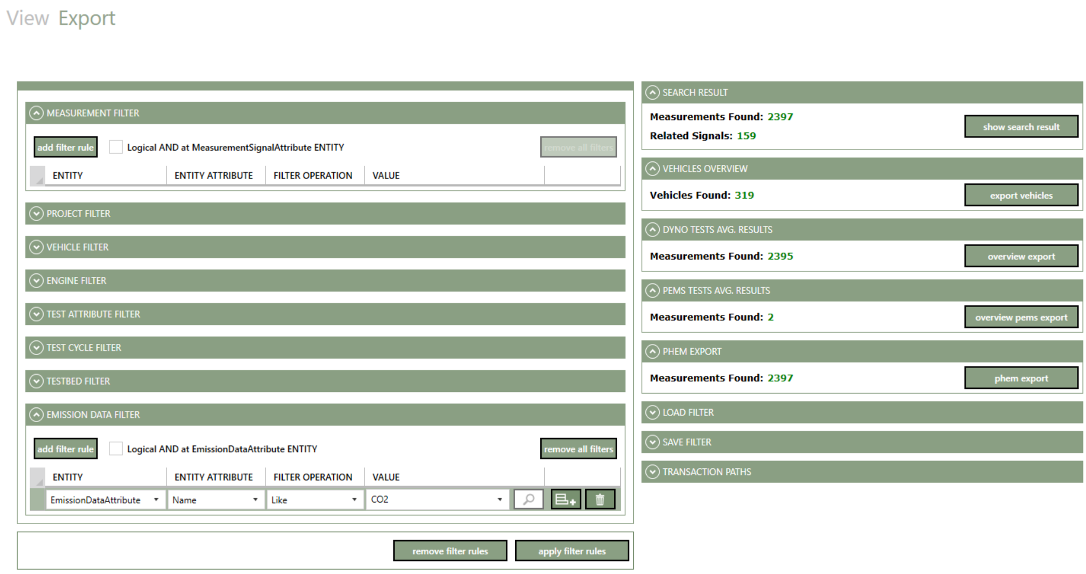
The data base for road vehicles exhaust emissions for HBEFA (DBEFA) was established for the work on HBEFA 4.2 as the successor to an old MS Access database, which had run out of memory and was not very user-friendly. Indeed, only one person was in the position to run queries with the old database. The new DBEFA is constantly maintained and test data from all HBEFA labs is collected via standardized forms in MS Excel.

The DBEFA is collecting all test data from cars, LDVs and HDVs from Euro 6 /VI on. Data on older vehicles is in the predecessor of the DBEFA. For 2-wheelers all Euro classes are collected in DBEFA.

The DBEFA provides a frontend programmed in in C#, based on the .Net framework 4.5.; A MySQL server version 5.6 acts as storage backend. The queries can be made by all users via the frontend app. All funding agencies, labs providing test data and/or are elaborating emission data for HBEFA have access to DBEFA.

For user friendly queries from the database, we have implemented a filter-based approach. Figure 4 shows the corresponding user interface. On the left side the user can define filter criteria for all attributes related to measurements, such as the project a measurement is assigned to, properties of the vehicle like engine, make, model, Euro class, properties of the test cycle, etc. In Figure 4 all tests with CO2 recordings are queried as example to show all relevant exhaust test data from vehicles with combustion engines.

Figure 4: Snapshot of the options for queries in the DBEFA showing all test data found including CO2 emissions.



The data found in a query can be exported as test average values, per cycle phase or as 1 Hz instantaneous test data. The DBEFA allows also to exclude or select time intervals from the export, e.g. the first 300 seconds of a cold start test to differentiate cold started tests into cold and hot driving conditions.

The DBEFA also includes an export form, which provides the test data in the format used by PHEM as input file to produce the engine emission maps to support a smoother elaboration of input data needed for the emission factor simulation from all available test data.

4.2. The PHEM model

The model PHEM has been developed at the Institute of Thermodynamics and Sustainable Propulsion Systems (ITnA) at Graz University of Technology since 1999. For the update of HBEFA (version 5.1) a new version of PHEM was developed (13.0.10.9), which includes novel tools for cold start extra emissions, brake-, tire- and road wear particles and resuspended particles. A short description is given below, more detailed information can be found, for example, in other TU Graz publications (Notter et al. 2022), (Matzer et al. 2019), (Hausberger, 2033).

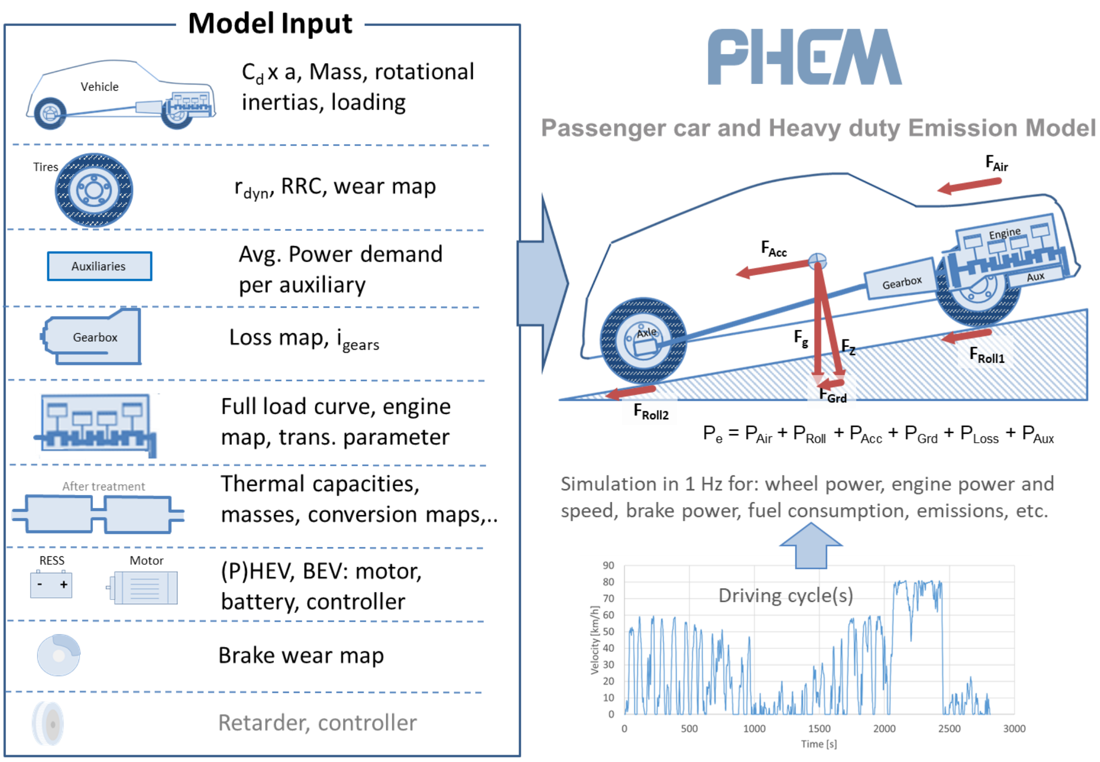
PHEM simulates the fuel consumption and emissions of road vehicles in 1 Hz for a specific driving cycle on the basis of the vehicle's longitudinal and lateral dynamics and emission maps (Figure 5). The engine power requirement is calculated in 1Hz for the cycle from the driving resistances and losses in the drivetrain. The engine speed is determined by the tire diameter, the final drive and the transmission ratio as well as a gearshift model. If the required engine power is above the full load curve at a given speed, a lower gear is selected first; if this is not sufficient, the acceleration in the relevant time interval is selected so that it corresponds to a full load acceleration every second until the specified speed curve is reached again.

Exhaust emissions and fuel consumption are then interpolated from engine maps. To increase the accuracy of the simulated emissions, correction functions are applied to account for different emission behaviour under transient engine loads. Furthermore, PHEM has models to take into account the efficiency of exhaust aftertreatment systems depending on the exhaust gas temperature and the flow velocity in the catalyst. The temperatures of the catalytic converters are simulated by a 0-dimensional heat balance and from the heat transfer between the exhaust gas and the catalyst material and from the exhaust line to the environment. This routine is particularly important in the simulation of SCR systems (cooling at low engine loads) and in the simulation of cold start effects. In addition, a driver model is implemented at to provide representative real-world gear shift manoeuvres.

For the calculation of abrasion particles from brakes, tires and road surfaces, the braking power, the rotational brake disc speed and the tire slip power are calculated in 1Hz resolution. Tire slip power is calculated in longitudinal and lateral direction depending on the radii of the curves and the actual velocity in a driving cycle. The associated particle flows (PM10, PM2.5 and PN23) are interpolated from characteristic maps and curves as function of the corresponding power values. For HBEFA 5.1 a generic function for average curve radii as function of the vehicle speed was developed from real drive records[8].

As the vehicle longitudinal dynamics model calculates the engine power and speed from physical relationships, every conceivable driving condition can be calculated using this approach. The simulation of different vehicle payloads in conjunction with longitudinal road gradients and variable speeds, accelerations and brake events can thus be illustrated by the model, as can the effects of different vehicle technologies, such as pure ICE, pure electric vehicles and hybrids.

Figure 5: Schematic of the PHEM model and the input data sets



The vehicle data for the simulation is based on EU registration statistics for average weight, engine power etc. and represents the weighted average according to the new registration shares for each vehicle segment. Vehicle segments represent common vehicle categories, size classes, engine types and EURO classes for exhaust emissions (e.g. passenger car gasoline EURO 6d-TEMP; delivery truck EURO VI DE, etc.). Vehicle data not available in registration statistics is based on the average values from the tested vehicles, all corrected to real world situations

[8] Please note, that the existence of curves causes ca. 2/3 of the tire wear, since wear from slip in lateral direction is more pronounced than in longitudinal direction. If you simulate tire wear for straight roads, you should reduce the tire wear PM and PN by ca. 65%.

where needed (e.g. CdxA corrected for side wind, trip shares with roof rackets, trailers etc., rolling resistance corrected for wet roads, shares of winter tires, etc.)

Each of the vehicle segments input data is completed by engine-emission maps which are gained from all collected test data of the corresponding engine type and EURO class. For non-exhaust emissions yet differentiation of the emission curves is made up to EURO 6. For EURO 7 the defined (brake wear for LDVs) and expected emission limits (tire wear for LDVs) are considered by specific emission polygons. More details are described in section 4.10.

Emission factors in [mg/km] and [PN #/km] respectively for "traffic situations" are simulated for each vehicle segment. Each traffic situation is represented by a 1 Hz vehicle speed and road altitude pro-file. Curve radii can be added optional. The emission factors for the entire fleet are then calculated by weighting the factors per segment according to their shares in the total vehicle kilometres driven in a specific traffic situation.

4.3. Vehicle models

4.3.1. L-category

The vehicle data for the L-Category is based on the HBEFA 4.2 values and was adjusted using new data from a Swiss registration database (CH-DB) provided by INFRAS, or completely recreated for entirely new categories such as MicroCars and Quads. The following changes have been made compared to HBEFA 4.2:

2-wheelers two-stroke

- Rolling resistance was reduced by 4% for Euro 5 and 8% for Euro6 compared to Euro 3.
- Mopeds (<=50cc) have been completely redesigned and derived from the 50 to 250cc displacement class, while air and rolling resistance, tyre size and gear shift model have been retained. The vehicle weight, engine power, drag coefficient, rated power and idle speed were taken from the Swiss registration database.

2-wheelers four-stroke

- For 50 to 250cc, the rated power was reduced from 11kW to 9kW based on data from the Swiss registration database.
- The displacement class >250cc was also reduced by 16kW per Euro class in terms of rated power. This was also based on data from the Swiss registration database.
- Mopeds (<=50cc) have been completely redesigned and derived from the 50 to 250cc displacement class, while air and rolling resistance, tyre size and gear shift model have been retained. The vehicle weight, engine power, drag coefficient, rated power and idle speed were taken from the Swiss registration database.

2-wheelers BEV

- In HBEFA 5.1, BEVs were generated for three size classes (<4kW, <10kW and >10kW while in HBEFA 4.1 and 4.2 only for one). The input data for the simulation with PHEM was determined using ADAC data and the Swiss registration database. The energy consumption maps for the electric motors and the battery model data have been gained from passenger car BEV model input data.

MicroCars

- The engine maps were derived from 2-wheeler four-stroke engines. The vehicle weight, engine power, drag coefficient, rated power and idle speed were taken from the Swiss registration database.

Quads

- The engine maps were derived from 2-wheeler four-stroke engines, the vehicle data was gained from internet research on typical quad configurations.

E-Bikes

- The vehicle data was elaborated via internet research, for the battery model and the electric motor low performing passenger car data was used. The main uncertainty is the average level of motor assistance at which the e-bikes are operated in real driving. Therefore, high accuracy is currently less relevant for the electric drive. We assumed on average 50% motor assistance.

4.3.2. Passenger Cars and LDV

The changes to the vehicle models of PC and LDV are described in this chapter. While PCs received several updates, the data for LDVs remains largely unchanged. The changes for LDVs are explicitly highlighted.

Vehicle mass, rated engine power and speed

The average values for diesel and petrol PCs of the Euro 6d-TEMP and Euro 6de emission standards are based on existing registration statistics. Since no detailed data is yet available for Euro 7, assumptions were made about the possible development of Euro 7 vehicles. The derivation of Euro 7 for petrol and diesel cars was achieved by extrapolating the developments between Euro 6d-TEMP and Euro 6d.

As there is no data available for the rated engine speed in the registration statistics, this was determined for conventional cars by weighting the rated engine speed of all vehicles available from the DBEFA using registration numbers.

BEV PCs were modelled in the same way based on the registration statistics. HEV and PHEV vehicles were derived from conventional vehicles, as already described in HBEFA 4.1.

Vehicle loading

The loading of the vehicles did not change. Thus, it was taken from HBEFA 4.1 assumptions.

Driving resistances and gear ratios

The data stored in the DBEFA was used as the basis for determining the driving resistances. As most of the vehicles were measured on the chassis dynamometer, the WLTC driving resistances were available for these vehicles. These were weighted together for Euro 6d-Temp and 6d using the registration numbers for the average diesel or petrol vehicle.

Euro 7 was derived from Euro 6d:

- Rolling resistance coefficient Fr0: 5 % improvement from Euro 6d
- Cross-sectional area A: Adopted from Euro 6d
- Drag coefficient Cd: 3.7 % improvement from Euro 6d

In order to derive the real driving resistances from the WLTC driving resistances, the factors developed in HBEFA 4.1 were applied.

- Cd correction:
  - Factor 1.05 for proportion of roof rack and trailer usage
  - Factor 1.03 for crosswind effects
  - Factor 1.028 for correction from 20 °C WLTP temperature to 12 °C average real temperature
- Fr0 correction:
  - 6 % rainy days with 30 % increase in rolling resistance
  - 30 % use of winter tyres with 15 % increase in rolling resistance

The derivation of these adjustments was developed and is exactly documented in Matzer et al, 2019 and Opetnik, 2019.

For the battery electric vehicles, the cross-sectional area and drag coefficient were derived from the Euro 6d petrol vehicles, due to similar size distribution. The cross-sectional area was adopted, while the drag coefficient was reduced by 10 %. This is due to the more aerodynamic design of battery electric vehicles. As battery electric vehicles are delivered from the factory with more fuel efficient tyres, a 50:50 mix of tyre labels A and B was assumed for them. The driving resistances of these tyre labels were taken from EU Regulation 1222/2009 and converted.

The changes to LDV are improvements in the rolling resistance coefficient Fr0 of 5 % compared to Euro 6d for all size classes. The only other change concerns the new BEV vehicle. In addition to improved rolling resistance, the Cd value has also been improved by 10 %.

In HBEFA 5.1, gear ratios for updated diesel and petrol vehicles were revised using data from Euro 6d-TEMP and 6d vehicles in the DBEFA with available gear ratio data. Weighted averages for petrol and diesel vehicles were then derived based on registration data. For HBEFA 5.1 both petrol and diesel vehicles from Euro 6d-TEMP onwards are equipped with a six-speed gearbox.

For battery electric vehicles, a 1-speed gearbox with a fixed ratio is used. The fixed ratio is 9.7, as already defined in HBEFA 4.1.

Auxiliary power demand and Start-Stop System

The auxiliary power demand was adopted from HBEFA 4.1 and not changed. This was calculated in HBEFA 4.1 for the annual average of air conditioning and heating used as well as other auxiliary consumers.

Since HBEFA 4.1, start-stop systems that affect the engine behaviour of the vehicle were taken into account from Euro 5 onwards. The average use of the start-stop system was adopted from HBEFA 4.1, as there was no new data available.

Additional BEV data

The electric motor efficiency map used for HBEFA 5.1 passenger cars and LDV was created in a study for the Umweltbundesamt Germany. The map was validated in that study to ensure the accuracy of the BEV model in PHEM (Helms et al., 2022) .

The battery capacity of PC BEV was derived from the registration statistics for Austria. The 5 best-selling BEVs per segment were analyzed, the battery capacities of these vehicle models were researched and the average gross capacity was derived. This results in a gross capacity of 70 kWh for the average electric car. The net capacity was defined as 63 kWh with a SOC min of 5 % to protect against too low discharge and a SOC max of 95 % to prevent overcharging. (Bundesamt für Statistik, 2024)

The battery capacities for LDVs were derived in a similar manner:

- N1-1: 52,5 kWh (0,75 x gross capacity PC)

- N1-II 70 kWh (gross capacity PC)
- N1-III 90kWh (registration data)

4.3.3. HDV

The HDV data in HBEFA 5.1 was updated to reflect recent developments in vehicle technologies. New vehicle models were developed for Euro VI DE, Euro 7 (covering both conventional and plug-in hybrid electric vehicles – PHEVs), and battery electric vehicles (BEVs) projected for the year 2030.

The primary data sources include:

- Work conducted at TU Graz for the development of the HDV CO_2 regulation (VECTO),
- Literature reviews, and
- Evaluation of European Environment Agency (EEA) monitoring data, including projected trends for the coming years.

The EEA monitoring data provides EU-wide information on CO_2 emissions, fuel consumption, and vehicle characteristics to track progress toward climate and efficiency targets. Currently, this data covers certain trucks over 3.5 tons (e.g., tractors and rigid trucks), but does not yet include information on buses and coaches.

Specifically, the data was evaluated for:

- 4x2 rigid trucks with a TPMLM (Technically Permissible Maximum Laden Mass) of 10 – 12 tons, 12 – 16 tons, and > 16 tons,
- 6x2 rigid trucks with a TPMLM of 26 tons
- 4x2 tractor trailer combinations with a TPMLM of 40 tons

In the future, additional data will be available that can be used to calibrate the models.

Vehicle categories from Euro 0 to Euro VI ABC remain largely unchanged from HBEFA 4.2, with the only exception being the rolling resistance values of the tyres. These values, derived for current Euro VI DE models, were retained, as older vehicles are also expected to be fitted with typical modern tyres.

4.3.3.1. Conventional vehicle models for Euro VI DE and Euro 7

Improvements in vehicle technologies directly influence possible CO_2 reductions. Therefore, the steering effect of the HDV CO_2 standards, and the corresponding binding reduction trajectory up to the 2030 targets, lead to an increase in reduction rates from Euro VI DE onwards.

Vehicle mass

A 2% reduction in vehicle mass was applied for Euro VI DE models compared to Euro VI ABC. This results in approximately the same absolute mass as obtained by extrapolating the available monitoring data (2019–2021). The same trend of mass reduction was continued in the transition from Euro VI DE to Euro 7.

Aerodynamic resistance (CdA)

The monitoring data from 2019 to 2021 shows a slight annual increase in CdA values (+0.2% to +1.6%). However, recent and upcoming vehicle models indicate significant aerodynamic updates. Therefore, a 10% CdA reduction was applied to Euro VI DE models compared to the 2020 monitoring values.

For vehicle categories not explicitly included in the monitoring data but covered in HBEFA 5.1, CdA values were derived based on expert judgment available at TUG. For buses and coaches, CdA values from Euro VI ABC were retained.

For Euro 7, further CdA improvements were extrapolated, including assumed aerodynamic improvements on trailers (where applicable), accounting for the steering effect of trailers being included in the CO_2 standards.

ICE fuel consumption map

The ICE fuel consumption map for Euro VI DE was derived from that of Euro VI AB, assuming an annual efficiency improvement of 0.4 percentage points, based on expert judgment from TU Graz. The same rate of efficiency gain was continued to generate the Euro 7 ICE map.

Rolling resistance coefficient (RRC)

Analysis of EEA monitoring data revealed:

- A 2% annual RRC reduction for vehicle categories with existing CO_2 reduction targets[9]
- A 0.5% annual reduction for other categories

Based on these trends, RRC values for 2024 (Euro VI DE) were derived and correlated with the dynamic tyre radius to compute values across all vehicle categories. As already mentioned, these RRC values were also applied retroactively to older Euro classes (down to Euro 0).

For Euro 7, RRC values were extrapolated from Euro VI DE, assuming a continued annual improvement of 2%.

[9] From 2019 to 2024, CO_2 standards apply to 4x2 and 6x2 vehicles with a TPMLM > 16 tons. From 2030 onwards, CO_2 standards will apply to all vehicles (except vocational vehicles).

Auxiliary power demand

Auxiliary power demand for Euro VI DE is based on reference simulations in VECTO for specific vehicle categories, using typical assumptions for 2024 auxiliary technologies. Rigid trucks/tractors and urban buses/coaches were treated separately due to their differing auxiliary systems and loads.

For Rigid trucks/tractors, a correlation was established between rated ICE power and auxiliary power demand, enabling estimation across all vehicle categories.

For Euro 7, a generic 20% reduction in auxiliary power demand (compared to Euro VI DE) was assumed. This estimate is based on work carried out at TU Graz, which assessed the CO_2 reduction potential of various technologies and vehicle characteristics, including auxiliaries.

4.3.3.2. PHEV models for Euro VI DE / Euro 7 and 2030 BEV models

Vehicle mass

The mass of PHEV models is based on the corresponding conventional vehicle models (Euro VI DE and Euro 7), with added weight for the electric components, including:

- Electric machines
- Installed battery
- Generic mass for the inverter and electronics

For Euro VI DE, the specific mass values (e.g. kg per kW for electric machines and kg per kWh for batteries) were derived from development work on VECTO. For Euro 7 PHEVs and 2030 BEVs, a lower specific battery weight was assumed, reflecting anticipated improvements in battery technology (Fraunhofer, 2023-1), (Fraunhofer, 2023-2).

For BEVs, the mass calculation also subtracts the removed components: ICE, and fuel, using typical specific weights for each.

Aerodynamic resistance (CdA)

CdA values for PHEVs are identical to their respective Euro VI DE and Euro 7 conventional counterparts. For 2030 BEV models, further CdA reductions were applied compared to Euro 7 models to improve energy efficiency and extend electric driving range. These reductions reflect

- Aerodynamic improvements already observable in current-generation BEVs (trucks and buses), and
- the increased use of more aerodynamic trailers, where applicable

ICE map and specifications

The ICE map and technical specifications (displacement, rated power, etc.) for PHEVs are carried over unchanged from the corresponding conventional vehicle models.

Rolling resistance coefficient (RRC)

RRC values for PHEVs are also unchanged from the conventional models.

For BEVs, similar to the aerodynamic adjustments, it is assumed that vehicles will use low rolling resistance tyres to extend electric range. The resulting RRCs for 2030 BEVs align with the lowest values of tyres available today.

Auxiliary power demand

For PHEVs, auxiliary power demands are unchanged from the conventional vehicle models.

For BEVs, the auxiliary loads were derived using VECTO reference simulations for the assumed typical electric vehicle technologies, leading to lower average loads.

Electric machine (EM)

The electric power consumption map for the EMs corresponds to the normalized map used for passenger cars.

For PHEVs, the EM is modelled with the same rated power as the ICE.

For BEVs, the EM uses the same rated power, but includes a short-term peak power capability of 1.5 times the rated value.

Energy storage system (battery)

Regarding the modelling of the battery for Euro VI DE PHEVs, the following considerations/assumptions have been taken into account:

- The nominal battery capacity was calculated based on a predefined electric driving range, reference values for energy consumption per kilometre, and an assumed usable SOC range. A generic electric range of 30 km was applied across all vehicle categories, reflecting the typical ranges of commercially available vehicles. The reference energy consumption per km was derived from HBEFA 4.2 results for Euro VI D vehicles under representative driving and loading conditions. The usable SOC range was set at a generic value of 80%.
- The battery's rated voltage was set at 600 V, which corresponds to the mean value of the voltage range of systems that are currently available (400–800 V).
- The internal resistance was modelled based on data available from VECTO xEV developments.

Battery modelling for Euro 7 PHEVs follows the same principles outlined above, but with a generic electric driving range of 80 km and a 10% lower reference energy consumption per kilometre compared to Euro VI DE PHEVs.

The modelling for BEVs follows the same general principles but accounts for category-specific electric driving ranges. Additionally, a further 5% reduction in reference energy consumption per kilometre is applied compared to Euro 7 PHEVs, reflecting continued reductions in driving resistances.

Gearbox and gear ratios for BEVs

A 3-speed automatic transmission was modelled for all vehicle categories. The corresponding axle ratios were defined using available data at TU Graz and/or literature sources. The gearbox ratios were then calculated to meet key performance requirements — for example:

- Ensuring sufficient torque for reliable vehicle drive-off
- Enabling the highest gear to achieve a good trade-off at important speeds (e.g. cruising at 88 km/h for long-haul trucks) with respect to efficiency, power reserve and effective electric braking over extended periods

4.3.3.3. Vehicle models exceeding 60 tons GVW

The single HBEFA 4.2 truck vehicle model for gross vehicle weights above 60 tons was divided into three distinct categories: >60–64 t, >64–74 t, and >74–90 t in HBEFA 5.1. These models were elaborated for Euro VI ABC, using data from the previously aggregated >60 t category, along with literature research to define typical specifications such as vehicle mass, ICE displacement, and rated power.

Each vehicle model assumes a 6x4 axle configuration for the tractor, while the number of trailer axles varies depending on the weight category—five axles for the 60–64 t class and up to seven axles for the 74–90 t configuration. The axle ratios were selected to ensure that, even in a fully loaded state, the vehicle could reliably drive off on a 6% incline, delivering accelerations comparable to that of the 40-ton configuration.

Vehicle categories for earlier Euro standards (Euro 0 to Euro V) were derived using established HBEFA methodologies, such as the application of scaling factors for parameters like vehicle mass and CdA.

Finally, new models for Euro VI DE, Euro 7, and BEVs were developed following the same approach, as outlined in the sections above.

4.4. Hot exhaust emission factors

The following section describes the work done for the elaboration of the emission factors. This includes an overview about the available data and used methods for L-category vehicles, PC and LDVs, and HDVs.

4.4.1. L-Category

4.4.1.1. Measurement data base

As part of the LENS project (L-vehicles Emissions and Noise mitigation Solutions), several labs (TUG, EMISIA, IFPEN, CZU, IDIADA) in Europe measured more than 150 vehicles in the L category from Euro 3 to Euro 5 in various engine capacity classes. In addition, the FH Biel is testing regularly motorcycles as input for HBEFA on behalf of BAFU. This extensive test campaign provides data on real world and type approval emission levels. Real world emissions were tested on the road and on the chassis dyno in real world cycles. These measurements have been used to update the emission factors for all L-category segments in HBEFA.

At the starting time of the work for the HBEFA update not all tests were finished. Thus, the data set for HBEFA 5.1 covers only 107 vehicles. Table 2 illustrates the data available for HBEFA 5.1. The segments not covered by test data are not listed.

Table 2: Overview on test data of L-category vehicles

MC class	MC ccm	Emission class	Chassis dyno	RDE	Not used(1)
MC 2 Stroke	<=50ccm	EURO3	1	1	2
		EURO4	0	0	1
		EURO5	0	0	-
	>50 - <=250ccm	EURO5	1	0	-
MC 4 Stroke	<=50ccm	EURO3	0	0	1
		EURO4	0	0	1
		EURO5	2	1	0
	>50 - <=250ccm	EURO3	4	1	4
		EURO4	6	1	3
		EURO5	8	7	7
	>250ccm	EURO3	11	1	3
		EURO4	13	5	4
		EURO5	27	12	16
Quad	>250ccm	Stage V[10]	2	2	-
MicroCar (Diesel)	>250ccm	Euro5	1	0	-

(1): Data not useful because of missing mandatory signals for the HBEFA routines (in most cases engine speed) or vehicle category not defined in HBEFA (Off-Road MC, 3-wheeler))

[10] Stage V represents a Non-Road Mobile Machinery classification.

4.4.1.2. Base emission factors

The emission maps were generated with PHEM based on the available test data.

Looking at motorbikes first, the Euro classes Euro 0 – Euro 2) were not covered by new test data. The emission models for these Euro categories were taken from HBEFA 4.1 without updates.

For the other L-category vehicles, MicroCars and Quads, which are introduced for the first time in this version of HBEFA, emission maps of the motorbike classes or derivatives were used for the Euro classes not covered by test data.

- For quads 50 to 250cc the emission maps of the motorbike 4-stroke engines of the same engine size category were used.
- For quads >250cc, the Euro 5 emission map of the quads >250cc was used for all Euro classes. The simulation quality if taking emission maps from other categories with similar technologies like motorbikes or cars was tested based on the available Euro 5 test data, but the results were not sufficient. Consequently, taking the Euro 5 data also for earlier Euro standards is the best solution.
- For diesel MicroCars, the emission map created for the >250cc size class is used for all size classes (<50cc, 50 to 250cc and >250cc) and Euro classes.
- For petrol MicroCars (<50cc, 50 to 250cc and >250cc), the emission maps of the corresponding motorbike size and Euro classes are used due to the general lack of measurements for this segment.

4.4.1.3. Validation of emission factors

The base emission factors for PM and PN are validated with remote sensing measurements in the LENS project, this exercise is still ongoing. For model validation, we simulated the WMTC[11] and compared the results with all measurements carried out in this test cycle[12] separated according to Euro classes and size categories and calibrated the emission maps if needed.

4.4.1.4. L-Categories exhaust emission results

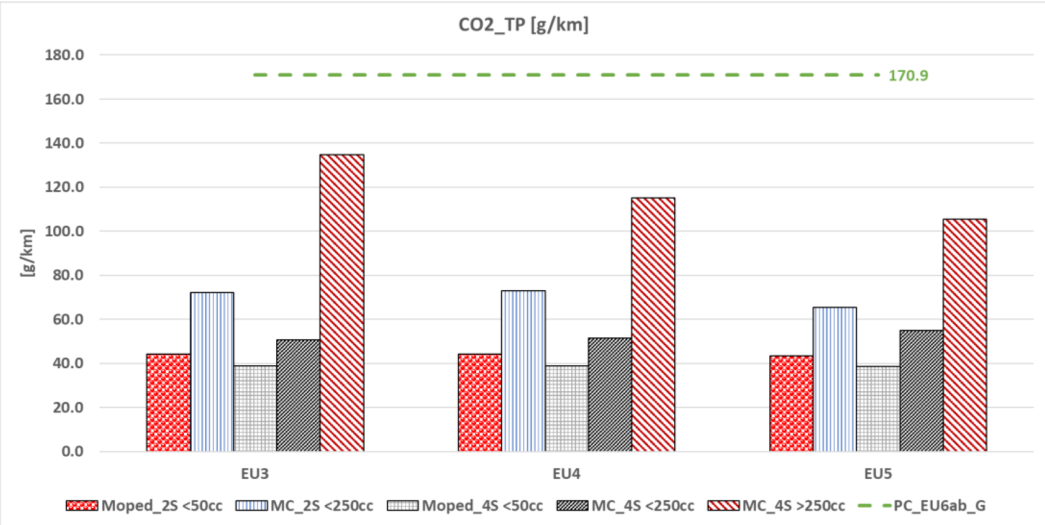
Only those Euro classes for which updates have been made compared to HBEFA 4.1 and for which a sufficiently high number of tested vehicles was available are illustrated below. These are the two-wheelers from Euro 3 to Euro 5. For the comparison, all HBEFA cycles are simulated and weighted according to the German traffic situation mix.

CO2 emissions increase from smaller engine displacements to larger ones inside each Euro class (Figure 6). Due to the less efficient design, CO2 emissions from two-stroke engines

[11] The World Motorcycle Test Cycle (WMTC) is the regulatory test cycle for motorcycles on the chassis dyno.
[12] The data set for the comparison includes also the test data not used to create the maps.

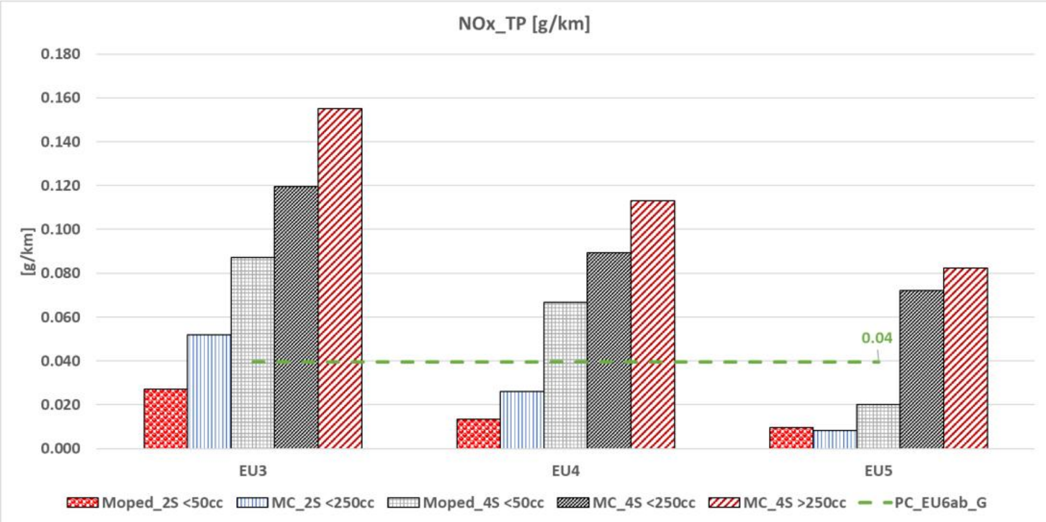
(marked with “2S”) are always higher than from four-stroke engines (marked with “4S”). Across the Euro classes, CO_2 emissions from motorcycles have decreased over time, while those from mopeds have remained on the same level. Compared to a EURO 6ab passenger car, the CO_2 emissions per km from a Euro 5 motorcycle are around 1.5 to 2.8 times lower.

Figure 6: HBEFA 5.1 CO2 emissions of motorcycles in the German traffic situation mix



NOx emissions increase from small displacement engines to larger ones within each Euro class (Figure 7), and two-stroke NOx emissions are lower than four-stroke emissions. This effect is based on two measurements on a two-stroke Euro 5 vehicle and one Euro 3 vehicle. In measurements carried out on older vehicles than Euro 3, the two-stroke engines <50cc had NOx emissions similar to four-stroke engines. Compared to a Euro 6ab petrol car, Euro 5 four-stroke motorcycles cause NOx emissions per km that are ca. 2 times higher.

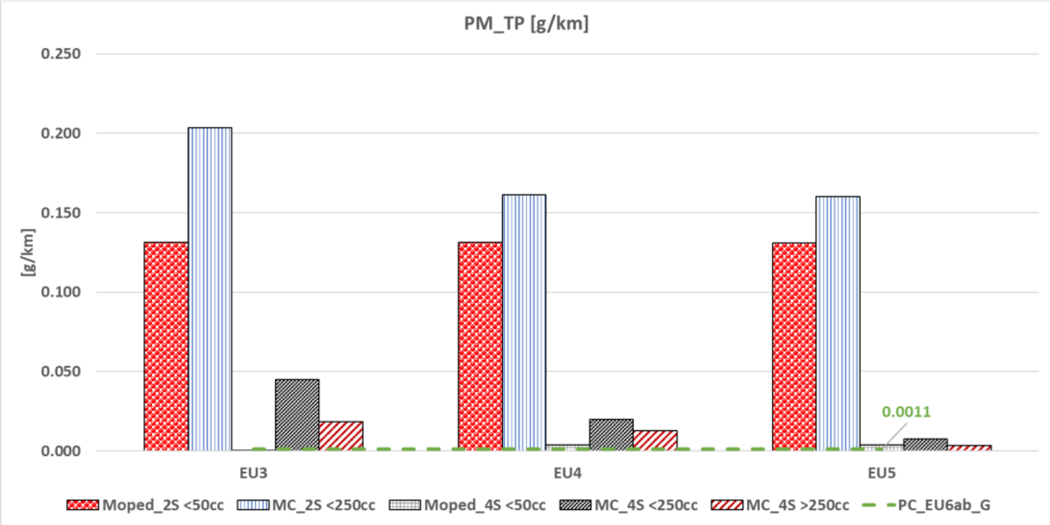
Figure 7: HBEFA 5.1 NOx emissions of motorcycles in the German traffic situation mix



The Euro 5+ standard is a tightening of the Euro 5 emissions standard for motorcycles, which has been mandatory for all new registrations since 1 January 2025 and has stricter requirements for the durability of catalytic converters and more detailed on-board diagnostic systems (OBD 2 Plus). Catalytic converters shall then last at least for 35,000 km. There is no tightening of the limit value for particulate matter, which remains at 4.5 mg/km as in Euro 5. Before Euro 5, there was no limit value for PM emissions for motorcycles. The measurement data used for HBEFA 5.1 does not include Euro 5+ vehicles and thus it is not included in the emission models.

Two-stroke engines emit significantly higher particle masses than four-stroke engines mainly because of unburned heavy hydrocarbons and oil mist when burning the fuel-oil mixture. In four-stroke engines with separate oil lubrication only a small amount of oil enters the combustion chamber, resulting in lower particle mass emissions. However, the three measurements (2x RDC & 1x WMTC) carried out on the two-stroke motorcycles showed that than none of the vehicles complied with the required limit value for Euro 5 (4.5 mg/km). This may be due to deterioration effects or malfunctions of the in-use vehicles selected for the tests in LENS. The four-stroke motorcycles met the limits in the <50cc and >250cc categories, while the 50 to 250ccm category exceeded it more frequently in the LENS measurements (RDE and test bench). This trend can then also be seen in the simulations and consequently in the HBEFA results. Compared to a petrol EURO 6 passenger car, the PM emissions of motorcycles are significantly (ca. 3 to 6 times) higher.

Figure 8: HBEFA 5.1 PM emissions of motorcycles in the German traffic situation mix



4.4.2. Passenger Cars and LDV

In this HBEFA update, the Euro classes Euro 6d-TEMP to Euro 7 were updated for PC and LDV.

Euro 6d-TEMP and Euro 6d were modelled on the basis of approximately 90 measured vehicles. Euro 7 was derived from Euro 6d by estimating the reductions required in order to comply with the limit values, taking into account ageing, cold start behaviour and a safety margin. The Euro 7 model derivation is separately described in chapter 4.6.

Earlier Euro classes (up to Euro 6c) are not updated compared to HBEFA 4.2. One exception is Particle number (PN23) for Diesel vehicles with DPF. The effect of DPF regeneration was considered using a new approach that differs from HBEFA 4.2.

4.4.2.1. Measurement data base

Several labs (TUG, EMPA, TUD, BFH-Biel) in Europe measured more than 90 vehicles in the PC and LDV category from Euro classes 6d-TEMP and 6d. These measurements provide data on real world and type approval emission levels. Real world emissions were tested on the road and on the chassis dyno in real world cycles. These measurements are used to update the emission factors for all PC and LDV categories.

The following table shows what was used to produce the emission factors. PC are designated as M1 here, while N1 covers LDV. N1 is further subdivided according to gross vehicle weight into N1-I, N1-II and N1-III, which correspond to small, medium and large vans respectively.

Table 3: Overview on test data of M1 and N1 vehicles

	Chassis dyno # of vehicles	RDE # of vehicles	Total # of vehicles	Not used for base map *
M1 D Euro 6d-TEMP	16	12	17	6
M1 D Euro 6d	11	11	12	3
M1 G Euro 6d-TEMP	18	13	20	6
M1 G Euro 6d	22	18	23	3
N1-I D Euro 6d-TEMP	3	3	3	-
N1-II D Euro 6d-TEMP	1	1	1	-
N1-III D Euro 6d-TEMP	7	8	8	-
N1-I D Euro 6d	-	-	-	-
N1-II D Euro 6d	2	2	2	-
N1-III D Euro 6d	2	3	3	-
N1-I G Euro 6d-TEMP	-	-	-	-
N1-II G Euro 6d-TEMP	-	-	-	-
N1-III G Euro 6d-TEMP	-	-	-	-
N1-I G Euro 6d	1	1	1	-
N1-II G Euro 6d	-	-	-	-
N1-III G Euro 6d	-	-	-	-

(*): mostly vehicles with high mileage, so not suitable for EFA map creation. This data is used for deterioration functions only.

4.4.2.2. Map creation

The methods used to create the emission maps have been adopted unchanged from HBEFA 4.2.

Generic CO2 maps from the previous HBEFA version were already available for Euro 6d-Temp and Euro 6d. For each vehicle that was measured on the chassis dynamometer with sufficient dynamic cycles (RWC, Ermes) and for which the chassis dynamometer settings are known, the HBEFA 4.2 CO2 map was calibrated using PHEM.

The creation of individual pollutant emission maps for each vehicle was based on the CO_2 interpolation method. The same criteria for selecting measurements were applied here as in HBEFA 4.1. (no DPF regeneration, temperature window, driving styles, etc.)

These maps were then weighted into an average map based on the registration statistics for the respective make and model. This means that models with higher shares of the respective fleet of technology and emission standard have a greater influence on the average map. If more than one vehicle of a model was measured, the corresponding registration numbers were divided.

The following corrections were made to the resulting maps:

- For each component, map points with negative emissions were set to the value 0
- Correction of NO and NO2 as proportions of NOx, to match the NOx sum
- Correction of HC components so that neither the sum nor individual components are higher than HC

4.4.2.3. Ki-factors

The correction factors used to account for DPF regeneration, also referred to as K_i factors, have been updated for Passenger Cars and LDVs. These are applied to the PHEM emission maps that do not include regeneration events. These K_i factors have been implemented in earlier HBEFA versions but have now been updated, as more data is available. The method for determining the Ki factors is unchanged: Measurements are used in which active DPF regeneration has taken place and been completed. For each measurement, a paired measurement is required that was carried out under the same conditions and in which no DPF regeneration took place. In the case of RDE measurements, this means a measurement with the same route and driving style. In the case of chassis dynamometer tests, this means a measurement of the same driving cycle.

The following database from Euro 6ab to Euro 6d was available for determining the Ki factors for CO2, CO, NOx, HC and PN:

- 13 pairs of measurements in the DBEFA, of which:
  - 6 pairs of measurements with DPF regeneration during measurements on the chassis dynamometer
  - 7 pairs of measurements with DPF regeneration during RDE measurements
- 4 measurement pairs that were measured by LAT in RDE with active DPF regeneration (published in (Dimaratos et al., 2022))
- 5 measurement pairs measured by TNO in RDE with active DPF regeneration (published (de Ruiter et al., 2020)).

While the K_i factors in HBEFA 4.1 were multiplicative for all affected components, the factors were changed to additive for CO, HC and PN. During regeneration, a fixed number of additional particles and carbon, and also unburned hydrocarbons can be released, regardless of the emission level during regular driving. An additive factor is therefore more realistic: a constant amount is added to the base emissions to take account of the regeneration components.

By increasing NOx and HC, the associated components (NO and NO2 or HC components) are also increased proportionally.

The following table shows the Ki factors from HBEFA 4.1 and the newly determined ones for HBEFA 5.1. Here you can see that the new version for CO, HC and PN23 has changed from a multiplicative effect to an additive effect. The multiplicative factors for CO2 and NOx are in a similar ratio.

It is noticeable here that the multiplicative factor for NOx has increased. The reason for this is that NOx emissions at operating temperature without DPF regeneration have fallen, while those related to regeneration have remained the same, leading to an increase in the factor.

Table 4: Correction factors for regenerating particulate filters (Ki-factors)

Version	CO2	NOx	CO	HC	PN23
[-]	[-]	[-]	[g/h]	[g/h]	[#/h]
HBEFA 5.1	1.012	1.085	0.621	0.025	3.49E+12

These factors were applied to hot emission maps—multiplicatively for NOx and CO2, and additively for CO, HC, and PN.

4.4.2.4. Hot emission factors

The emission maps were generated with PHEM based on all available test data. For vehicle categories, that were not covered by measured vehicles, the emission maps were taken from similar categories in terms of technology and consequently emission behaviour:

- N1-I diesel Euro 6d-TEMP and 6d: emission maps from M1 diesel were used.
- N1-I, II, III petrol Euro 6d-TEMP and 6d: no vehicles have been measured; thus the M1 petrol emission maps were used.
- Emission factors were cross-checked for NOx emissions with the respective class averages from remote sensing campaigns in different countries.

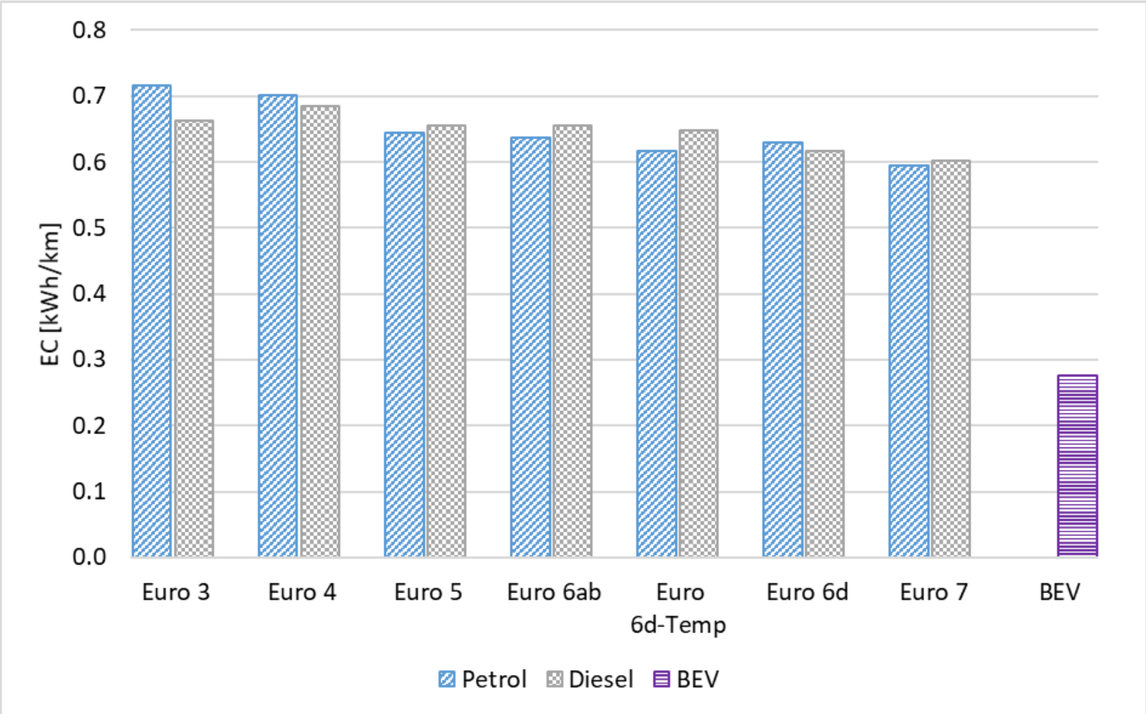
The emission factors for passenger car energy consumption, NOx and PN23 are shown below as examples. These emission factors represent the average emission behaviour at 20°C and a mileage of 50,000 km. The following graphs include petrol and diesel vehicles from Euro 3 to

Euro 7 and BEV cars. Although all emission components have been updated starting with Euro 6d-TEMP, the Ki factors apply to all Euro classes with a DPF (from Euro 4 onward).

Figure 9 shows the energy consumption (EC in kWh/km) of passenger cars with diesel and gasoline engines by emission standard (Euro 3 to Euro 7), as well as battery electric vehicles. Since BEVs do not consume fuel, the fuel consumption of ICE vehicles used for comparison here.

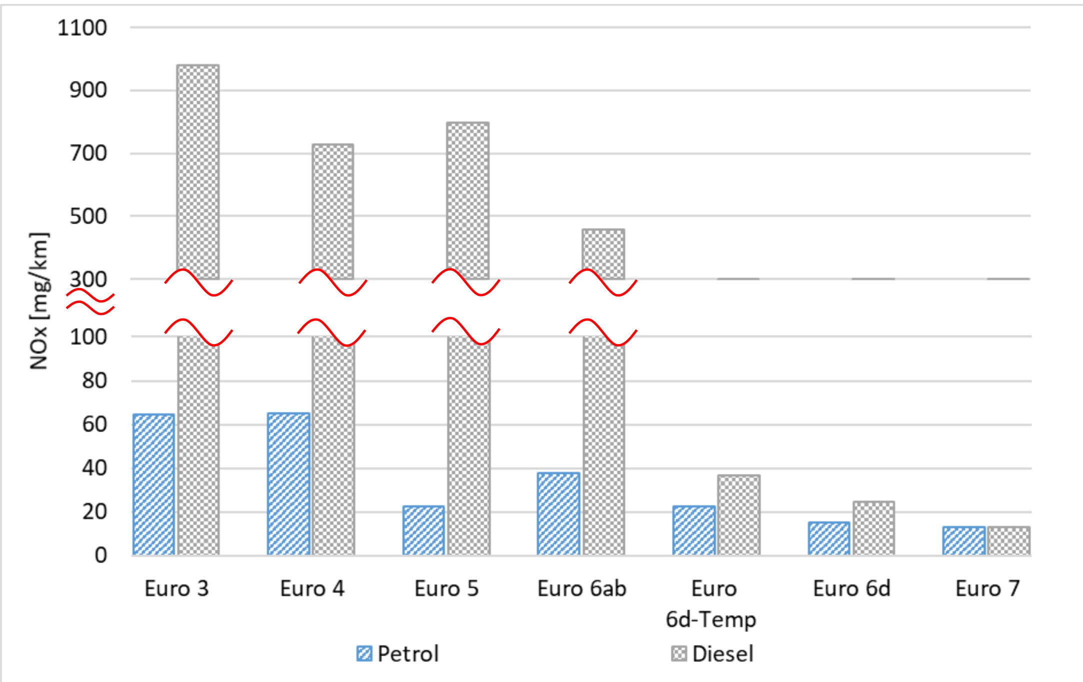
For gasoline and diesel vehicles, energy consumption remains largely constant across the Euro standards, with slight improvements between Euro 3 and Euro 6d (12 % for petrol and 7 % for diesel). However, no significant reduction is observed, efficiency gains from technical improvements appear to be offset by stricter exhaust aftertreatment systems and increasing vehicle mass. BEV (on the right) exhibit a much lower energy consumption per kilometre (below 0.3 kWh/km), being 56% lower than Euro 6d petrol vehicles.

Figure 9: Average energy consumption of passenger cars in Germany by emission standard (Euro 3–7) and Powertrain Type (petrol, diesel, electric)



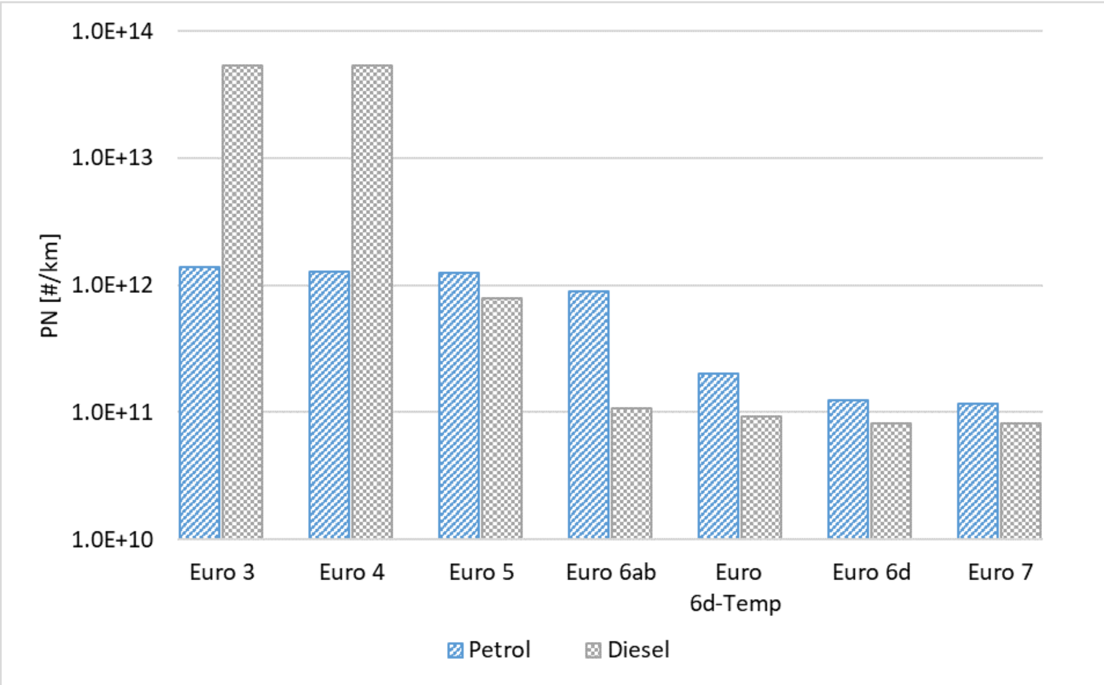
The results show the progress made in reducing NOx emissions from passenger cars, particularly from Euro 6d-TEMP onward. Historically, diesel cars emitted in real-world driving far higher NOx levels than petrol cars, with values near 1000 mg/km at Euro 3 compared to less than 100 mg/km for petrol. By Euro 6d-TEMP, diesel NOx emissions under hot conditions are reduced to around 40 mg/km due to the introduction of RDE tests, while petrol cars already emit less than 30 mg/km. Euro 6d shows a reduction for both petrol and diesel vehicles, diesel reaching below 30mg/km and petrol below 20 mg/km. In Euro 7, both technologies are expected to converge at even lower levels, typically below 20 mg/km. These results highlight how recent standards have successfully closed the historical gap between diesel and petrol, bringing both to very low NOx values under hot operation.

Figure 10: Average NOx emissions of petrol and diesel passenger cars in Germany by emission standard (Euro 3–7)



Petrol vehicles show a significant drop from Euro 6ab to Euro 6d-TEMP with the broad introduction of gasoline particle filters (GPF) since the introduction of particle number limits for petrol vehicles. This reduction continues with Euro 6d and Euro 7 (a reduction of one order of magnitude since Euro 6ab), which proves the effectiveness of GPFs. Diesel vehicles display a similar pattern, with a strong drop from Euro 4 to Euro 5 (almost two orders of magnitude with introduction of DPF), as particle number limits were introduced for diesel vehicles. Another strong drop occurred from Euro 5 to Euro 6ab, with Euro 6d-TEMP and Euro 6d achieving hot emissions below 10^{11} #/km, highlighting the success of particle filters and enhanced engine controls in curbing combustion-related particle emissions.

Figure 11: Average PN23 emissions of petrol and diesel passenger cars in Germany by emission standard (Euro 3–7)



4.4.3. HDV

The introduction of the new emission standard Euro VI E and the publication of the Euro 7 limits set a demand for an update of the HDV base emission factors. The Euro VI DE emission model was elaborated based on real world test data illustrated in the following section. The Euro 7 model was derived from the Euro VI model by estimating the reductions required in order to comply with the limit values, taking into account ageing, cold start behaviour and a safety margin, see chapter 4.6.2.

The base emission models for the Euro classes Euro VI ABC and earlier are not updated. However, the additional data since HBEFA 4.2 for Euro VI ABC was used for the cold start and deterioration model.

4.4.3.1. Measurement data base

TU Graz and AVL MTC conducted the tests on HDV. Both labs did tests on the chassis dyno and in real world driving.

The main test cycles on the chassis dyno are the WHVC, which mimics the WHTC[13] load profile on the chassis dyno, and a low load test, which shows the emission behaviour in rush hour driving. The main on-road tests are ISC tests. These tests give a comprehensive picture about real-world driving behaviour in urban, rural and motorway driving conditions. This leads to a broad coverage of possible driving situations including cold start.

FTIR measurements in combination with particle measurement systems enable the coverage of all regulated and in addition all relevant non-regulated emission components.

The data set covers all HDV categories: rigid trucks, long haul trucks, coaches and urban buses. The data set is focused on diesel driven vehicles because of their high share in the vehicle mileage. The following table gives an overview on the entire HDV test vehicles for this HBEFA version.

Table 5: Overview on number of heavy-duty test vehicles

Vehicle category	Total	Chassis dyno	RDE	Additional comments
HDV Euro VI ABC*	30	26	28	• Rigid truck: 17 • Long haul truck: 10 • Coach: 1 • City bus: 2
HDV Euro VI D	37	32	35	• Rigid truck: 17 • Long haul truck: 18 • Coach: 0 • City bus: 2
HDV Euro VI E	20	17	20	• Rigid truck: 8 • Long haul truck: 10 • Coach: 1 • City bus: 1

* no update of hot emission factors Euro VI ABC, data only used for cold start model and deterioration

In addition, remote sensing test data and data from sniffing car tests was used for the elaboration of deterioration functions and high-emitter shares, notably for NO_X emissions.

4.4.3.2. Emission factor modelling

The following section describes the most important points regarding the methodology for HDV emission factors in HBEFA 5.1:

[13] The WHTC is the type approval test cycle on the engine test bed for HDVs and contains urban, rural and motorway driving parts.

- The Euro VI E test data illustrates only a slight decrease of the emission level compared to Euro VI D. This led to the decision that the separate Euro VI D and Euro VI E emission models are combined to one Euro VI DE model. The Euro VI DE model in HBEFA 4.2 was only based on Euro VI D data and is consequently updated.
- In order to simulate the NOx emission performance of the HBEFA 5.1 Euro VI DE test data in all driving situations with high quality, the physical exhaust after-treatment model in the simulation tool PHEM was modified in terms of catalyst heating strategies, AdBlue dosing and ammonia storage performance according to recent test data.
- As already described in chapter 3.1, the preconditioning cycles were updated compared to HBEFA 4.2. This can lead to different starting conditions for the same HBEFA cycles in version 5.1 than in version 4.2 and consequently to different performance of the exhaust after-treatment system especially at the start of the test. This impacts the NOx emission factors in addition to the already described model updates.
- The data set is mainly based on HGV tests and contains a lower number of coaches and urban buses. However, the similar emission performance of the different vehicle categories allows the pooling of all data for setting up one comprehensive HDV emission model. This model was successfully validated for all different HDV categories based on the real-world test data. Thus, all HDV categories use the same emission model.
- HBEFA 5.1 provides emission factors for all HGV, coach and urban bus size classes also for alternative propulsion systems. In HBEFA 4.2 emission factors were calculated for all 22 HDV size categories only for diesel driven vehicles. For all other propulsion systems only a limited number of HDV size classes have been simulated. HBEFA 5.1 provides emission factors for all propulsion systems for all HDV size categories.

4.4.3.3. Emission factor results

This chapter contains exemplary HBEFA 5.1 hot emission factor results for a tractor trailer combination and a 3-axle urban bus in the most relevant traffic situations, average motorway driving for the tractor trailer combination and average urban driving for the urban bus. Both driving situations represent the specific average German traffic situations. The tractor trailer combination is represented by the HBEFA category TT/AT 34-40t. The urban bus is a CB >18t half loaded. Both vehicles are loaded according to the average of the German fleet data. The results represent results at a mileage of 50 000 km without deterioration effects.

The following graphs illustrate the updated Euro VI DE and new elaborated Euro 7 emission factor results. In addition, the results for Euro VI ABC and Euro V are shown, because these vehicles have still a noticeable fleet share.

The real-world energy consumption of both vehicle categories, tractor trailer combination and urban buses, are continuously reduced due to the introduction of new vehicle technologies. The reduction rates have especially increased in the recent years because of the steering effect of the HDV CO2 regulation. The reduction rates from Euro VI DE to Euro 7 are up to 8 % for tractor trailer combinations and even 10 % for urban buses. These reduction rates are similar looking at CO2 emissions.

Battery electric vehicles based on technology expected in 2030 decrease the energy consumption by additional 62 % respectively 54 %. This can be explained by the higher efficiency of electric powertrains and the possibility of recuperative braking.

Figure 12: energy consumption factors, tractor trailer combination in German average motorway driving and 3-axle urban bus (or "city bus", CB) in German average urban driving

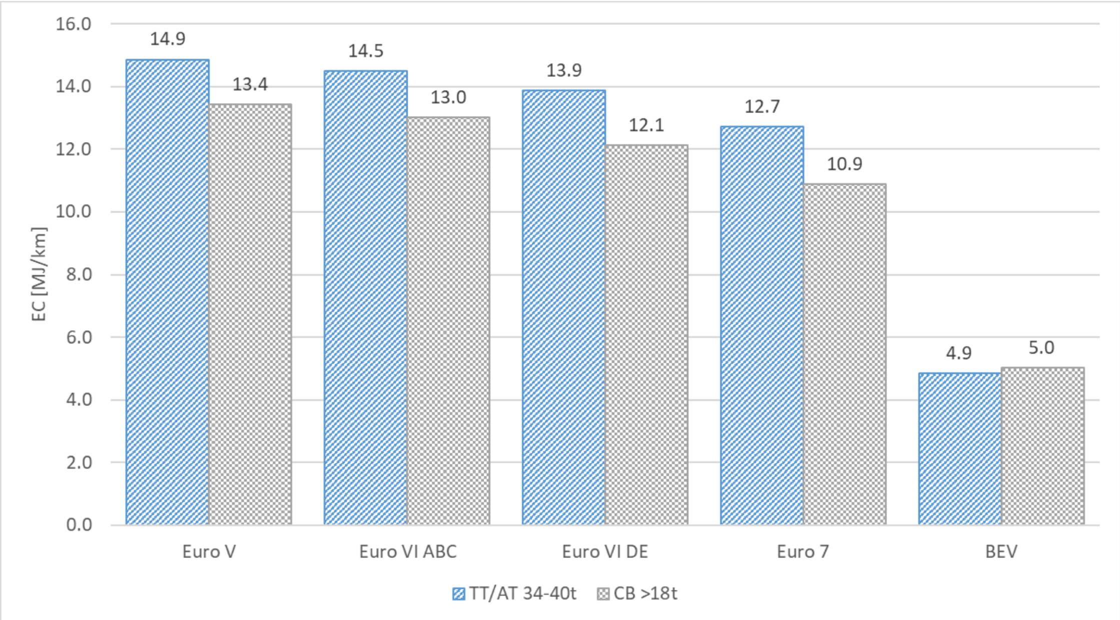
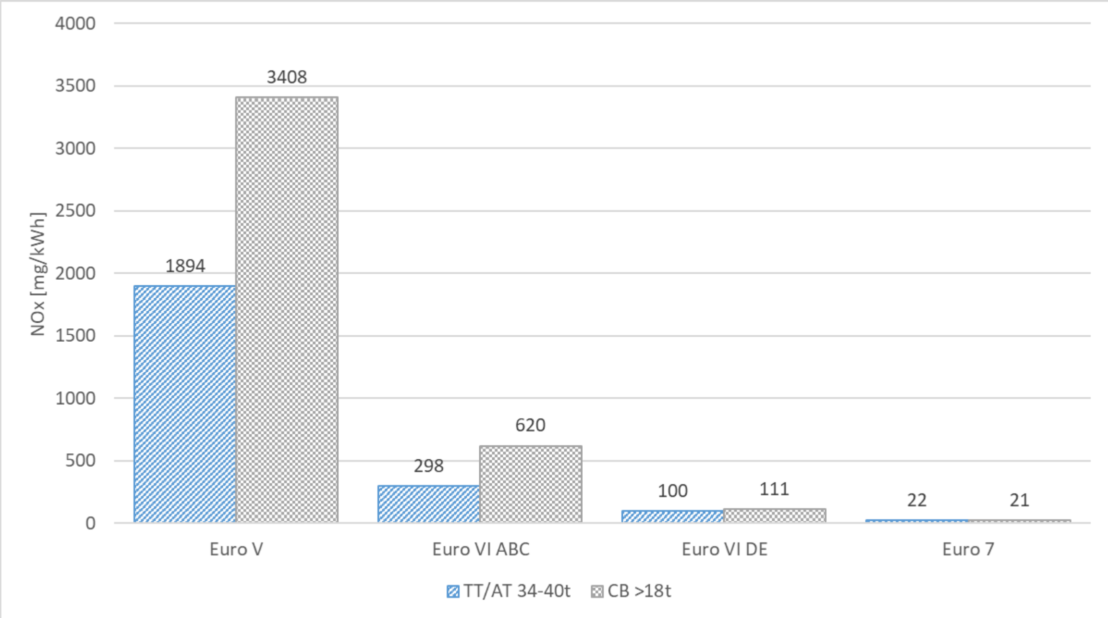


Figure 13 illustrates the real-world NOx emission factors in g/kWh[14]. The results show a significant trend of decreasing emissions with newer engine and emission reduction technologies. Each main step in the regulation[15] leads to an NOx emission reduction of 66 to 84 % for tractor combinations and about 80 % for urban buses.

[14] g/kWh for gaseous emissions respectively #/kWh for particle emissions are the units used in the Euro regulations. These units enable the comparison of the emissions of different vehicle categories and size classes due to the relation to the engine work instead of the distance.

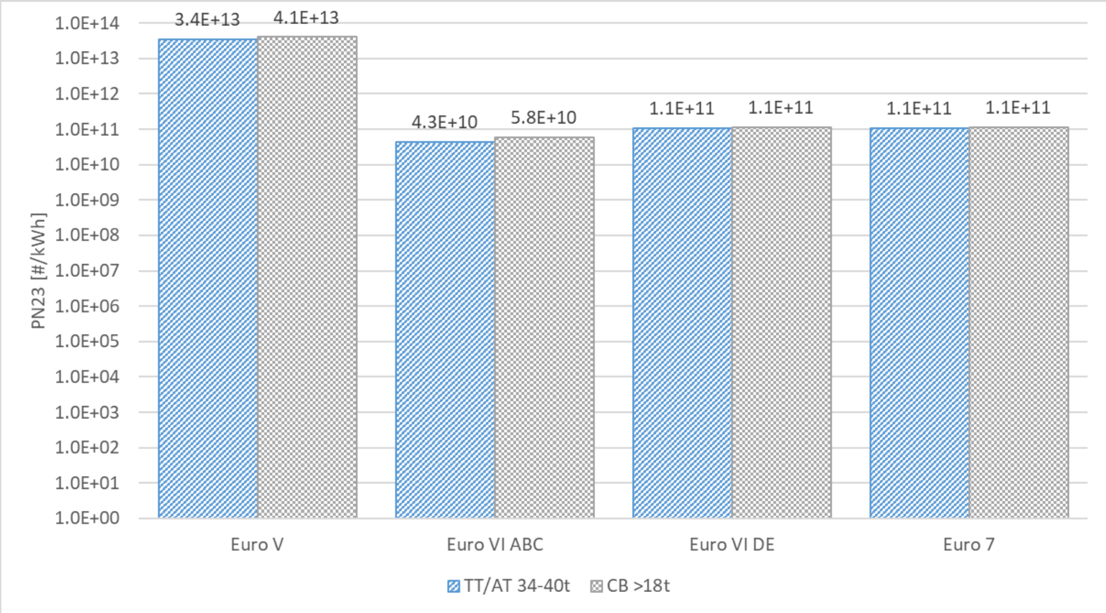
[15] The steps from Euro VI A to B, b to C and further on from D to E have only low impact on the emission behaviour of HDVs, but the decrease of the power threshold for valid moving average windows in the evaluation of real-world tests from Euro VI C to D leads to a noticeable increase emission performance. Thus, Euro VI is split in Euro VI ABC and DE.

Figure 13: NOx emission factors, tractor trailer combination in German average motorway driving and 3-axle urban bus (or “city bus”, CB) in German average urban driving



The PN23 emissions are illustrated in Figure 14. The remarkable decrease from Euro V to Euro VI can be explained by the introduction of a PN limit with Euro VI. This PN limit forced the installation of DPFs in all vehicles. The Euro VI DE emission factors are higher than the ones of Euro VI ABC, what is proven by measurement data. However, Euro VI DE real world PN23 emissions are still below the Euro VI limit of 6 E+11 #/kWh. For Euro 7 the PN23 emissions maps are exactly the same as for Euro VI DE. The Euro VI DE PN23 performance leads to the conformity regarding Euro 7 limits and thus no modification is needed.

Figure 14: PN23 emission factors, tractor trailer combination in German average motorway driving and 3-axle urban bus (or "city bus", CB) in German average urban driving



4.5. Cold start extra emission factors

The cold start extra emission factors were created using a new modelling approach that allows cycle-specific cold start extra emissions to be simulated second-by-second for each emission component as a function of shutdown duration and ambient temperature. For this purpose, the cold start behaviour was modelled for each vehicle from measurements with cold start. As with the emission maps, an average cold start model for Euro-classes Euro 6d-TEMP and 6d was derived using registration numbers.

The cold start extra emission factors were simulated in a matrix with the following variables:

- parking time from 0 to 735 min
- ambient temperature from -20 to +30 degrees Celsius
- driving distance from 0.1 to 30 km

These combinations lead to 4004 scenarios of parking time, ambient temperature and driving distance. Cold start emissions were calculated for PC, LDV and HDV.

4.5.1. PC and LDV – data base

The Euro classes Euro 6d-TEMP and Euro 6d were sufficiently covered by the available measurement data. Earlier Euro classes were covered with data sets supplied by EMPA. (See Table 6)

Cold start emission factors for Euro classes not covered by EMPA data (petrol before Euro 3 and diesel before Euro 4) were calculated using HBEFA 4.2 for the same matrix of parking time, ambient temperature, and driving distances as the new HBEFA 5.1 values. N2O and NH3 emission factors have not been part of the HBEFA 4.2 cold start model, thus the emission factors for these vehicles were calculated using the tier 3 methodology of the EMEP EEA.

Furthermore, PM and PN emissions for diesel vehicles with Euro classes before Euro 6ab were also filled with the values from HBEFA 4.2. For petrol vehicles with Euro classes before Euro 6ab no cold start emission factors were available in HBEFA 4.2, so the values for HBEFA 5.1 for Euro 6ab were used as an approximation. This is assumption is valid, because also older vehicles use already a TWC for emission reduction.

Cold start emission factors for vehicles with other technologies (CNG, Ethanol, etc) were derived from petrol or diesel emission factors using the same relation factors as for hot emission factors.

Table 6: Overview on cold start test data of M1 and N1 vehicles

	FC	**NOx**	**CO**	**HC**	PN	N2O	NH3
Euro 3	EMPA (2)	EMPA (2)	EMPA (2)	EMPA (2)	factor	factor	factor
Euro 4	EMPA	EMPA	EMPA	EMPA	EMPA	factor	factor
Euro 5	EMPA	EMPA	EMPA	EMPA	EMPA	factor	factor
Euro 6ab	EMPA	EMPA	EMPA	EMPA	EMPA	factor	factor
Euro 6c	EMPA	EMPA	EMPA	EMPA	EMPA	factor	factor
Euro 6d-TEMP / 6d / 7	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec

(2) only for gasoline vehicles

4.5.2. HDV data base

HBEFA provides cold start emissions for HDV for the first time in the version 5.1. The share of cold start emissions is of course lower for heavy-duty vehicle categories than for passenger cars, but it still makes up a significant part of the total emissions.

The data set for HDV covers second by second data for Euro VI ABC and Euro VI DE vehicles, which is used for the generation of detailed CSEE models. The CSEE for other emissions standards are derived by factors in relation to Euro VI. The factors for Euro V and earlier emission standards are based on a study of TU Graz (Rexeis, 2013). The Euro 7 factors are designed in order to meet the Euro 7 emission limits.

The following table gives an overview about the covered emission components by Euro class and shows also the data source.

Table 7: Overview data sources for HDV cold start by pollutant and Euro standard.

	FC	NOx	CO	HC	PN	N2O	NH3
Euro 0	factor	factor	factor	factor	factor	factor	factor
Euro I	factor	factor	factor	factor	factor	factor	factor
Euro II	factor	factor	factor	factor	factor	factor	factor
Euro III	factor	factor	factor	factor	factor	factor	factor
Euro IV	factor	factor	factor	factor	factor	factor	factor
Euro V	factor	factor	factor	factor	factor	factor	factor
Euro VI ABC	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec
Euro VI DE	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec	Sec-by-sec
Euro 7	factor	factor	factor	factor	factor	factor	factor

4.5.3. BEV methodology

Heating-up the battery when starting the vehicle demands extra energy. This is the cold start effect for BEVs.

In (Helms, 2022), the heating demand for the battery and the passenger compartment to reach the target temperature levels after cold starts at low temperatures has been assessed ("cold start extra consumption"). From this data and the battery masses with the specific heat capacities of battery cells we calculated a simple equation for the cold start extra consumption for application for any BEV in the simulation with the model PHEM. The battery weight is calculated from the battery capacity using average energy densities.

$$E_{Bat-cond} = m_{bat} * c_{bat} * \left(t_{target} - t_{start}\right)$$

$$\textit{for } t_{target} > t_{start}, \textit{ otherwise zero}$$

$E_{Bat-cond}$	…	Electrical energy needed for heating the battery after a cold start [Wh]
m_{bat}	…	Mass of battery to be heated for conditioning [kg]
c_{bat}	…	Specific heat capacity of the battery [Wh/kgK]
t_{target}	…	Temperature of the battery at start [°C]
t_{start}	…	Target temperature of the battery for heat up phase

4.5.4. Results

The results for the cold start extra emissions for selected components are illustrated here as examples. The first three graphs show the cold start behaviour of passenger cars in relation to the respective hot emission factors for average driving behaviour in Germany. The additional cold start emissions were calculated using the distribution matrix of temperature and parking duration in Germany. The resulting g/start values are based on an average driving distance of 24 km per cold start in order to obtain an emission value in g/km.

Figure 15 shows the energy consumption (EC in kWh/km) of passenger cars with diesel and gasoline engines by emission standard (Euro 3 to Euro 7), as well as battery electric vehicles. Since BEVs do not consume fuel, the fuel consumption of ICE vehicles shown as energy consumption.

The “cold” shares (the upper segments in each pair of bars) are constant for petrol at all Euro stages (2 %) due to increased friction and lower combustion efficiency in cold start conditions. Diesel vehicles show a rise of cold start energy consumption with newer technologies (5% for Euro 7). This can be attributed to stricter exhaust emission limits, which are achieved by measures to heat up the exhaust aftertreatment (particularly the SCR) more quickly, but lead to higher energy consumption during cold starts in addition. Battery electric vehicles show a cold start share of 5 %, this stems from battery behaviour in low temperatures and the need to heat the cabin and battery system electrically, not from engine inefficiencies and the need to heat up exhaust aftertreatment systems as in combustion vehicles.

Figure 15: Average energy consumption of passenger cars in Germany by emission standard (Euro 3–7) and Powertrain Type (petrol, diesel, electric) including cold start

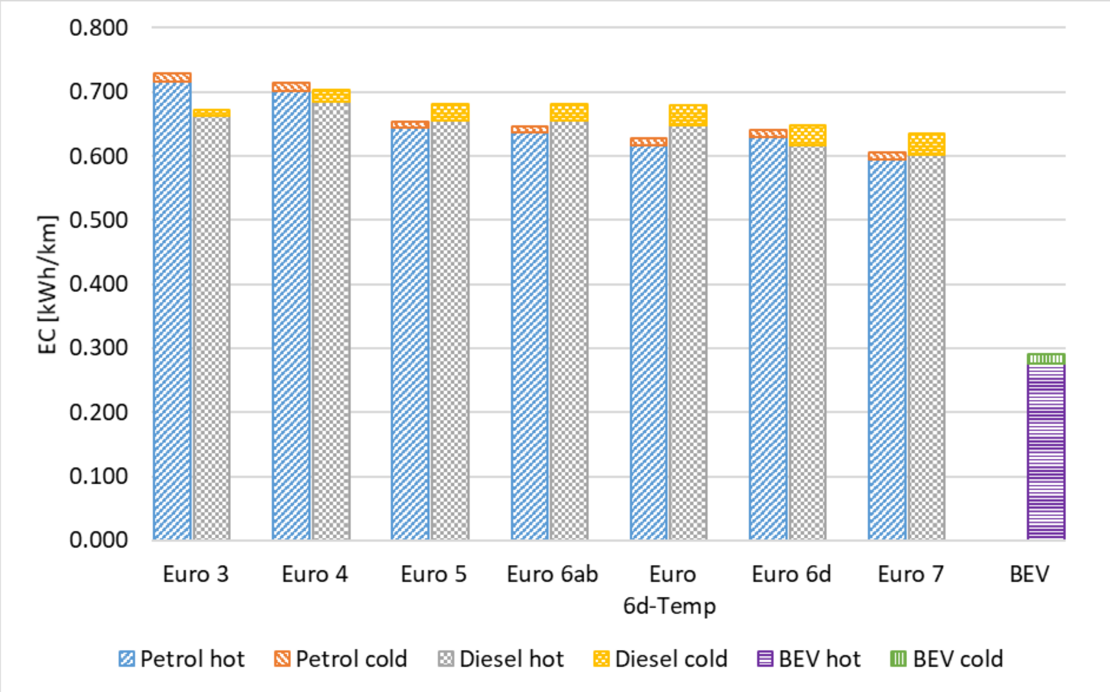


Figure 16 illustrates the average HBEFA-results of NOx emissions of passenger cars with petrol and diesel engines across emission standards, from Euro 3 to Euro 7, under both hot and cold conditions.

Cold start emissions remain a significant factor even as overall levels decrease. In earlier Euro standards, cold starts added around 15–25% extra NOx for petrol cars, while diesel cold contributions were less noticeable due to already high baseline emissions. In the most recent classes (Euro 6d-Temp to Euro 7), the relative importance of cold starts has increased as hot emissions are reduced to very low levels. Cold starts now account for roughly 25% of total NOx emissions in petrol cars and up to 30% in diesels, making them a key contributor to remaining emissions. This underscores the importance of accurate modelling and mitigation of cold start behaviour in the latest Euro standards, since they represent a growing share of total fleet emissions despite the overall reduction in absolute values.

Figure 16: Average NOx emissions of petrol and diesel passenger cars in Germany by emission standard (Euro 3–7) including cold start

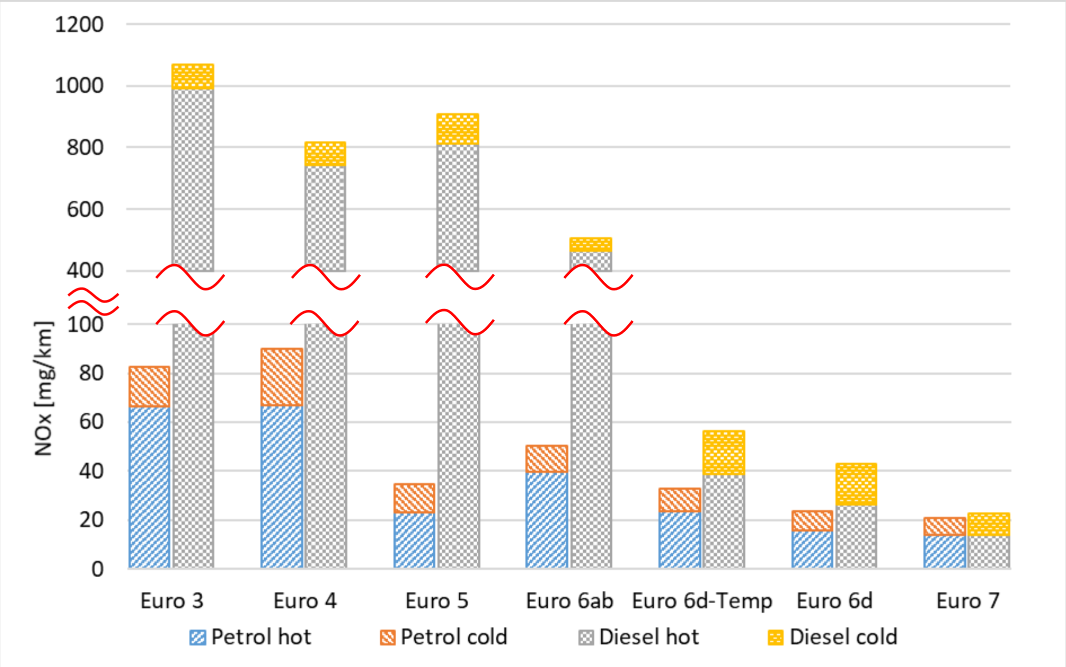


Figure 17 illustrates the average HBEFA-results of particle number emissions of passenger cars with petrol and diesel engines across emission standards, from Euro 3 to Euro 7, under both hot and cold conditions. Please note that the y-axis is logarithmically scaled. Cold-start particle number emissions remain a key challenge despite overall reductions across Euro standards. For petrol vehicles, earlier standards showed very high cold-start emissions, up to three times higher than hot emissions. With Euro 6d-Temp and newer, these emissions dropped sharply but still account for about one-third of total PN output, showing that cold-start conditions continue to contribute significantly. Diesel vehicles, equipped with DPFs since Euro 5, show much lower and more stable cold-start emissions. Euro 7 highlights the lasting effectiveness of particulate filters and improved calibration. Overall, since the introduction of DPFs, diesel cars have remained cleaner than petrol ones, which still show a stronger cold-start effect.

Figure 17: Average PN23 emissions of petrol and diesel passenger cars in Germany by emission standard (Euro 3–7) including cold start

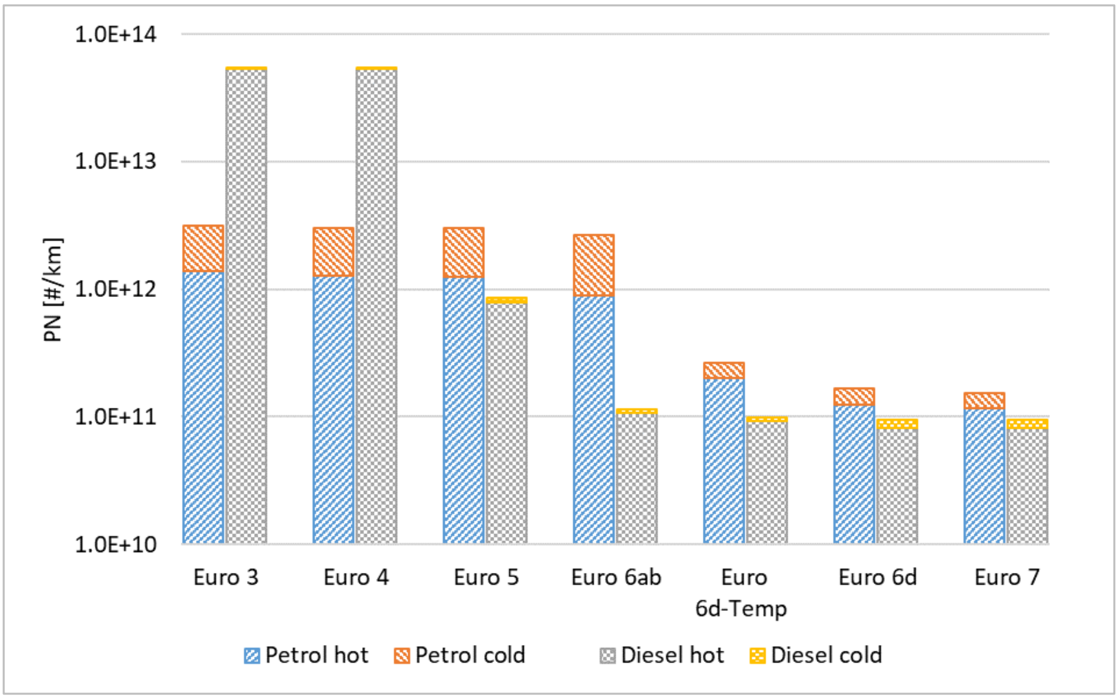


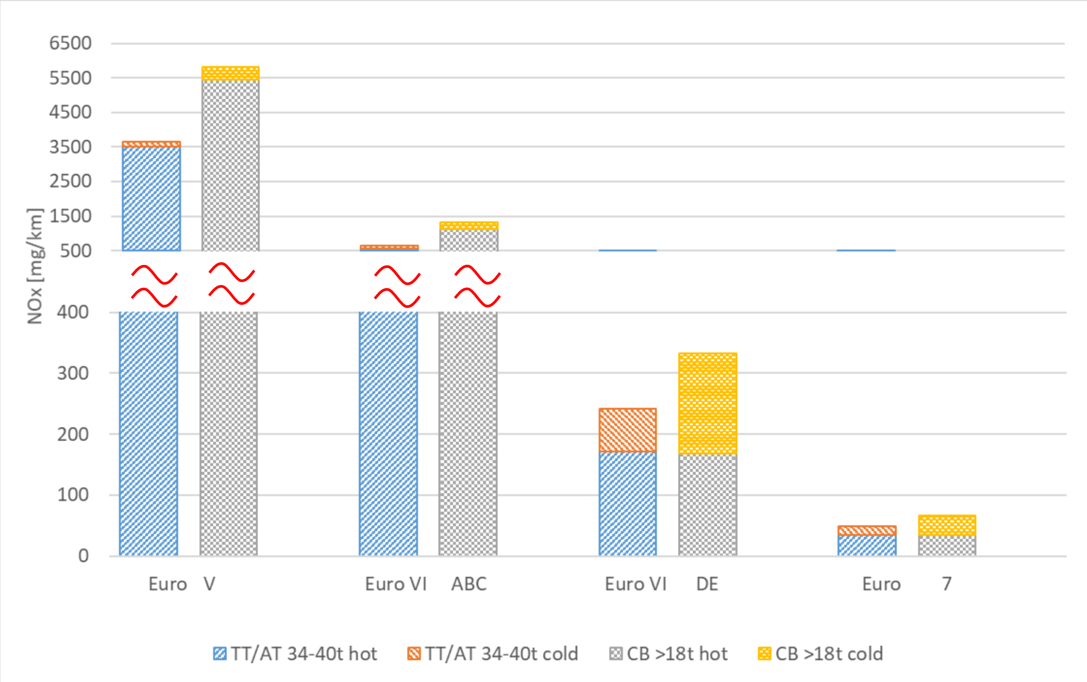
Figure 18 illustrates an example for the relation of cold start NOx to hot NOx emissions for heavy duty vehicles, in this case a tractor trailer combination and an urban bus, in average German driving conditions. The average daily trip is assumed with a distance[16] of 480 km and 1.5 cold starts for a tractor trailer combination and 240 km and 3 cold starts for an urban bus.

The absolute cold start extra emissions decrease with the development of engine and exhaust aftertreatment technologies due to the introduction of new Euro regulations. The reduction rate is about 80 % for each regulation step. However, the share of cold start emissions in total emissions (cold + hot) raises at the same time. This can be explained by the even higher decrease of the hot emission factors. The share is in average 5 % for Euro V, 15 % for Euro VI ABC and between 30 % (urban bus) and 50 % (tractor trailer combination) looking at Euro VI DE and 7.

Comparing the shares for the different vehicle categories shows that the impact of the cold start emissions is higher for urban buses compared to a tractor trailer combination. This can be related to the different operation profiles of whole-day urban or long-haul driving conditions.

[16] The numbers for the daily distances are based on values for the VECTO.VECTO is the simulation tool used for calculating the official values for the HDV CO2 regulation

Figure 18: Average NOx emissions of tractor trailer combinations and urban buses (or "city buses", CB) in Germany by emission standard (Euro V–7) including cold start



4.6. Euro 7 emission factors

The Euro 7 regulation will come in place in 2026/2027 for passenger cars and light-duty vehicles and in 2028/2029 for heavy-duty vehicles. No vehicles are on the road at this point and thus no test data is available. However, Euro 7 vehicles are integrated in the simulation tool PHEM (Passenger Car and Heavy-Duty Emission Model) for the calculation of the HBEFA emission factors in order to represent the upcoming fleet in the next years. The following section illustrates how the Euro 7 emission models were derived based on the existing Euro 6/VI data and the already published Euro 7 limits.

4.6.1. Passenger Cars and LDV

The CO2 map for Euro 7 was then derived from the corresponding Euro 6d CO2 maps. A relative improvement of 2% was assumed over the entire map. The following table shows the average CO2 emissions normalized to the rated power between the full load and drag curve.

In order to estimate the Euro 7 data, the legal framework conditions must first be clarified. The limits for the WLTC were adopted from the Euro 6e regulation. All limits have remained the same except for the number of particles. The limit value of 6x10^11 [#/km] for the number of particles has remained the same, but this now refers to PN10 instead of PN23. The conformity factors for the RDE limits have been reduced from 1.43 to 1.1 for NOx and from 1.5 to 1.34 for PN (Regulation (EU) 2023/443).

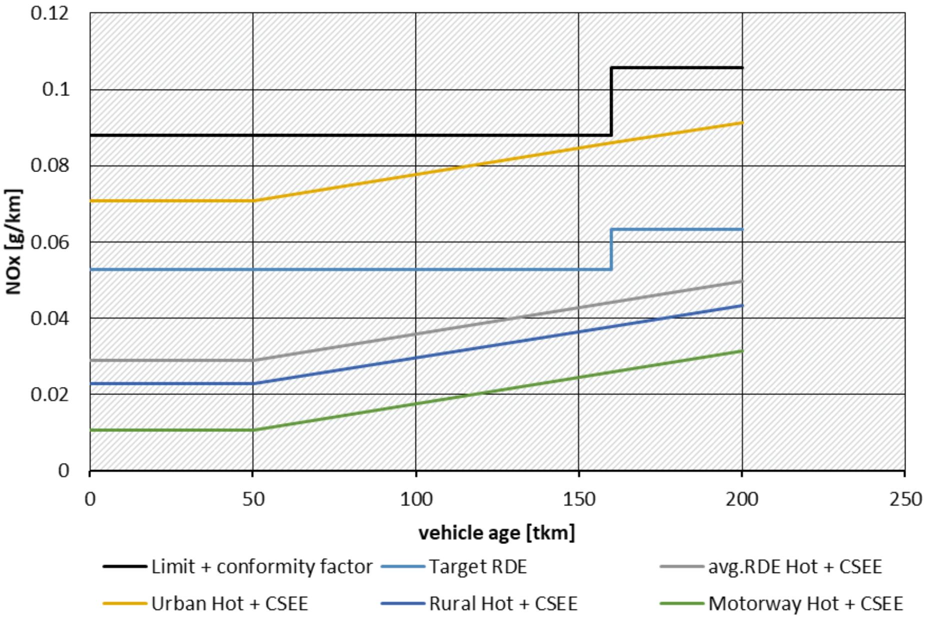
Furthermore, in Euro 7 the main service life, during which passenger cars must comply with the emission limits, has been increased to 160,000 km. After the main service life, the additional service life is defined as 200,000 km or 10 years, whichever comes first. During the Additional Service Life, the limit to be complied with is multiplied by the durability multiplier 1.2, taken from Regulation (EU) 2024/1257.

The above definitions form the framework conditions for the derivation of Euro 7 from Euro 6d. The Euro 7 vehicle model was simulated with the Euro 6d emission maps and Euro 6d cold start effects. The deterioration function was then included. This was derived from Euro 6d.

These parameters were used to simulate the WLTC cycle, three representative RDE cycles (urban, rural, motorway) and an average RDE cycle. A cold start temperature of 20°C was defined in the WLTC. The RDE cycles were simulated as a worst-case scenario with an ambient temperature of 0°C. As a target value, the WLTC limit and consequently the RDE Not-to-exceed limits were reduced by a safety margin. One reason for this is that the average Euro 6d map also includes vehicles that emit more than the average vehicle and these must also comply with the WLTC limit in the certification. To define the WLTC target value, the WLTC limit was therefore reduced by 25%. The RDE target value calculated by reducing the Not-to-exceed limit by 40%, as the RDE measurements show more variability in trip dynamics.

The simulated emission values were compared with the above-mentioned target values and the maximum relative exceedance was determined. This relative exceedance was defined as the reduction target from Euro 6d to Euro 7. As an example of this method, the results for Diesel NOx are shown in the following graph.

Figure 19: Euro 7 target values and simulated results for NOx to derive the Euro 7 model



For diesel vehicles, it was assumed that the reduction measures for NOx will have the same effect in both warm and cold start behavior, so they are divided equally. In the case of petrol vehicles, it was assumed for the gaseous components that approximately 70% of the reductions would be achieved in the hot operating behavior and approximately 30% in the cold start behavior. The resulting reduction measures for deriving Euro 7 from Euro 6d are shown in the following table. These reduction targets were used to calculate both the emission maps and the cold start curves for petrol and diesel Euro 7.

Table 8: Calculated reduction targets from Euro 6d to Euro 7 for diesel and petrol vehicles

	NOx [%]	CO [%]	HC [%]	PN10 [%]
Diesel emission map	46.8%	no reduction		
Diesel cold start	46.8%			
Petrol emission map	13.5%	26.7%	9.9%	6.9%
Petrol cold start	10.4%	18.6%	4.0%	no reduction

The reduction of NOx and HC also has an effect on the NOx and HC components. These were reduced by the same ratio.

The Euro 7 LDV hot emission maps were derived using the same method as for passenger cars. The reduction measures required to comply with the Euro 7 limits were determined individually for each size category.

4.6.2. Heavy-duty vehicles

The Euro 7 regulation for HDV will come into force in 2028 for all new models and in 2029 for all vehicles according to Regulation EU 2024/1257. The test cycles will remain the same as for Euro VI. The WHSC and WHTC will continue to be tested on the engine test bench, and emission behaviour in real traffic and operational conformity will be tested using ISC tests (renamed to RDE tests). The boundary conditions for valid ISC tests correspond to the Euro VI E specifications, with the exception of a lower power limit for valid moving average windows (MAWs), which is removing low load parts of a test in the evaluation method of the EMROAD[17]. This enables Euro 7 RDE tests to cover most of the low-load range that is critical in terms of NOx emissions, which occurs, for example, in urban driving with high traffic volumes or in traffic jams and is therefore particularly relevant in urban areas. Ambient temperatures for valid RDE tests must still be between -7°C and 30°C, with evaluation beginning when the coolant temperature reaches 30°C or after 10 minutes at the latest. Operational conformity must still be demonstrated in ISC tests up to a mileage of 300,000 km for vehicles with a maximum permissible mass of less than 16 tonnes and up to 700,000 km for vehicles with a maximum permissible mass of more than 16 tonnes[18].

Furthermore, the limit values have been adjusted. The Euro 7 limit values for NOx are 57% lower in the WHTC and 62% lower in the ISC tests than in Euro VI. For CO, the reduction is just under 70%. In addition, limit values have been introduced for other components, such as N2O and PN10. The limit values for HDV vehicles in Euro 7 are shown in Table 9.

[17] The EMROAD evaluation tool is already used in Euro VI but used a 20%/10% threshold for the average power/rated power ratio per window while Euro 7 used a 6% threshold.
[18] The maximum mileage for ISC tests is increased by 25% for the additional lifetime, but the limit values are also adjusted by a factor of 1.2 (current proposal). (Weller, 2025)

Table 9: Euro 7 HDV limits, Regulation EU 2024/1257

Pollutant emissions	WHSC and WHTC	RDE
	per kWh	per kWh
NOx in mg	200	260
PM in mg	8	-
PN10 in #	$6x10^{11}$	$9x10^{11}$
CO in mg	1 500	1 950
NMOG in mg	80	105
NH3 in mg	60	85
CH4 in mg	500	650
N2O in mg	200	260

Based on the current state of technology, two different systems relating to engine and exhaust aftertreatment technology are being considered for achieving the Euro 7 limits:

- On the one hand, there is the option of using an exhaust aftertreatment system that is very similar in design to that used in Euro VI and achieving the stricter limits with improved components (e.g., more effective catalyst materials) and a reduction in raw emissions from the engine, in the case of NOx with increased exhaust gas recirculation (EGR).
- The other option is to install an additional SCR catalyst closer to the engine, which is smaller than the SCR catalyst in the Euro VI exhaust aftertreatment box. This SCR catalyst closer to the engine (and thus upstream of the DPF) reaches its operating window earlier during a cold start than the SCR catalyst downstream and ensures higher NOx conversion rates under low-load driving conditions. At higher engine load the SCR catalyst downstream is in the ideal temperature area and overtakes most of the NOx conversion. Although this system is more complex, it allows for higher raw emissions and lower EGR rates. This can have a positive effect on fuel consumption and particulate emissions.

At this point in time, it is not yet clear which of the systems will prevail or whether both will be used in parallel. From today's point of view, most OEMs will use the dual SCR system. However, for the assessment of Euro 7 emission levels with the model PHEM, we used the Euro VI E model as basis and increased the entire SCR volume, adjusted the thermal management strategies and conversion efficiencies etc., since a complete optimization of a new system without yet having Euro 7 test data was out of scope of this study. Details are described below. The emission trends simulated with these settings shall show Euro 7 behavior of both possible systems well.

Discussions with manufacturers during the development of the Euro 7 legislation showed that, in addition to the WHTC, the transient test bench test, worst case ISC tests will also be defined for development. Worst case refers to the driving cycle itself on the one hand, but also to the environmental conditions on the other.

For this purpose, two different cycles were developed based on previously recorded real-world driving. The focus is on the start of the test because in this phase the engine and exhaust aftertreatment are cold, and this part therefore has the greatest influence on overall emissions. The cold start part is weighted at 14% and must be included in the proportion of urban driving.

- The so-called high-load test begins with high-load uphill driving in urban areas. Due to the high load and the resulting high exhaust gas temperatures, the engine and exhaust aftertreatment heat up very quickly, but raw emissions are very high before the operating window is reached.
- The low-load test starts with a very low-load urban drive, with the average power output just above the six per cent of rated power required for a valid test. In this phase, the raw emissions are relatively low, but the system takes longer to heat up due to the lower exhaust gas temperatures. At the end of the low-load drive, the cycle then includes a high-load uphill drive, which places high demands on exhaust aftertreatment, especially in the first few seconds due to the abrupt increase in load.

The cold start phase is followed by a mix of city, interurban and motorway driving in accordance with the ISC framework conditions. This is the same for both tests and this warm test phase is weighted with 86%.

In addition, the ambient temperatures were varied at the start of the test. It is assumed that the temperatures of the vehicles, engine and exhaust aftertreatment have fully adjusted to the ambient temperature due to a sufficiently long standstill period before the start of the test. This is also required in the regulations for valid tests up to a deviation of five degrees Celsius.

- At a starting temperature of -7°C, exhaust gas aftertreatment takes the longest of all possible ISC-compliant test conditions to reach the operating window. These test conditions therefore also result in the highest emissions. However, since the evaluation only begins at a coolant temperature of 30°C or after ten minutes at the latest, a large part of these increased emissions is not taken into account in the evaluation.
- The starting temperature of 30°C is the other extreme, the highest possible starting temperature. At this temperature, the exhaust aftertreatment system reaches its operating

window more quickly, but the evaluation begins at the start of the test. This means that all emissions are recorded from the start of the test.

For NOx the cold start is modelled with the exhaust aftertreatment model in PHEM. For all other components the cold start extra emissions were calculated using the HBEFA methodolgy (see chapter 4.5).

The development target is defined in such a way that, due to dispersion in series vehicle production and safeguarding against driving cycles that are even more challenging than the defined worst-case scenarios, the limit value for the maximum permissible mileage is undershot in all tests by a safety margin in the range of 50%. The slightly higher safety margin in the ISC compared to the RDE test for passenger cars was assumed due to additional statistical uncertainties in the moving average window evaluation method for HDV. In the WHTC, the safety margin can be lower because the cycle is known and only the series dispersion needs to be taken into account.

Table 10 and Table 11 show the comparison with the limit values for the various simulations. The first column shows the test, while the second column indicates whether the ISC tests are for the low-load or high-load urban section. The third column shows the vehicle class, with N2 standing for rigid trucks and N3 for long-haul vehicles. The ambient temperature is also shown. The results are then illustrated as a percentage, showing the proportion of the limit value. This means that 100% corresponds to the emission value exactly matching the limit value, and 10% corresponds to the value being 90% below the limit value.

In order to achieve the NOx development target in all worst-case test cycles, exhaust gas heating was increased, resulting in higher temperatures in the exhaust aftertreatment system and thus better conversion rates. This has a positive effect on NOx emissions, especially during cold starts and low-load driving conditions. Furthermore, heat losses in the exhaust system were reduced. This was achieved by improving the insulation of the exhaust system. Another measure is to lower the limit temperature for AdBlue injection, which can be achieved through fundamental system development. In addition, the NH3 storage capacity of the SCR catalytic converter has been increased based on assumed further developments in catalyst materials. The improvement of the SCR catalytic converter also has an effect through improved NOx conversion rates and a reduced influence of ageing effects. Increasing the EGR rate also reduces engine NOx emissions, which is particularly important during cold starts. Compared to the Euro VI DE base model, these measures reduce NOx emissions by 50 to 90 per cent, depending on the driving situation. This means that the emission value in the most challenging ISC scenario for NOx (rigid truck, high load in cold start, ambient temperature -7°C) is 40 % of the Euro 7 limit value. In the WHTC at -7°C, NOx emissions fall below the limit value by one quarter. The measures therefore lead to the Euro 7 development target being met even in worst-case scenarios.

NH3 emissions were reduced by up to 70% compared to Euro VI DE, mainly due to an assumed improvement in AdBlue dosing control in combination with the slip catalyst and a reduction in ageing-related emission increases through material development. This means that the Euro 7 development targets are achieved in the WHTC and under worst-case ISC test conditions.

N2O is reduced by means of an improved AdBlue injection strategy and the use of catalyst materials that are less prone to N2O formation, for example vanadium. Compared to Euro VI DE, these measures result in a 30% reduction in emissions, thereby achieving the Euro 7 development targets.

CO emissions increase by up to approximately 120% compared to Euro VI DE due to the increased heating measures and increased EGR rates. Nevertheless, emissions are still below ten percent compared to the Euro 7 limit value.

The measures listed are not expected to have any significant impact on emission behaviour for PN10, NMHC/NMOG and CH4. As these emission values for Euro VI DE are already at a low level compared to their respective limit values, no reduction measures were necessary to achieve the Euro 7 limit values for these components.

Table 10: emission levels of the Euro 7 model compared to the Euro 7 limits, part 1

Test	ISC-test base	Vehicle category	Temperature	NOx	PN10	NMHC/NMOG	NH3
ISC	high-load	N3	-7°C	42%	34%	33%	4%
ISC	low-load	N3	-7°C	43%	36%	34%	4%
ISC	high-load	N3	30°C	53%	34%	33%	4%
ISC	low-load	N3	30°C	49%	36%	34%	4%
ISC	high-load	N2	-7°C	40%	28%	43%	48%
ISC	low-load	N2	-7°C	40%	29%	43%	48%
ISC	high-load	N2	30°C	54%	28%	43%	48%
ISC	low-load	N2	30°C	47%	29%	43%	48%
WHTC	-	-	-7°C	75%	47%	55%	68%
WHTC	-	-	30°C	62%	47%	55%	68%

Table 11: emission levels of the Euro 7 model compared to the Euro 7 limits, part 2

Test	ISC-test base	Vehicle category	Temperature	N2O	CH4	CO
ISC	high-load	N3	-7°C	28%	1%	7%
ISC	low-load	N3	-7°C	30%	1%	7%
ISC	high-load	N3	30°C	27%	1%	7%
ISC	low-load	N3	30°C	30%	1%	7%
ISC	high-load	N2	-7°C	47%	1%	7%
ISC	low-load	N2	-7°C	49%	1%	7%
ISC	high-load	N2	30°C	46%	1%	7%
ISC	low-load	N2	30°C	49%	1%	7%
WHTC	-	-	-7°C	56%	2%	9%
WHTC	-	-	30°C	56%	2%	9%

In addition to adapting the engine and exhaust aftertreatment system, the vehicle data for Euro 7 vehicles was updated based on Euro VI DE data. The most important measures are the reduction of unladen weight, air resistance and rolling resistance, as well as an increase in the efficiency of the engine itself and the auxiliary units. These measures result in a reduction in fuel consumption and are necessary from today's perspective in order to achieve the 2030 CO_2 fleet targets. For a standard tractor trailer combination travelling on the motorway, the reduction in fuel consumption of Euro 7 compared to Euro VI DE is around ten per cent.

The PHEM emissions model, which is based on truck data, is also used for coaches and urban buses. For validation purposes, corresponding driving cycles were simulated in advance and the function of the model was tested. For buses, the truck model leads to similar reduction rates from Euro VI DE to Euro 7 as calculated for trucks. Thus, the truck model is also used for busses and coaches.

4.7. Correction factors for the deterioration of exhaust gas aftertreatment systems

This chapter illustrates the work and results for the correction factors for the deterioration of exhaust gas aftertreatment systems for passenger cars, light duty vehicles and heavy-duty vehicles.

The components of the engine, such as injection systems, EGR valves, lambda- and NOx-sensors etc. as well as catalytic converters undergo deterioration effects over the vehicle life time with effects on the exhaust emission levels. Main effect for modern vehicles is the thermal and chemical deterioration of the catalysts, which usually lead to increasing emissions of those exhaust gas components converted by the catalysts (CO, HCs, NOx) but decreasing emission levels of components formed during the catalytic processes (such as NO2, NH3). This effect is considered in the HBEFA via the deterioration functions.

4.7.1. Deteriorations functions for PCs and LDVs

In HBEFA 4.1, the deterioration factors for NOx and CO were revised in order to take better account of the findings on the influence of vehicle mileage on emissions (Matzer et al, 2019). For HC emissions, on the other hand, no new data could be taken into account for HBEFA 4.1, which is why the corresponding factors were adopted from HBEFA 3.3 (Hausberger and Matzer, 2017). The basis for the update was exclusively remote sensing data, as no suitable vehicle measurements were available in which vehicles in new condition and with sufficiently high mileage could be directly compared.

For the version 5.1 update, two different data sources and analytical approaches were used:

- Remote Sensing data from the pan-European CARES database
- Individual vehicle pairs with low and high mileages.

It should be noted that LDVs did not have their own deterioration function in HBEFA 4.1 and that PC ageing was used. This approach has been retained here.

4.7.1.1. Analysis of Remote Sensing data

Remote sensing data provides information about the emission behaviour of groups of vehicles as they are passing different measurement locations (Borken-Kleefeld and Dallmann 2018). Here we analyse records from Euro 5 and Euro 6 gasoline and diesel cars as remotely measured in Belgium, the Czech Republic, Germany, Italy, Poland, Sweden and Switzerland between years 2017 and 2023. Full details are given in (Kumawat and Borken-Kleefeld 2025); here we summarize the essential steps.

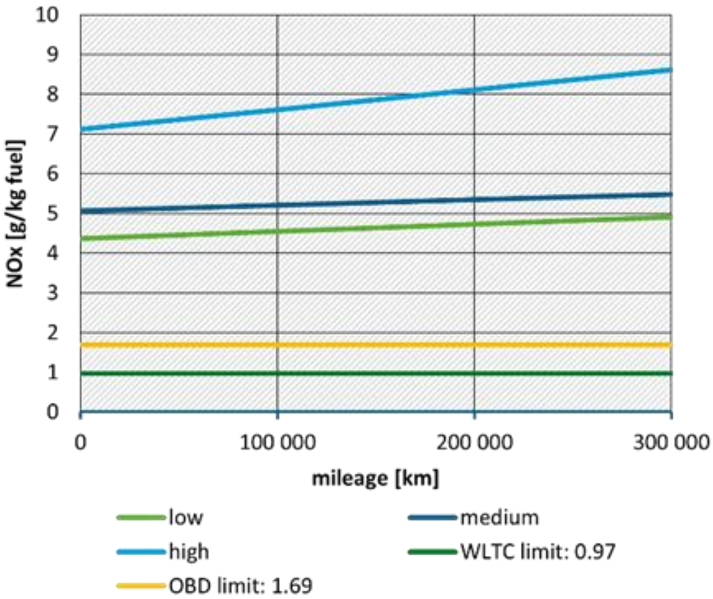
For each emission record the vehicle age is known, which in turn is converted to an average cumulative mileage using HBEFA’s lifetime mileage functions. Then emission records are clustered into mileage bins with a minimum of at least 100 records each. Finally, the average emission is calculated as function of mileage for each vehicle layer. The increment of the regression lines, normalised to a base emission factor at 50’000 km, is then the fleet averaged increase with vehicle mileage as determined by remote sensing.

Before all processing, utmost care has been given to eliminate artefacts: Data were extensively quality controlled removing outliers, sites with high shares of cold-started vehicles, inconsistent data, wrong labels and misclassifications. Furthermore, several known confounding effects have been accounted for, most importantly (Davison et al. 2022, Borken-Kleefeld and Potturu 2025):

- The influence of temperature notably on NOX emissions from diesel cars is controlled by stratifying the data first into temperature bins. The deterioration calculated here is given for an ambient temperature bin of 18°C to 25°C. Thus, the effect of ageing/mileage is separated from an influence of temperature; the temperature effect is represented by a correction function of its own.
- The influence of engine load, again most notable for NOX emissions from diesel cars, is controlled by grouping records into three, roughly homogenous bins characterised by their vehicle specific power. For each power bin, the development over age/mileage is analysed separately. The influence of engine load is in itself accounted for by the PHEM modelling.

In previous deterioration analyses, e.g. Borken-Kleefeld and Chen 2015), there were not enough records for this separation into three main factors of age/mileage, temperature and engine load. This careful data treatment was possible here thanks to in total 950’000 remote sensing records available. After all filtering 120’000 fully valid and suitable records remained. Full results are given in (Kumawat and Borken-Kleefeld 2025). Here we highlight the results for diesel cars with Euro 6abc emission standard (Figure 20). Their deterioration of NOX emissions can be approximated by a linear line. Both, the absolute emission level as well as the slope, i.e. the deterioration, differ by engine load as indicated by the different VSP classes. That is however not the case for modern gasoline cars.

Figure 20: NOx emissions of diesel Euro 6abc cars over vehicle mileage, differentiated by engine load. Source: (Kumawat and Borken-Kleefeld 2025)



4.7.1.2. Deterioration functions for Euro 6ab

The deterioration factors for Euro 6ab vehicles were updated here, as more comprehensive remote sensing data sets are now available, which also include vehicles with significantly higher mileages (sufficient data up to 160.000 km) and thus enable a more realistic representation of the ageing effect. The data used originates from measurement campaigns carried out during several remote sensing campaigns in Europe. In total, more than 120,000 vehicles were measured and used for these deterioration functions. Since remote sensing data could not provide clear information about deterioration effects for CO, and HC cannot be measured with RS, the deterioration factors for these components of Euro 6ab vehicles were calculated considering the data from HBEFA 4.1 and Euro 6d-TEMP deterioration functions.

4.7.1.3. Deterioration functions for Euro 6d-TEMP and 6d

For vehicles of the Euro 6d-TEMP and Euro 6d emission standards, the available remote sensing data currently only provides information up to a mileage of around 80,000 kilometres. However, this data basis is not sufficient to derive a reliable and stable deterioration behaviour of the emissions over the entire service life of the vehicles. In order to nevertheless be able to make reliable statements, targeted measurements on the chassis dyno and on-road with PEMS were carried out in which vehicle with identical engine models with both low and high mileage were examined. These vehicles are also stored in the DBEFA. Based on these direct comparative measurements, specific deterioration factors for Euro 6d-TEMP and Euro 6d vehicles could be determined.

A total of 7 pairs of diesel vehicles and 6 pairs of petrol vehicles were used for this evaluation. It was important to ensure that measurements of identical cycles on the chassis dynamometer were used. The measurements of the vehicle pairs include the WLTC, the high-load Ermes cycle, and the urban IUFC. Since the chassis dynamometer measurements do not show any trend toward different deterioration behaviour with changing driving dynamics, the same deterioration was applied to passenger cars and LDVs for all driving situations.

4.7.1.4. Deterioration functions for Euro 7

The deterioration factors for Euro 7 were estimated, this is documented in chapter 4.6.

4.7.1.5. Deterioration functions for other Euro classes

For NOx and CO from diesel and gasoline vehicles, the deterioration functions up to Euro 5 were adopted from HBEFA 4.1. Since there was no deterioration function for HC from diesel vehicles in HBEFA 4.1, the deterioration effects from Euro 6d-TEMP were adopted. For gasoline vehicles, the HBEFA 4.1 data was adopted up to Euro 2. Since the deterioration modelled in HBEFA 4.1 was too low from Euro 3 onwards, the newly calculated value for Euro 6d-Temp was adopted from Euro 3 onwards.

The deterioration function for Euro 6c was interpolated between Euro 6ab and Euro 6d-TEMP.

Deterioration factors were multiplicative in HBEFA 4.1, but were changed to an additive influence in HBEFA 5.1. The reason for this is that due to the very low emission level of Euro 6d-TEMP and 6d with increased mileage, multiplicative factors of up to 10 would be necessary in some cases to accurately represent the deterioration effects. However, this would lead to a high absolute increase in emissions in certain driving situations in which the average map shows slightly higher emission behaviour. For this reason, the calculation was changed to an additive method. The following equation shows the calculation of the emission factors as a function of the mileage.

$$Efa_{x\,km} = Efa_{50kkm} + DF_{mileage}$$

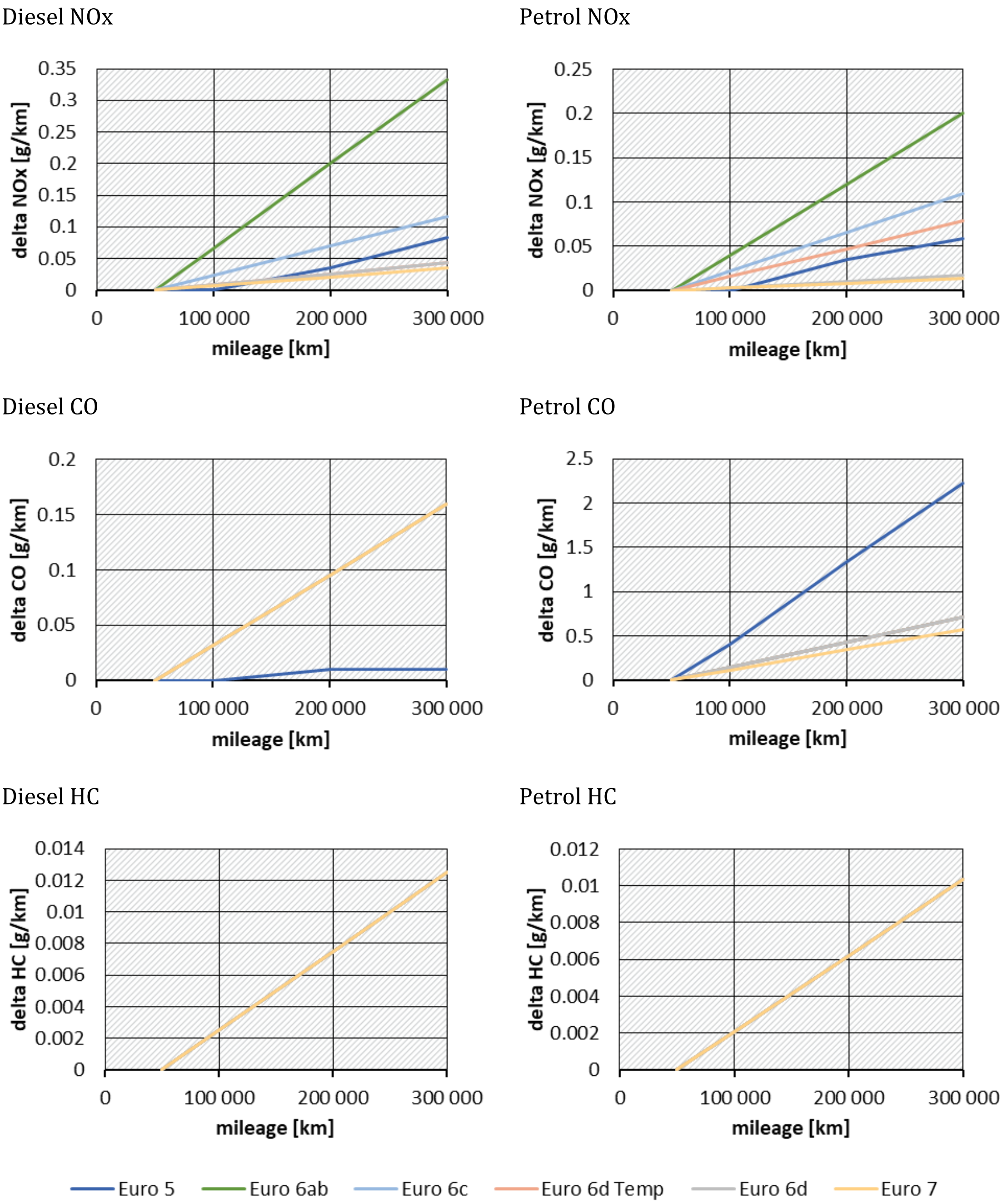
$Efa_{x\,km}$	…	emission factor at x km mileage [g/km]
Efa_{50kkm}	…	base emission factor at 50.000 km mileage [g/km]

$DF_{mileage}$ … deterioration factor depending on mileage [g/km]

The following figure shows the deterioration factors that were determined in the course of this work. The deterioration factors from Euro 0 to Euro 4 are not shown here, as otherwise the effect of the current Euro classes would not be recognizable.

For diesel CO deterioration, only Euro 5 and Euro 7 are visible in the graph, as the deterioration function is identical for Euro 6ab to Euro 7. The same applies to petrol CO Euro 6ab to Euro 6d and to all HC deterioration functions.

Figure 21: deterioration functions for NOx, CO and HC for petrol and diesel vehicles



4.7.2. Deterioration functions for HDVs

Modern heavy-duty vehicles use exhaust aftertreatment systems in order to reduce engine out emissions to meet the tailpipe limits. The systems can reach conversion rates of more than 99 % in best operating conditions, especially the latest Euro VI and upcoming Euro 7 technology.

However, chemical, thermal and mechanical ageing effects can reduce the performance over the lifetime. Measurement data proves these effects and the upcoming Euro 7 technology considers this also in the limit values. [19]

For that reason, deterioration functions for heavy-duty vehicles were first included in HBEFA 4.1. These functions were only set up for NOx for Euro VI ABC vehicles based on chassis dyno and PEMS test data[20]. The method was revised for HBEFA 4.2 due to a broader data base including remote sensing data in addition to chassis dyno and PEMS data. These ageing functions comprised also CO and NO2 in addition to NOx and included a vehicle speed dependency in order to include the effects of different driving situations on the deterioration. At that point, data was available for Euro V and Euro VI ABC vehicles[21].

For HBEFA 5.1 the database was extended with additional chassis dyno and PEMS test data:

- First Euro VI D vehicles with high mileage were on the road and consequently tested
- The Euro VI ABC dataset could be enlarged by additional vehicles, for example with mileages up to 1 000 000 km or vehicle categories not covered so far
- The broad availability of FTIR test data allows the elaboration of deterioration functions for all relevant gaseous emission components
- The test data allows a differentiation in rigid trucks and long-haul vehicles. The various mission profiles lead to different deterioration behaviours of the vehicle categories
- Test data for urban buses with high mileage was also available for the first time for this HBEFA version, but finally not used due to the low number of test vehicles and low fleet coverage (only two brands)

Table 12 illustrates the available data set for HBEFA 5.1 for chassis dyno and PEMS HDV test data for deterioration functions.

[19] K. Weller, S. Hausberger, B. Plakolmer: Durability of Euro 7 heavy-duty vehicle emissions, Technical report – LOT 2, Graz University of Technology on behalf of the European Commission, 2025
[20] C. Matzer et al., 'Update of emission factors for HBEFA Version 4.1; Final report', Graz University of Technology, Graz, 2019.
[21] B. Notter, B. Cox, S. Hausberger, C. Matzer, K. Weller, M. Dippold, N. Politschnig, S. Lipp, M. Allekotte, W. Knörr, M. André, L. Gagnepain, C. Hult, M. Jerksjö: HBEFA 4.2, Documentation of Updates, Infras, TU Graz, ifeu, IFFSTAR, ADEME and IVL on behalf of BAFU CH, UBA D, UBA AT, ADEME, Trafikverket and Miljodirektoratet, 2022

Table 12: Number of test vehicles[22] for HDV deterioration functions

Emission standard [-]	number of test vehicles - total [-]	number of test vehicles - rigid trucks [-]	number of test vehicles - long-haul trucks [-]
Euro V	*	*	*
Euro VI ABC	21	11	10
Euro VI DE	16	6	10

* Euro V was not updated and is still based on remote sensing test data as in HBEFA 4.2.

The database covers mainly heavy good vehicles (HGV) and only a low number of coaches (1 vehicle with high mileage) and urban buses (4 vehicles with high mileage). Thus, all data was pooled to one HDV database without separation for HGVs, coaches or urban buses, although urban bus data indicates a different deterioration behaviour due to the special operating conditions. However, the urban bus data covers only 2 different brands and does not allow a fleet representative conclusion.

In addition, further remote sensing test data was available. This data contains mainly Euro VI ABC and Euro V vehicles and covers only CO and NOx emissions. Due to this limited coverage of Euro-classes and exhaust components, remote sensing test data was used for validation of the functions. The functions have been produced on basis of the available chassis dyno and PEMS test data.

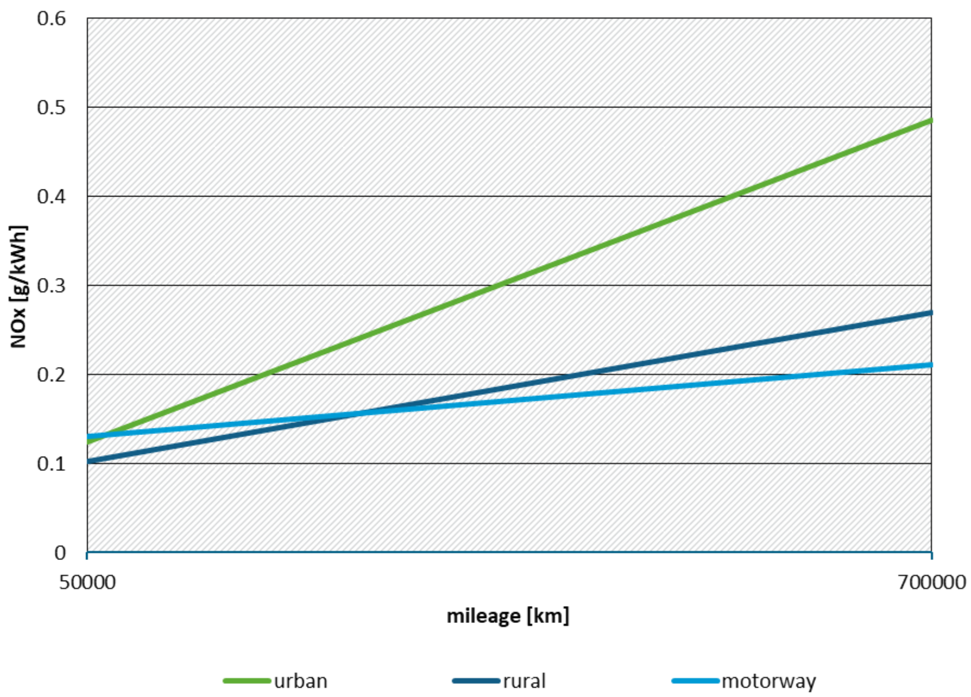
The following part describes the method for the elaboration of deterioration functions based on the chassis dyno and PEMS data:

- The test vehicles for the chassis dyno and PEMS tests were selected in order to gather vehicle pairs. That means each vehicle with high mileage was selected based on the reference vehicles available with low mileage. In the best case, the vehicle with high mileage is exactly the reference vehicle, but this is not feasible in most cases as hundred thousands of kilometres of driving are needed between the measurements. Thus, the vehicles with high mileage were selected as the same make and model as one of the reference vehicles with low mileage. In addition, the aim of the vehicle selection is to be fleet representative covering different brands and vehicle categories.
- The next step is the elaboration of the deterioration functions according to following specifications:

[22] These numbers include all single vehicles used for the elaboration of the functions, thus vehicles with low and with high mileage.

- Test cycle: the increase of the emissions over mileage was elaborated based on a hot started WHVC[23] test[24, 25], which includes urban, rural and motorway driving. This test allows to distinguish the effects of different driving situations on the ageing behaviour. This effect is illustrated in Figure 22 for the NOx emissions of a tractor trailer combination with emission standard Euro VI DE. The deterioration for NOx is higher in urban driving compared to rural and especially motorway driving. High-speed and thus high-power driving as in motorway situations leads to perfect operating conditions for the exhaust after treatment system. In these situations, the deterioration effects are obviously less distinctive as in low load urban driving. Low load driving challenges the catalyst system in terms of operating temperature, which is at the lower border of the operating window.

Figure 22: Emissions over mileage per road category, NOx, Euro VI DE, long-haul trucks

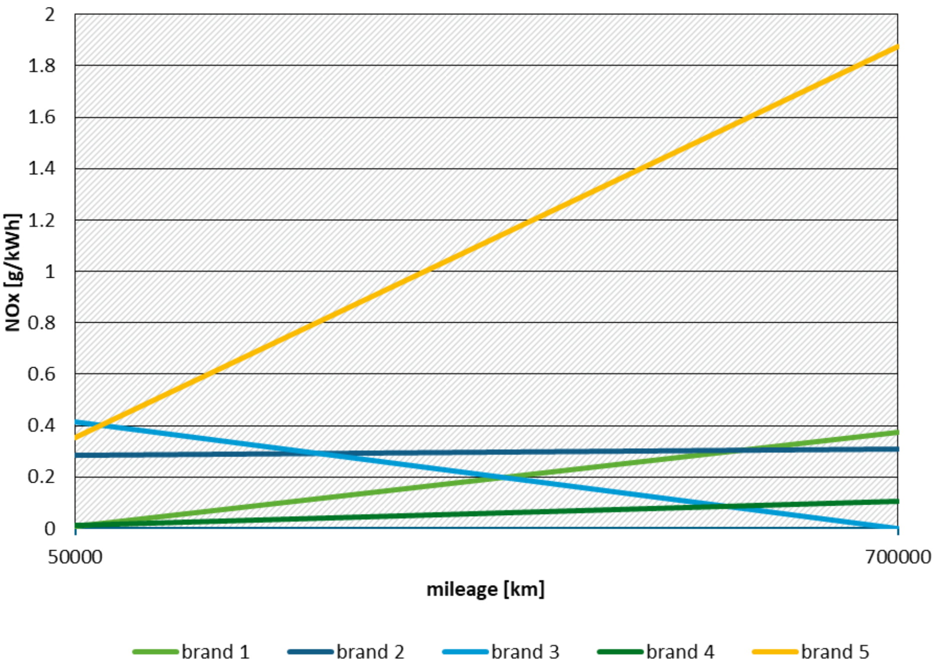


- Brand: the deterioration functions are set up for vehicle pairs of each brand. These functions are illustrated in Figure 23 for the absolute NOx emissions of Euro VI DE long-haul trucks. The sample shows the big spread between the different vehicles in the fleet. In a

[23] The deterioration functions in HBEFA represent hot driving conditions. Latest research shows that deterioration effects are different for cold start and low load driving. This will be a topic for HBEFA 5.2.
[24] The WHVC represents the WHTC, the HDV Euro VI engine test bed, on the chassis dyno.
[25] If no WHVC test was available, ISC test data was used.

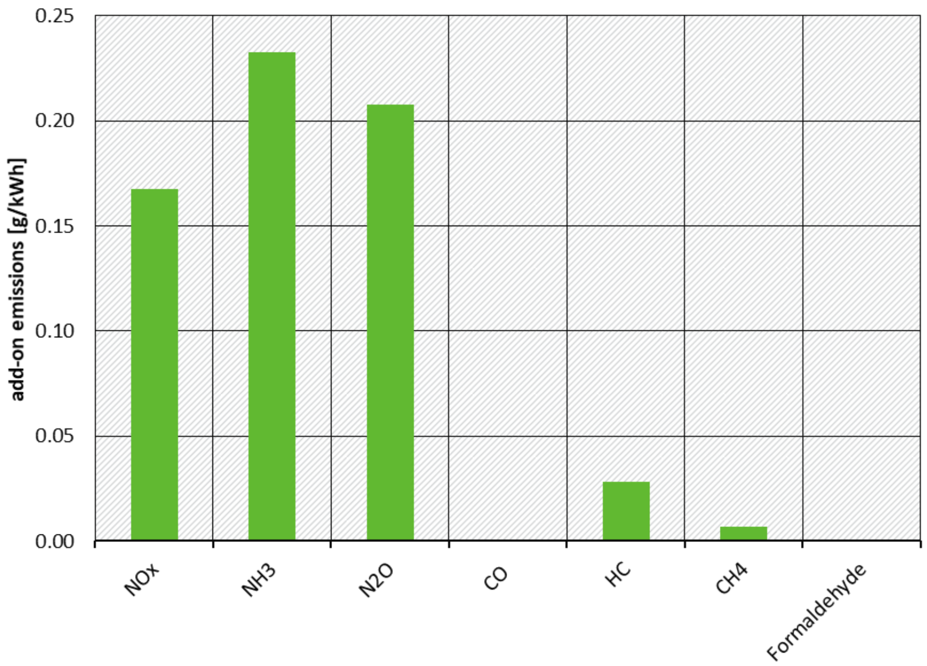
next step these brand specific functions are combined to fleet representative deterioration functions according to the fleet share of each brand in the EU.

Figure 23: Absolute emissions over mileage per manufacturer, NOx, Euro VI DE, long-haul trucks



- Emission components: The combination of particle and FTIR measurement system covers up to 30 different emission components. Not all of them show deterioration effects by mileage and some are on an emission level below the limit of detection of the analysers. Thus, the HBEFA deterioration functions are finally set up for NOx, NH3, N2O, CO, HC, CH4 and Formaldehydes. In addition, a deterioration function for the NO2 to NOx ratio was elaborated. The add-on emissions are shown in Figure 24 for a long-haul truck in a typical rural driving situation. NOx, N2O and NH3 increase most over mileage.

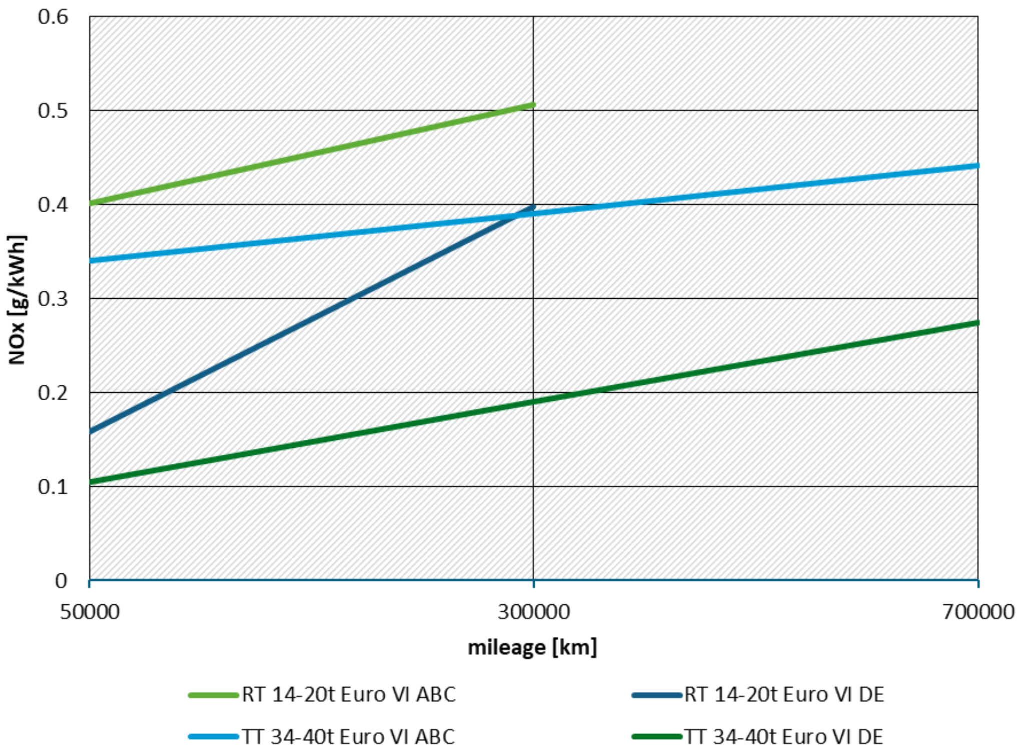
Figure 24: Add-on emissions from 50 000 km to 700 000 km for an average German traffic situation, long haul trucks, Euro VI DE[26]



- Vehicle category: the data set enables a split in rigid and long-haul trucks. Figure 25 shows the different fleet representative NOx deterioration functions for Euro VI ABC and DE split in a rigid truck and a long-haul truck for the average German traffic situation mix. The upper mileage represents the specific maximum mileages, for which emission limits have to be met in in-service conformity (ISC) tests, which is 300 000 km for N2 and N3 < 16 tons gross vehicle weight (GVW) and 700 000 km for all N3 > 16 tons GVW. The base emission factors at a mileage of 50 000 km are higher for rigid trucks compared to long-haul vehicles, but more relevant for this chapter is the higher deterioration for rigid trucks compared to long-haul vehicles. This can be explained with the different mission profiles, which are obviously more challenging for rigid trucks due to a higher frequency of cool down and heat up cycles. In addition, the frequency of DPF-regenerations is higher for rigid trucks due to the lower share of motorway driving including the possibility for passive filter regeneration.

[26] CO and Formaldehyde increases also by mileage due to deterioration in principle, but only in urban driving conditions. This is included in HBEFA by the speed dependent deterioration function.

Figure 25: Fleet representative absolute emissions over mileage for a rigid truck and a tractor trailer, NOx, Euro VI ABC and Euro VI DE, average German traffic situation mix



- Emission standard: According to the categories in HBEFA the Euro VI data was split in Euro VI ABC and DE vehicles. For Euro V no additional test data was available since the last HBEFA, thus the function is not updated. The difference of Euro VI ABC and DE is illustrated in Figure 25.

The emission increase by mileage of all components remains at a constant level when reaching the on-board diagnosis (OBD) threshold. Such a threshold does only exist for NOx looking at Euro V and Euro VI. Reaching this threshold leads to an activation of the motor investigation light (MIL) and consequently to a repair of the entire after-treatment system. Thus, this repair affects all emission components and not only NOx.

These deterioration functions were validated by remote sensing data, so far available. The trends which are based on remote sensing show similar trends for the increase of the NOx emissions over mileage for Euro VI ABC vehicles.

As already explained in chapter 4.7.1, the multiplicative method has changed to an additive one due to the low base emission levels.

4.8. Correction factors for temperature effects for PC and LDV

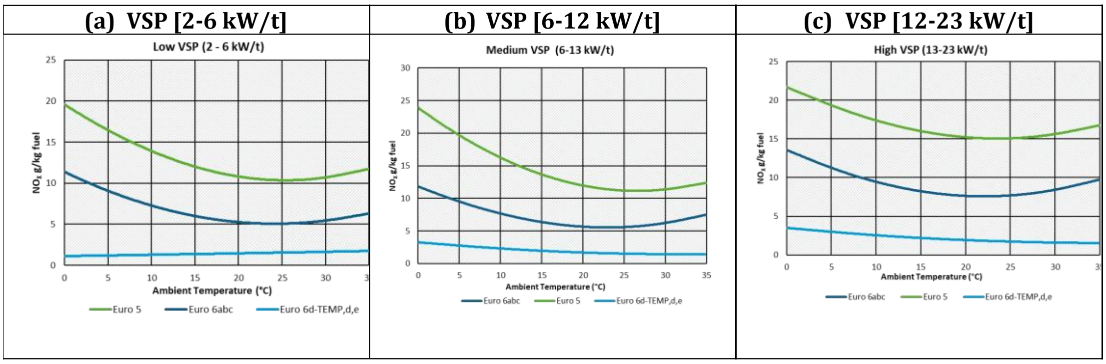
This chapter describes the correction factors for temperature effects for passenger cars and light duty vehicles. The measurement data for HDVs does not show significant temperature effects.

EGR rates need to be reduced at very low and high temperatures to avoid damages on the engine, e.g., due to condensing hydrocarbons and corresponding formation of deposits. Before the introduction of RDE tests with emission limits with EURO 6d-TEMP, several manufacturers of diesel cars reduced EGR rather early and also the dosing of the reagent into the SCR systems was partly reduced outside of the chassis dyno type approval ranges. This leads to increasing NOx emissions with decreasing temperatures from ca. 20°C on. The temperature correction functions consider this effect in the HBEFA.

Temperature corrections notably for NOX emissions from diesel cars and light duty vehicles were already included in HBEFA 4.1. Here, pan-European remote sensing data is used to cross-check. Data is processed as already described in chapter 4.7.1. The important issue is to determine the NOX emissions as function of ambient temperature while controlling for engine load and ageing. Full details are given in Potturu and Borken-Kleefeld 2025. In conclusion, and as seen multiple times before, Euro 5 diesel cars emit least NOX when the ambient temperature is in the range of 20°C to 25°C. The emissions increase however by 80% to 100% when temperature decreases to 0°C for low and medium engine loads (Figure 26). Given significantly higher emission levels at higher engine loads, the rate of increase is smaller. A similar increase of NOX emissions with decreasing ambient temperature is also observed for Euro 6abc diesel cars, i.e. homologated still in the laboratory. Only after on-road homologation tests became mandatory onwards with Euro 6d- TEMP emission standard, the engine and after-treatment are performing fully across the temperature range from 0°C to 30°C.

All this has already been properly accounted for – by linearised correction functions - in HBEFA 4.1. It is hereby confirmed also for recent vehicle generations. Note however that NOx emissions from Euro 5 and Euro 6abc cars tend to increase also when ambient temperatures approach 30°C. This behaviour has not yet been represented in HBEFA.

Figure 26: Average NOx emissions as a function of ambient temperature for diesel cars (Euro 5, Euro 6abc, Euro 6d-TEMP,6d, e) modelled using LinearGAM



4.9. Exhaust emission factors for HEV and PHEV

The model PHEM includes subroutines for electric and hybrid propulsion systems including beside the combustion engine model also a model for the electric motor (consumption map) and for the battery (losses as function of internal resistance) combined with a hybrid control strategy. The hybrid control strategy searches in each time step for the possible combinations of load points of the combustion engine, the electric motor and the transmission for the best possible weighted energy consumption, with restrictions due to drivability, battery life, etc. The weighting factor between fuel and electric energy considers the state of charge (SOC) of the battery.

- The HEV and PHEV model is used to simulate energy consumption, CO2 emissions and non-exhaust emission factors for all vehicle categories.
- The pollutant emissions from HEVs and PHEVs in charge sustaining mode in contrary are taken from the simulation of the corresponding vehicle layer with pure combustion engine drive trains.
- The effect of electric driving from PHEVs on pollutant emissions is considered via shares of pure electric driving with zero pollutant emissions but electric energy consumption from the battery.

The reason for not using HEV and PHEV specific pollutant emission factors is the huge impact of the hybrid control strategy on the simulated pollutant emission factors, since the strategy often results in very different load points compared to conventional vehicles. Consequently, the results for pollutant emissions vary significantly against conventional vehicles in several traffic situations, when the average emission maps from the large sample of conventional cars is used. In contrary, the test results at EMPA and TUG on HEVs and PHEVs show, that the emission levels of the pollutant emissions from PHEVs and HEVs in RDE tests are quite similar to the ones of conventional vehicles.

The reason is that the combustion engines of HEVs and PHEVs in real life have adapted engine controls and thus different pollutant emission behaviour and/or often avoid driving at load points with higher pollutant levels to meet the RDE exhaust emission limits. The real-world hybrid operating strategies seem to vary depending on the brand and type. Taking the average characteristic maps of the limited number of measured PHEVs proved therefore not to be a robust solution either. Compiling a PHEV and HEV strategy with corresponding representative pollutant emission models in PHEM would be a challenging task. From our current perspective, this effort would not pay off for pollutants. For consumption and CO2 as well as for non-exhaust emissions, the hybrid model provides robust and reasonable results for all traffic situations. Electric braking (recuperation) proved to be quite important for the resulting brake wear. These effects yet have not been validated, only plausibility checked due to a lack of test data including brake activations in real driving (see Chapter 4.10.1).

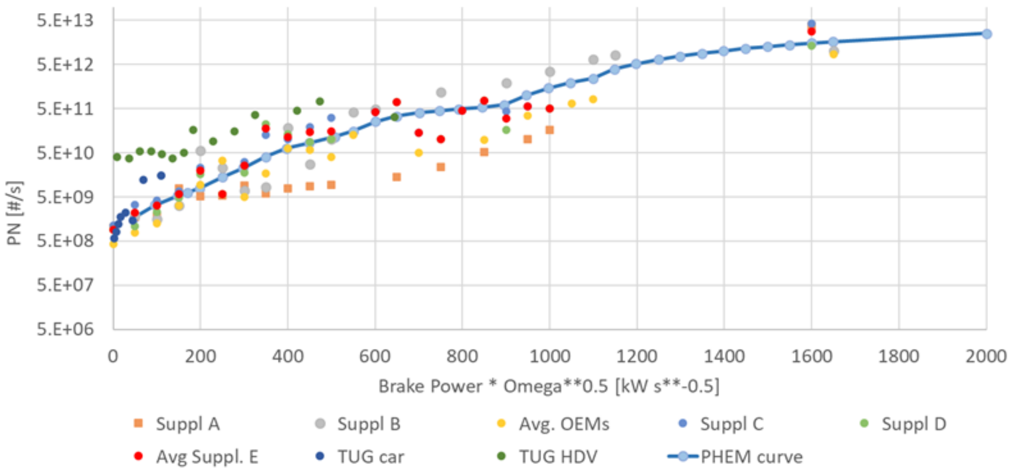
4.10. Non-exhaust emission factors

The model approaches for non-exhaust emission factors are newly implemented in PHEM and allow a better differentiation of the influence of traffic situations and vehicle technologies on the resulting emissions. Effects of road gradients, brake energy in a cycle etc. have not been considered in previous emission factors. A detailed description of the functions and the data uses is given in a study of TU Graz (Hausberger, 2024).

4.10.1. Brake wear emissions

The brake wear PN and PM10 emissions in a driving cycle are interpolated according to the simulated brake power in 1 Hz from the characteristic polygons (Figure 27). The characteristic polygons are averaged from the existing test data, which currently is quite limited (6 different ECE brake disc and pad combinations). To set up the brake polygons, we integrate the brake PN emissions from start of a brake event until start of the following brake event from the instantaneous test records. These brake emissions are then allocated to the brake power and rpm measured during the brake event. This approach gives one data set per brake event. All measured data sets are then sorted into brake power*speed bins, then in each bin the average is calculated.

Figure 27: Brake emission polygons for ECE brake systems and average polygon used for all vehicle segments up to EURO 6/VI in this study



The simulation of the brake power of the friction brakes considers the recuperative braking from electrified vehicles according to the full-load curve of the installed electric motor and possible restrictions in the batteries capacity to store the electric power. For HDVs also the endurance brake is considered, which reduces the remaining friction brake power as function of speed, road gradient and brake energy.

The resulting emission factors meet the average values found for real driving in literature well. A simulation of the WLTP brake cycle with PHEM meets the average of the PM 10 values reported in literature for the WLTP brake cycle (ca. 20 mg/km) almost exactly[27].

However, it is unclear if the average literature data is representative for the average real world mix of brake pad and disc combinations. Furthermore, the existing test data covers only seven LDV and one HDV brake systems. Overall the uncertainty of simulated brake emission factors is certainly significantly higher than for exhaust emissions while brake emissions already contribute much more to PM 10 and PM 2.5 from road traffic than exhaust particles.

Therefore, more test data shall be collected systematically to extend the data base for the brake emission polygons and to further improve the model for HBEFA 5.2. In a next version, assuming that sufficient test data will be available, the influences of rotational speed and bake power should be considered by a brake emission map instead of a polygon and off-brake

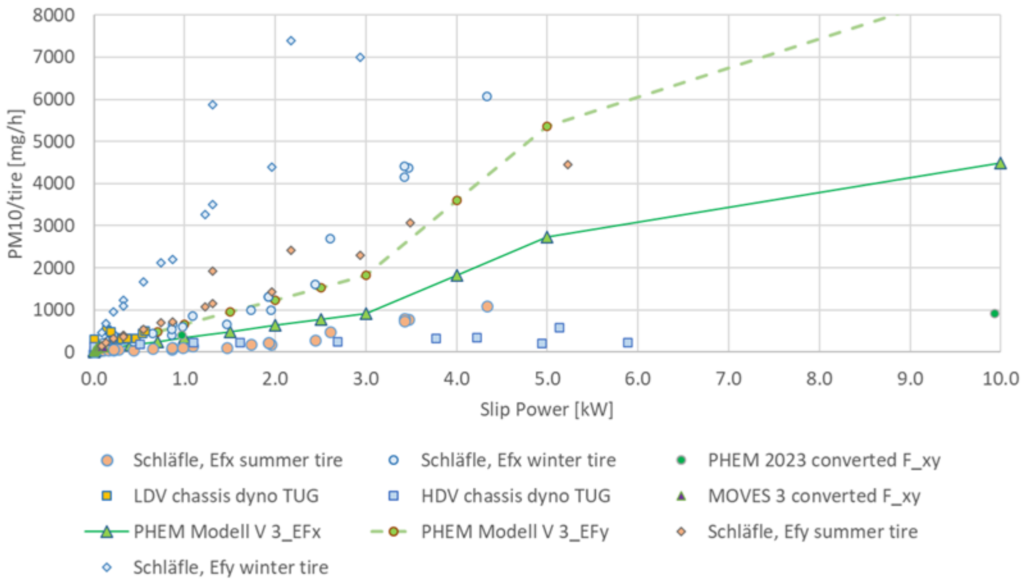
[27] Hausberger, S., Landl, L., Ketan, E., “Messung und Simulation von Non-Exhaust Partikelemissionen”, report number: I-01/25/Hb-EM-Inst-23/04/30-670, January 21, 2025.

emissions shall be considered separately as function of the rotational speed. For higher brake power, also the disc temperatures should be considered.

4.10.2. Tire wear emissions

Tire wear is simulated as function of the slip-power, which represents the power in longitudinal- and lateral direction multiplied with the relative speed between road and tire (slip). This parameter showed the best correlation to PM and PN emissions in the available test series. The slip power in a driving cycle is simulated in 1 Hz and the corresponding tire wear is then interpolated from the characteristic tire wear polygons for PN and for PM10 (Figure 28). The average tire wear polygons are based on test data on six tires, where the measured tire wear is binned in slip power classes. Then in each slip power class the average per tire is calculated. Test data shows higher emission rates in lateral direction than in longitudinal direction. For reasonable lateral slip power simulation, a generic function was developed, which allocates a representative radius as function of the actual vehicle speed. Users, who want to simulate tire wear on straight roads only, should reduce the HBEFA 5.1 tire wear emission factor by 65%.

Figure 28: Characteristic tire wear polygons for PM10 emissions due to longitudinal (EFx) and lateral slip (EFy) for simulation in PHEM, as well as available measurement and literature data



The resulting emission factors meet the average values found in literature well (Hausberger, 2024).

As mentioned already for brake wear emissions, it is open if the six measured tires used to produce the characteristic emission polygons represent the fleet average and also the average of literature data is not necessarily representing fleet average emissions for average driving behaviour. For tires additional uncertainties result from the test methods. Drum tests, which are the source for the test data we used in the model, lack of road dust in friction pairing, and partly have differences in their surface and temperature compared to real roads. On-road tests typically collect beside tire wear also road- and brake wear and resuspended particles. Thus, tire wear emission values can hardly be extracted from this mix. As basis for larger measurement campaigns on tire wear, further research on representative test conditions is recommended.

Beside the optimisation of test procedures, also more test data shall be collected in a systematic way. More test data is especially needed in low power conditions, typical for non-driven rear axles, to consider also internal friction in the tires as parameter to explain tire wear, if it proves to be a relevant influence.

Nevertheless, the new model for tire wear in HBEFA 5.1 seems to be a significant improvement compared to other emission factor sources and allows an easy extension with more test data in future, similar to the method used for exhaust emissions.

4.10.3. Road wear emissions

Test data and literature indicate, that road wear is caused by the same mechanism as tire wear. Therefore, the road wear emission factors are simply calculated from the tire wear simulation results using fixed factors. For PM10 road wear is set to 1.5 times the tire wear, for PN the factor is 0.1.

4.10.4. Resuspended particle emissions

The resuspended particles are simulated as function of the dust load on the road, the kinetic energy (resuspension due to turbulent air flow) and the slip power between tires and road (mechanical resuspension). The parameters have been calibrated to meet average vehicle speed dependencies found in literature. No specific measurement campaigns have been performed for the HBEFA update.

It has to be noted, that we used a constant value for the dust (silt) load on the road for each road category. For rural roads the dust load is 1/3 lower than for urban roads, for motorways it was set ca. 75% lower than for urban roads. These factors represent the effect, that with higher traffic densities mor dust from the road is resuspended and thus less particles per vehicle remain on the road to be resuspended. This effect is more pronounced at higher velocities due to higher resuspension rates per car with increasing speed and wheel power. However, the situation depends a lot on local road, traffic and weather conditions and can deviate significantly from the emission factors calculated with the averaged data.

4.11. Gasoline evaporation emission factors

4.11.1. Background and objectives

Evaporation emissions occur from petrol-fuelled vehicles and only include hydrocarbons (i.e. HC and HC components). HBEFA implements the Tier 3 methodology described in the EMEP/EEA Emission Inventory Guidebook that was developed for the COPERT model to calculate evaporation EF. The input data regarding ambient and traffic conditions are HBEFA-specific and do not correspond to the data suggested in the EMEP/EEA Guidebook. Therefore, the evaporation EF from HBEFA can differ from those in COPERT in spite of using the same methodology.

The previous HBEFA Version 4.2 implemented the 2016 version of the "Gasoline evaporation" chapter of the EMEP/EEA Emission Inventory Guidebook (Mellios et al. 2016). With HBEFA 5.1, evaporation has been updated to the latest available EMEP/EEA Guidebook version (Mellios et al. 2024). The new version differs from the previously implemented version in the following respects:

- Low degradation carbon canisters are assumed for all Euro-6d and newer vehicles. These lose less capacity over the lifetime of the vehicle (4% to 9%, instead of 12% to 20% as the "high degradation" carbons);
- Higher canister purge rates during driving are assumed for Euro-6d and newer vehicles (see Eq. 14 in Mellios et al. 2024);
- New permeation rates are given in Tab. 3-10 of current EMEP/EEA Guidebook (Mellios et al. 2024). These include small leakages, which were calculated separately in previous versions;
- Updated fuel tank and canister sizes for various vehicle types are suggested in Table 3-13 of the current EMEP/EEA Guidebook. These have been adopted for HBEFA 5.1.

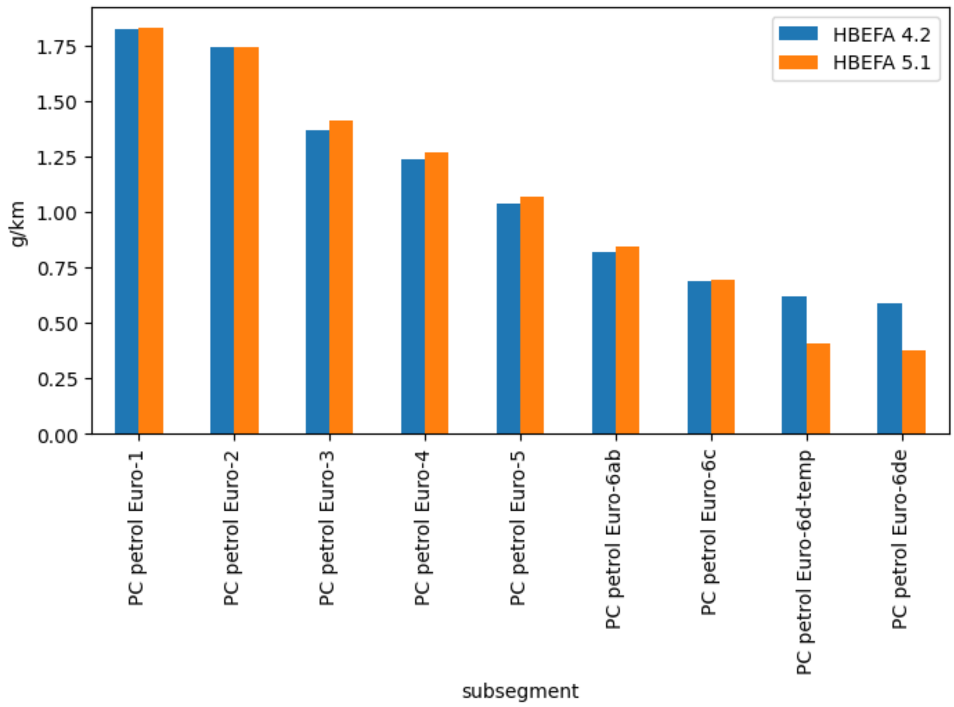
Besides these changes in the COPERT methodology, evaporation emission factors in HBEFA 5.1 are also affected by new data model of ambient condition patterns introduced due to the cold starts of HDV (see Chapter 5.2). This allows specifying different driving behaviour patterns (trip length, parking time, traffic distribution over the day) for different vehicle types; the changes in these patterns cause some changes in evaporation emission factors.

4.11.2. Effects on emission factors

All in all, the evaporation methodology updates result in reduced evaporation EF for newer vehicles (Euro-6d and newer, see e.g. Figure 29). Emission factors for older vehicles also differ between the two versions due to the different driving behaviour distributions used (see above) – in some cases the new emission factors are somewhat higher and in other cases lower.

In the latest COPERT update, leakages are not accounted for separately anymore – they are now included in the permeation rates expressed in g/h (Table in 3-10 in Mellios et al. 2024). In the HBEFA implementation of the COPERT methodology, leakages are assigned to the "evaporation diurnal" emission category. Since all vehicles with fuel injection (i.e. all LDV from Euro-1) only had leakage losses as cause of "evaporation soak" and "evaporation running losses" emissions, and these are now included in permeation (and thus the "evaporation diurnal" category), **"evaporation soak" and "evaporation running losses" EF are now zero for all LDV Euro-1 and newer**. The option to assign permeation from some time after stopping to "soak" and for the driving time to "running losses" was examined, but it would have lead to redundancy in the code, and it would have not been consistent, since also all losses via the canister are assigned to "diurnal" evaporation, regardless of whether they take place during driving or parking.

Figure 29: Diurnal evaporation HC emission factors for petrol passenger cars.



Graphics by INFRAS. Source: HBEFA 4.2/5.1

4.12. Emission factors from other sources

Emission factors based on other sources than those described above include:

- NH3, N2O: Emission factors up to Euro 6c (for LDV/MC) and up to Euro VI A-C (for HDV) are based on the EMEP/EEA Emission Inventory Guidebooks
- HC components (CH4, NMHC, Benzene, Toluene, Xylene): Shares in HC up to Euro 6c (for LDV/MC) and Euro VI A-C (for HDV) are based on various sources (see e.g. INFRAS et al. 2019, Chapter 11)
- BC: Shares of BC in PM2.5 (exhaust) are based on the EMEP/EEA Emission Inventory Guidebooks
- Zn, Cd (exhaust): Fuel contents are based on the EMEP/EEA Emission Inventory Guidebooks
- CO2, Pb, SO2: Fuel contents by country, fuel type, and year are updated by each country in the course of the country data updates (see Chapter 5)
- For Formaldehyde (HCHO), Acetaldehyde (CH3CHO), Isocyanic acid (HNCO) and Nitrous acid (HNO2), test data was available from Euro 6 and VI LDVs and HDVs onwards since FTIR analysers were not used in test campaigns before. The emission factors for Euro 0 to Euro 6 / VI are calculated using constant “segment-factors” for each Euro-class, separated for HDV

and LDV and separated for gasoline and diesel engines. The emission factors simulated with the model PHEM for Euro 6d-TEMP and Euro VI DE for HDV are multiplied with these segment-factors to produce the emission factors for all older vehicle segments per traffic situation.

Table 13: Country-independent emission factors based on other sources than those described in Chapters 4.1 to 4.11: Updates in HBEFA 5.1

Pollutants	Updates for HBEFA 5.1
N2O, NH3	▪ EF for Euro 5 and 6 passenger cars and LDV were updated (their EFs were previously set equal to Euro 4) based on EMEP/EEA 2023. However, in HBEFA 5.1, only EMEP/EEA factors up to Euro 6abc are used, since from Euro 6d-temp/VI DE onwards, base EF from PHEM are available for petrol and diesel vehicles. ▪ EF from own dedicated studies (input from ifeu, TU Graz for HB41) were retained
BTX % in HC	▪ New fractions are available in the EMEP/EEA guidebook for Euro 5 and higher (Table 3-90b); however, kept current values of HB4.1 for Euro 4-6 that are based on more specific studies (Louis et al 2016, Liu et al 2017, see Development Report HBEFA 4.1)
BC share in PM2.5	▪ No updates for HB5.1
Cd-ex, Zn-ex	▪ Exhaust EF were updated for all countries based on EMEP/EEA 2023
HCHO, CH3CHO, HNCO, HNO2	▪ "Segment factors" for Euro classes before Euro 6 /VI are derived from single tests available from literature and tests at TUG, (Heidt, 2025)[28]

5. Country data

5.1. Overview/methodology

The country data collection process for HBEFA 5.1 was similar to that of HBEFA 4.1 and 4.2. In the first step, the excel template used to gather country specific data was updated and pre-filled with the most recent data available for each country. Countries then had the opportunity to either make their changes in this excel template and read the updated template back into HBEFA, or to update the data directly in via the main front end. This is a deviation from previous HBEFA versions. In the past, countries returned their completed data templates to INFRAS, who then performed the work of inserting the data into HBEFA. In the newly migrated version of HBEFA, with a central server architecture, this is no longer needed. Country data providers can now update their own datasets, either with the template, or directly in the user interface.

[28] Heidt C., et.al.: Nationale und internationale Abgasgesetzgebung bei Pkw, leichten und schweren Nutzfahrzeugen; Hrsg. Umweltbundesamt Deutschland,, 2025

5.1.1. Inputs to HBEFA fleet model

The following is a summary of the most important country specific data that is required by HBEFA 5.1:

- Vehicle stock (for historic period, or optionally for entire timeseries)
  - Absolute number by vehicle category
  - Share by segment including age distribution
  - Share with DPF by segment, including age distribution
- New registrations (for projected time period, if vehicle stock not provided for future)
  - Absolute number by vehicle category
  - Share by segment including age distribution and survival probability
  - Share with DPF by segment
- Traffic activity (at vehicle category level)
  - Annual mileage per vehicle
  - Share of driving per road category (URB/RUR/MW)
  - Traffic situation distributions
  - HGV transformation patterns (shares of trucks that are registered as one segment, but drive as another, for example, a rigid truck that drives with a trailer as an articulated truck.
- Traffic activity (at segment level)
  - Share of driving per road category (URB/RUR/MW)
  - Age dependency of annual mileage by road category
  - Load patterns by road category
- Traffic activity (Either at vehicle category or segment level)
  - Distribution of driving throughout the day, parking times, and trip lengths
- Introduction schemes of emission concepts
- Energy efficiency
  - Calibration values for vehicle energy consumption, including real-world excess
- Technology mixes
  - For multi-technologies (e.g. CNG-petrol bi-fuels, PHEVs), shares of vehicle kilometres travelled on each technology
  - EGR/SCR split for HGV
  - Shares of diesel Euro 5 and Euro 6ab passenger cars with software updates
  - Shares of high-emitting heavy-duty vehicles with tampered (for NOx control devices)
- Fuel quality, i.e. CO2, SOx, Pb emission factors by fuel type
- Fuel mix i.e. shares of fossil fuels/biofuels by fuel type
- Share of charging station type for electric vehicles (relevant for charging losses)

- Distribution of vehicle kilometres by traffic situation and gradient, by vehicle category

Compared to HBEFA 4.2, the most important changes to the set of required data are

- Energy efficiency
  - CO_2 monitoring and real-world excess can now be entered separately into HBEFA, making assumptions more transparent
  - Values can be entered separately for each base energy, so that multi-fuel technologies such as plug-in hybrids can be modelled more accurately
- Trip length and parking time distributions can now be added at either the vehicle category or segment level, instead of having one set of distributions for all vehicle categories.
- Energy mix scenarios are no longer required, as HBEFA 5.1 does not calculate well-to-tank emissions

In order to improve consistency across all HBEFA countries, guidelines and suggested inputs were created by the HBEFA working group for some important country data inputs. Country data providers were encouraged to follow these guidelines, but were allowed to deviate provided there was a good reason for doing so. The following country datasets were harmonised for HBEFA 5.1:

- Technology shares in future new registrations.
- Energy efficiency scenarios: CO_2 monitoring values and real-world excess
- Introduction dates for Euro 7
- Technology mixes
- Software updates
- Shares of tampered high-emitting heavy-duty vehicles

5.1.2. Fleet model outputs

Once the country specific inputs are completed, the HBEFA fleet model calculates the share of vehicles and mileage of each subsegment for each year. These are the basis for weighted emission actor queries and can be viewed in the HBEFA application under the heading Fleet --> Analyse fleet composition.

5.2. Adapted data structures for cold start and evaporation inputs

The fact that cold start extra emission factors became available for HDV with HBEFA 5.1 necessitated a change in the data model of “ambient condition patterns”.

Up to HBEFA 4.2, “ambient condition patterns” contained climate data (mainly temperature distributions), fuel data (Reid Vapour pressure, RVP), and also driving behaviour data such as the distribution of traffic volumes over a typical day, trip length distributions and parking time distributions. An "ambient condition pattern" typically consisted of four seasonal subpatterns, and trip length and parking time distributions could be varied for every hour of a typical day in every season. It was not possible, however, to use different driving behaviour patterns for different vehicle types. This was an acceptable simplification as long as cold starts were only available for LDV.

With cold starts available for HDV as well, it would not be acceptable anymore to assume the same driving behaviour for all vehicle types. Therefore, the data model has been extended so that different driving behaviour patterns can be assigned to different vehicle types via the fleet model. This is the new default in HBEFA 5.1. This is done via the fleet composition data (see last subchapter "Traffic and ambient conditions" of each country chapter below) for "weighted" emission factor queries. For "unweighted" queries, default driving behaviour patterns are assigned to each vehicle type independently from country-specific fleet data.

Besides the patterns describing average conditions per country, there are also patterns that allow querying cold start EF for specific temperatures, parking times, or trip lengths. For these, a flat distribution is assigned to the respective temperature, parking time, or trip length, and the distribution is directly linked to the ambient condition pattern (so it is not taken from the fleet composition or the default data per vehicle type). Such patterns can be recognized by the value "True" in the columns "distrib_traffic_from_pattern", "parkingtime_from_pattern", or "triplength_from_pattern" in menu *Traffic conditions > Ambient condition patterns.*

5.3. Derivation of high emitter shares (all countries)

This chapter illustrates the derivation of the high emitter shares for HDV in NOx emissions and gives a short overview on the work done for PN high-emitters. This analysis covers all countries.

5.3.1. HDV NOx high-emitters

Plume chasing measurements find a significant share of high-emitting heavy-duty trucks notably on highways[29]. High emitters have (NOx) emissions above level reached by ordinary ageing[30] without defects[31] or active manipulation (see chapter 4.7.2).

These high emitting vehicles come along with significantly increased NOx emissions due to defects or active manipulation of the SCR system. The emission level of defect or manipulated

[29] Most studies are performed by D. Pöhler, e.g. (Pöhler et al., 2023)
[30] Standard ageing: chemical, thermal or mechanical effects
[31] OBD has to identify emission increasing defects and has to activate the MIL (motor investigation light) in such cases. Thus, defects have to be repaired short-time after occurring and do not lead to long-time high emissions. However, manipulation software can be used to deactivate the MIL without repairing the system. This leads to long-time high emissions and represents the defects mentioned in this chapter.

vehicles is the same as the measured engine out level in HBEFA. Looking at Euro V, a high-emitting vehicle emits 5 times more NOx than the fleet average of new and well-functioning vehicles in motorway driving. For Euro VI ABC this factor is 15 and for Euro VI DE at 68 due to lower base emission factors. The Euro 7 factor is even at 189 based on the very good performance of Euro 7 emission reduction systems and thus low emission level of well-functioning vehicles.

Country specific high emitter shares for trucks and coaches are introduced in HBEFA 5.1 for the first time. It was not part of the former versions. There is no data available for urban buses and consequently no high emitter shares defined.

Table 14 gives an overview on all available plume-chasing test data, which is the base for the following high-emitter analysis. The table includes the number of test vehicles and the share of high-emitting HDVs. The column "comment" shows that the vehicle selection is not fleet representative in all cases. Some studies focused on Eastern European vehicles due to the expectation of a higher share of high-emitters, see results for Slovakia or the Czech Republic. The Austrian data shows this fact also if one compares the higher value for 2018 with focus on Eastern European vehicles to the value for 2022 without specific vehicle selection.

Based on that data, it was decided to derive one specific high emitter share for Western Europe (WE) and one for Central Eastern Europe (CEE), see the last two lines of the table. Germany is used as base for Western Europe, because Germany gives the most representative picture for that case taking the available data into account. The result weighted according to the number of test vehicles and only using the two most recent studies of 2022 and 2023[32] lead to a high-emitter share of 22.0 % for Euro V and 3.4 % for Euro VI. CEE is defined as the weighted average of the high-emitter shares of Czech Republic and Slovakia resulting in 38.4 % for Euro V and 10.2 % for Euro VI.

[32] The study for Germany in 2019 does not include information on the fleet representativeness. Thus, it is excluded.

Table 14: Overview on available plume-chasing test data for high-emitter HDVs

country	Euro V		Euro VI		Comment
	number of test vehicles	% high-emit-ters	number of test vehicles	% high-emit-ters	
Slovakia (2023)	324	36.0%	1142	12.0%	real world fleet representative ve-hicle selection
Czech Republic (2023)	24	50.0%	104	13.0%	real world fleet representative ve-hicle selection
Germany (2023)	9	22.0%	122	2.0%	real world fleet representative ve-hicle selection
Austria (2022)	27	41.0%	279	6.0%	
Germany (2022)	32	22.0%	302	4.0%	real world fleet representative ve-hicle selection
Czech Republic (2022)	145	42.0%	746	7.0%	real world fleet representative ve-hicle selection
Belgium (2021)	82	29.0%	484	3.0%	
Denmark (2020)	97	9.0%	357	2.0%	vehicle selection focused on East-ern European vehicles --> does not represent the real-world fleet
Germany (2019)	40	18.0%	100	6.0%	
Austria (2018)	48	29.0%	137	10.0%	vehicle selection focused on East-ern European vehicles --> does not represent the real-world fleet
Germany (2016)	102	15.0%	68	1.0%	vehicle selection focused on East-ern European vehicles --> does not represent the real-world fleet
WE	424	22.0 %	41	10.2 %	Weighted average of G 2022 and 2023
CEE	1992	38.4 %	493	3.4 %	Weighted average of CZ and SK

In a next step, the high-emitter fleet shares for HGVs and coaches for HBEFA 5.1 are calculated by combining these WE and CEE high emitter shares with mileage-based fleet shares for WE vehicles and CEE vehicles for the specific countries. The results are illustrated in Table 15.

The Austrian fleet share contains 45 % WEV and 55 % CEEV based on data from statistic Austria. This high share of the Eastern European fleet results in the highest values with 31.0 % for Euro V and 7.1 % for Euro VI. For France the Belgium data was also taken into account as representative. The HBEFA 5.1 value is the weighted average of WE and BE. Germany is exactly the WE value, of course. The fleet shares of Norway[33] (17 % CEE, 83 % WE) lead to a weighted high-emitter share of 24.8 % for Euro V and 4.6 % for Euro V. The numbers for the fleet share

[33] https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/godstransport-med-lastebil/artikler/mindre-frakt-med-utenlandske-lastebiler

of Sweden from SwedStat are 11 % CEE and 89 % WE. This leads to high emitters shares of 23.8 % respectively 4.2 %. Switzerland is a special case. It has a quite stringent on-road control regime and a low share of transit traffic compared to other countries like Germany. However, data of the on-road controls was available only for Euro VI (3.0 %). For Euro V it was decided to take the value of Denmark, because Denmark has also a very well-functioning control of tampering similar to Switzerland (9.0 %).

With the introduction of OBM in Euro 7 a better fleet surveillance is expected. This leads to the assumption that the numbers of high-emitters for Euro 7 are half the Euro VI numbers. This assumption is valid for all countries.

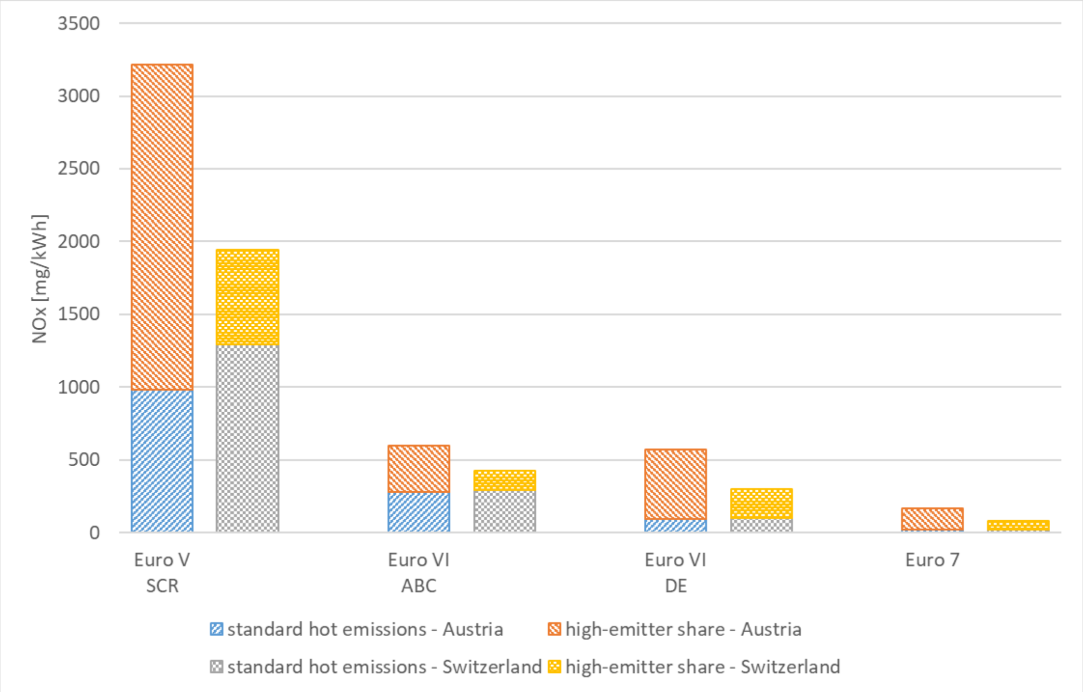
Table 15: high-emitter fleet shares for HGVs and coaches in HBEFA 5.1

country	Euro V SCR	Euro VI[34]	Euro 7
Austria	31.0%	7.1%	3.6%
France	26.7%	3.2%	1.6%
Germany	22.0%	3.4%	1.7%
Norway	24.8%	4.6%	2.3%
Sweden	23.8%	4.2%	2.1%
Switzerland	9.0%	3.0%	1.5%

Combining the share of high emitting vehicles and the related emission factors leads to an increase of the fleet emissions shown by Figure 30 for a tractor trailer combination in average driving for Austria (worst case in terms of tampering shares) and Switzerland (best case). The results show a share of high-emitters on the total emissions of 69 % for Austria and 33 % for Switzerland looking at Euro V. The shares are 53 % (Austria) respectively 32 % (Switzerland) for Euro VI ABC and raise to 84 % and 68 % for Euro VI DE. Euro 7 brings another increase to 88 % for Austria and 74 % for Switzerland, although the high-emitter fleet shares are only at 3.6 % for Austria and 1.5 % for Switzerland. The increase of the shares of Euro VI DE and especially Euro 7 can be related to the very good performance of the exhaust aftertreatment systems with NOx reduction rates of more than 99 % in best operation conditions. A malfunction or tampering of these systems leads to a significant increase of the emissions.

[34] The plume chasing data does not enable a distribution in Euro VI ABC and Euro VI DE. Thus, the tampering shares for Euro VI ABC and DE are the same.

Figure 30: NOx fleet emissions – standard emission factors + high-emitter emissions, tractor trailer combination, average driving



The data for high-emitter shares comes along with some uncertainties so far and demands additional research work for HBEFA 5.2. Beside more representative data for all countries, the introduction of an age dependent tampering share seems to be a relevant topic.

5.3.2. PN high-emitters

PTI tests show a significant share of defect or manipulated particle filters. This is not only the case for HDV, but also or even more so for passenger cars. However, the data comes along with high uncertainty so far and the topic needs more research work. Consequently, the implementation of a share for high-emitters with respect to particle emissions is deferred to the next HBEFA version.

5.4. Switzerland

Switzerland’s country data were significantly updated for HBEFA 5.1. The following subchapters provide more details about the changes made.

5.4.1. Vehicle stock

The vehicle stock from 2010 to 2024 were recalculated using national statistical data[35]. Vehicle stock data before 2010 were, in some cases, also adapted to improve consistency. New registration data from 2025 to 2060 are based on assumptions by INFRAS and discussions with the Federal Offices for Energy and the Environment as well as the HBEFA working group.

5.4.2. Traffic activity (mileage, starts/stops)

Vehicle traffic activity at the vehicle category and segment level were also completely reworked compared to HBEFA 4.2 to improve consistency. Sources for this were vehicle mileage data in the national registration database[36], National statistics[37], and data from the heavy goods vehicle charge database[38]

5.4.3. Energy efficiency

Energy efficiency assumptions for light duty vehicles were also completely reworked based on NEDC and WLTP consumption data for newly registered vehicles[39] and their shares in the new vehicle fleet[40]. These data were adapted to consider “real-world” fuel consumption values using on-board fuel consumption monitoring (OBDFCM)[41], and discussions between the HBEFA 5.1 workgroup and Jan Dornoff from the ICCT. Furthermore, these data were calibrated so that the overall fuel consumption data calculated by HBEFA was comparable to national fuel sale statistics. Efficiency improvements for future vehicles in all vehicle categories were developed by INFRAS and TU Graz as part of the HBEFA 5.1 work programme.

5.4.4. Sub-technology scenarios (tampered/high-emitter shares, software updates, utility factors etc)

Assumptions for software update shares of diesel passenger cars were updated compared to HBEFA 4.2 using shares from the German Office for the Environment from November 2024.

Assumptions for the utility factors for LDV plug-in hybrids remain unchanged compared to HBEFA 4.2 and are still based on the ICCT white paper from 2020[42].

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[35] https://opendata.astra.admin.ch/ivzod/1000-Fahrzeuge_IVZ/
[36] https://opendata.astra.admin.ch/ivzod/1000-Fahrzeuge_IVZ/
[37] https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/verkehrsinfrastruktur-fahrzeuge/fahrzeuge/strassenfahrzeuge-bestand-motorisierungsgrad.html; https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/personenverkehr/leistungen.html
[38] Heavy goods vehicle charge (HGVC) - FOT
[39] https://opendata.astra.admin.ch/ivzod/2000-Typengenehmigungen_TG_TARGA/
[40] https://opendata.astra.admin.ch/ivzod/1000-Fahrzeuge_IVZ/1200-Neuzulassungen/
[41] https://circabc.europa.eu/ui/group/4cf23472-88e0-4a52-9dfb-544e8c4c7631/library/09779f26-940a-420f-857e-985b6ca62ad9/details
[42] https://theicct.org/wp-content/uploads/2021/06/PHEV-white-paper-sept2020-0.pdf

Shares for tampered/high-emitting heavy goods vehicles are:

- 9% for Euro V: This value is based on campaigns in Denmark. For Switzerland, police inspections discovered 1% of proven tampered Euro-V HGV – but this includes only vehicles in which a tampering device was actually found. The actual value of high emitters (including tampered vehicles in which the device could not be found, and defective vehicles) is likely closer to the value of Denmark, where frequent police controls happen as well.
- 3% for Euro VI: This value is based on an analysis of OBD data, remote-sensing campaigns, and police controls in Switzerland, and corresponds quite well with the Danish high-emitter share for Euro VI (2%);
- 1.5% for Euro-7 (assumption: 50% of the Euro-VI share as agreed by the HBEFA work group.

5.4.5. Traffic and ambient conditions

Swiss traffic conditions for HBEFA 5.1 were completely updated. Trip length and parking time distributions for passenger cars and motorcycles of different size classes were created using detailed data from the Swiss Microcensus 2015[43] (Data from the newest Microcensus were not used due to the potential influence of the Covid-19 pandemic on traffic patterns). Trip length and parking time distributions for light commercial vehicles were estimated using data from the Light Commercial Vehicle Survey results from 2013[44], while for heavy goods vehicles, data from the goods transport survey 2019[45] were employed. For the foreign heavy goods vehicle fleet the trip length distribution for Germany for RT12t and TT/AT is used. Parking time and trip length distributions for Urban Buses were created using on expert judgement based on data for several Swiss public transport operators. No data for coaches were available, so their trip length and parking time distributions were derived from heavy goods vehicles using expert judgement.

No changes to temperature distributions were made compared to HBEFA 4.2.

5.5. Austria

The Austrian country data was updated with current registration data up to 2023. A rather conservative development of electric vehicles was assumed as a forecast for the future, assuming some allowances for renewable liquid fuel use. For cars and LCVs, the BEV shares in new registrations are limited to 90% from 2035 on. For rigid trucks the limits used are 75%, for Articulated

[43] https://www.are.admin.ch/dam/are/en/dokumente/verkehr/dokumente/mikrozensus/verkehrsverhalten-der-bevolkerung-2015.pdf.download.pdf/Verkehrsverhalten%20der%20Bev%C3%B6lkerung%202015_en.pdf
[44] https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/erhebungen/lwe.html
[45] https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/erhebungen/gte.html

trucks and tractor trailers 50%, for coaches 68% and for urban buses 95%. The maximum electrification rate is assumed to be 50% for motorbikes and 65% for mopeds.

5.5.1. Vehicle stock

The Austrian Vehicle Stock is based on national statistical data up to 2023. New registration data from 2024 to 2050 are based on the trend scenario for national emission reporting “WEM” (With Existing Measures) of UBA Austria and TUG. The detailed fleet composition for WEM was calculated with the model NEMO.

For motorcycles 2-Stroke and 4-Stroke engines are considered in three displacement classes (<50ccm, >=50 - <250ccm and >250ccm). Minicars and quads are not considered for Austria in the HBEFA 5.1 due to a lack of detailed registration data. This might be changed in future updates.

5.5.2. Traffic activity (mileage, starts/stops)

The traffic activities consider specific yearly mileages per vehicle differentiated according to vehicle category, size class and vehicle age. The data is based on the evaluation of the ZDB (zentrale Datenbank), which contains the age and cumulated mileage from all vehicles registered in Austria from their periodical technical inspection (PTI). The total mileages per vehicle segment and per Euro class have been calculated with the model NEMO using these updated data sources.

5.5.3. Energy efficiency

Efficiency improvements for future vehicles in all vehicle categories were developed by INFRAS and TU Graz as part of the HBEFA 5.1 work programme.

5.5.4. Sub-technology scenarios (high-emitter shares, software updates, utility factors etc)

No new data is available on the share of software updates and utility factors compared to HBEFA 4.2. For the share of high-emitters (tampered and malfunctioning vehicles), see Chapter 5.3.1.

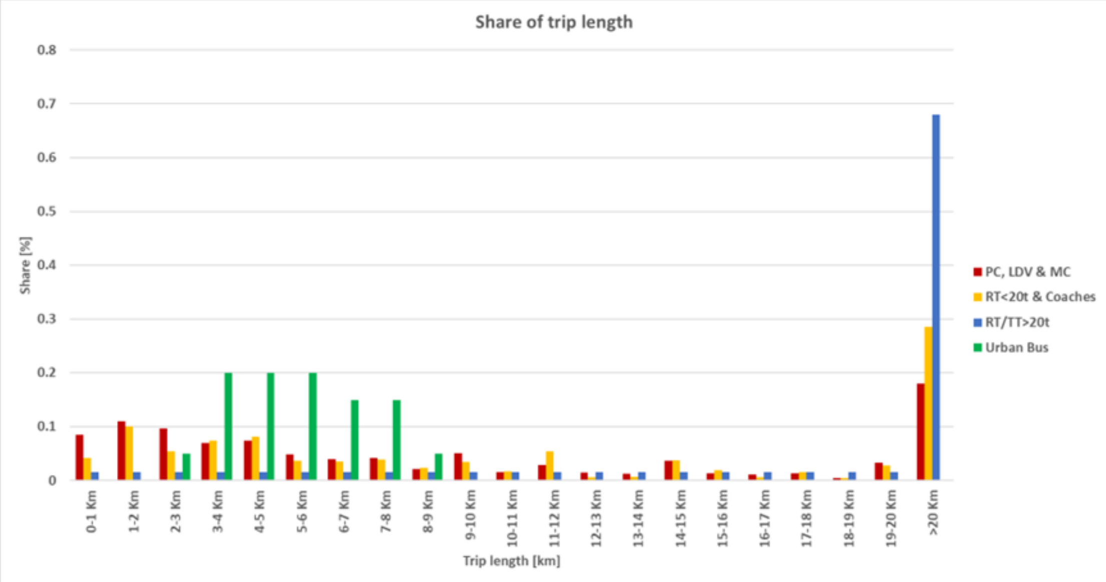
5.5.5. Traffic and ambient conditions

Trip length

The trip length for passenger cars, light duty vehicles and motorcycles are used from Germany since no corresponding data source and no study dedicated for Austria is available.
For HGV trip length distributions, the data from Germany was used as basis. Details have been adapted by an expert judgment by TUG. The trip length distributions are divided into the classes,

"RT<20t & Coaches" and "RT/TT>20t". For the urban buses the trip length distribution results from an expert judgment by TUG assuming typical route lengths, but with only short stops between rotations.

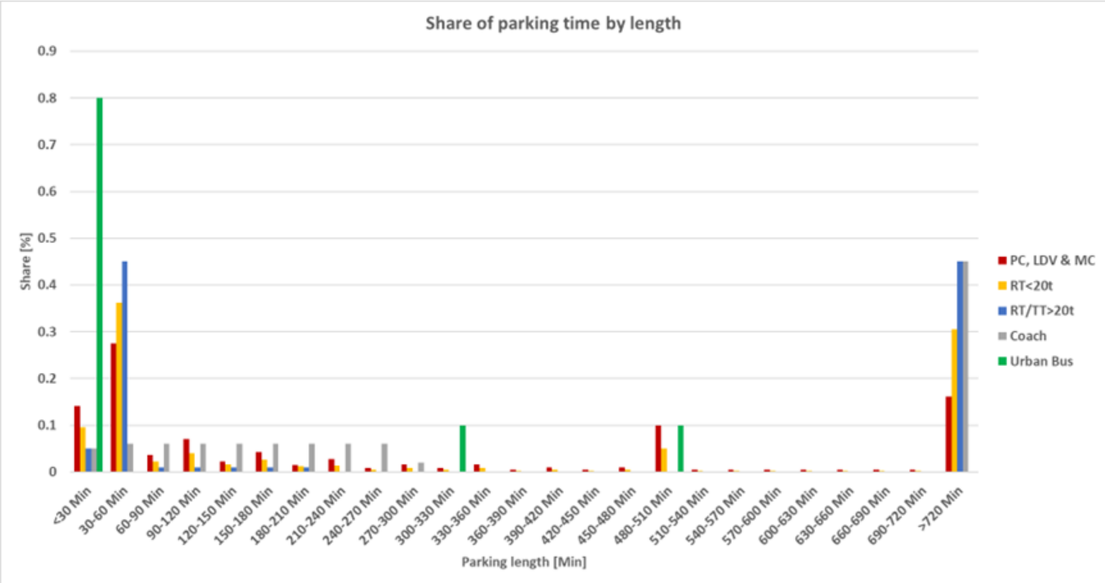
Figure 14: Trip length distributions used for AT in HBEFA 5.1.



Parking time

For the parking time distributions of cars and LCVs no new data is available so the HBEFA 4.2 data was used also in HBEFA 5.1. Since HBEFA 5.1 now includes cold start extra emissions for HDVs, parking time distributions for HDVs had to be elaborated. Since no statistical data is yet available, the parking time distributions for all HDV classes were elaborated using an expert judgment by TUG.

Figure 15: Park time definition in HBEFA 5.1 for AT.



Traffic distributions over the day

No new data was available in Austria so updated data from Germany for PC and HGV are used since it is unlikely that hourly traffic ratios differ significantly between Austria and Germany.

5.6. Germany

The country data for Germany in the HBEFA 5.1 were taken from the model TREMOD, Version 6.53. This includes data from different national statistics (e.g. vehicle registrations, mileage surveys) from 1990 until 2022 and preliminary data for 2023. Further on, TREMOD includes a reference scenario from 2024 until 2050 which considers the projections on transport demand by the ministry of transport, effects of policies which have already been implemented. More information is available in the report for the German Federal Environment Agency[46]

Some adaptations to TREMOD 6.53 which had to be done, are described in the following chapters.

5.6.1. Vehicle stock

Vehicle categories

Vehicle stock in TREMOD bases on data by the KBA and other sources which are specific for Germany. As in previous versions of the HBEFA some vehicle categories from TREMOD had to be adapted for the HBEFA, e.g.

[46] https://www.umweltbundesamt.de/publikationen/aktualisierung-tremodtremod-mm-ermittlung-der

- Coaches include long distance commuting busses (in TREMOD “Fernlinienbusse”) and other non-urban buses (in TREMOD “Sonstige Reisebusse”)
- TT/AT include trailer trucks (in TREMOD “Lastzüge”) and articulated trucks (in TREMOD “Sattelzüge”).
- Special vehicles (in TREMOD “Übrige Kfz”) are not included in the HBEFA.

CNG and electric trucks

Similar to the HBEFA 4.2 TREMOD 6.53 differentiates only three size classes for trucks with alternative fuels and aggregates all vehicles >12 tonnes to one segment per fuel type. Based on the data by the KBA these vehicles can be differentiated similar to diesel from the year 2014 on. For earlier years, CNG and electric trucks >12 t have been assigned to the size class 12-14t, as there were only few vehicles for those segments.

Mopeds

For mopeds TREMOD 6.53 does not differentiate in 2- and 4-stroke vehicles. The KBA does no differentiate those fuel types either. Therefore, the differentiation was carried out based on an email from ACEM to TU Graz. ACEM estimates that the share of 2-stroke mopes in new registrations decreased significantly in the past from 52% in 2009 to 33 % in 2018. This information was used and extrapolated for the moped fleet, so that from 2034 on no more 2-stroke mopeds will be registered.

Regarding the other segments, the KBA provided data on motorcycles differentiated by the number of wheels (additional to existing data, e.g. engine capacity). However, this data was not available in time and, therefore, minicars and quads are not considered for Germany in the HBEFA 5.1. This might be changed in future updates.

5.6.2. Traffic activity (mileage, starts/stops)

Average mileage per segment

Mileage data was taken directly from TREMOD 6.53, basing on different mileage surveys e.g. vehicle counts and tachometer data in behalf of the Federal Highway Research Institute (BASt).

Aggregated traffic situations

The aggregated traffic situations for Germany were update based on a study on behalf of the German Federal Environment Agency[47] and are labelled “UBA 2024…”. The same study was already available for the HBEFA 4.2, but for the HBEFA 5.1 the mileage shares to the area types

[47] https://www.google.com/search?client=firefox-b-d&q=uba+fl%C3%BCssiger+verkehr

“urban”, “rural” has been reallocated and an error in the allocation of the LOS “heavy” and “saturated” has been corrected.

Starts and stops

The number of starts and stops is calculated by the mileage and the average trip length and was updated for HBEFA 5.1 (see new data for ambient conditions in 5.6.5).

5.6.3. Energy efficiency

The data on energy efficiency was taken directly from TREMOD 6.53. Up to 2023 it is based on the monitoring of CO_2 emissions from cars and trucks by the KBA. The real-world correction factors are based on earlier studies for by the UBA. As part of the development of the HBEFA, other data sources such as studies by the ICCT and OBFCM data were identified, but could not be taken into account for the HBEFA 5.1 due to time constraints. The efficiency development from 2024 to 2050 is based on the TREMOD reference scenario. The improvements in fuel efficiency for cars, trucks and buses are mostly less than 1% per year, as it is assumed that the European CO_2 limits will be achieved through the sale of electric vehicles.

Other country dependent adjustment factors, e.g. for the energy consumptions of electric vehicles, have not been applied since the base consumption factors of HBEFA 5.1 have not been yet available at the time of the country data update.

5.6.4. Sub-technology scenarios

High-emitter shares

See Chapter 5.3.1.

Software updates

The number of diesel passenger cars with software updates was estimated by the UBA. The share for the Euro 5 and Euro 6 diesel passenger car fleet is given in Figure . Software updates were implemented in 2016 for Euro 5 and in 2019 for Euro 5 cars. By 2021 a large part of the affected vehicles in the fleet was already updated, afterwards a constant share is assumed.

Figure 31: Share of vehicles affected by software updates and share of updated vehicles by reference year.

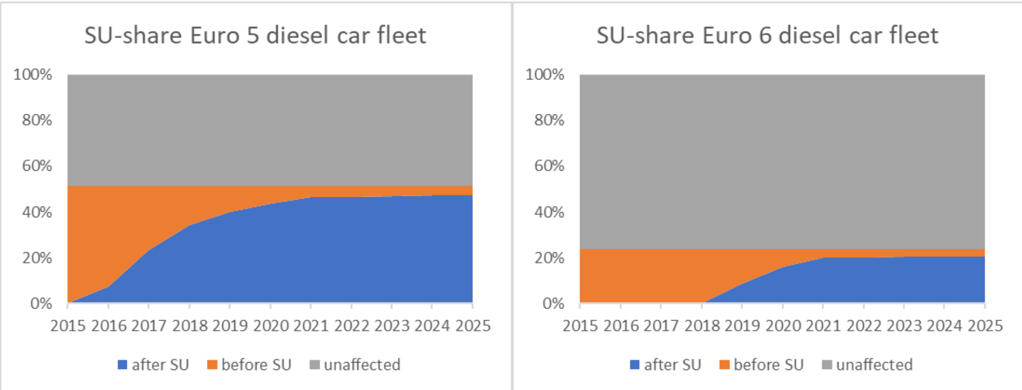


Figure by ifeu

Utility factors

The utility factors were taken from TREMOD 6.53. For example PHEV passenger cars have an electric share in mileage of 15 % on highways, 48 % on rural roads and 57 % on urban roads in 2023. In the reference scenario an increase in the utility factor is assumed.

5.6.5. Ambient conditions

The following chapter describes the update of the ambient conditions for the HBEFA 5.1. This data was not part of TREMOD 6.53 (which bases still on HBEFA 4.2), but taken from other sources.

Trip lengths

The trip length distributions and average trip lengths for passenger cars were updated based on the Survey Mobility in Germany 2017 ("Mobilität in Deutschland 2017[48]"). Compared to the previous data in the HBEFA 4.2, the share trips in higher distance classes have increased (Figure) and the average distance of trips longer than 20 km increased from 30 km to 57 km. Therefore, the average distance for all trips for the HBEFA 5.1 increased to 15.6 km compared to 9.2 km in the HBEFA 4.2. Due to a lack of data, for LCV and motorcycles, the same trip length distribution as for passenger cars was assumed.

[48] https://www.mobilitaet-in-deutschland.de/archive/publikationen2017.html

Figure 32: **Share of trips by distance classes for passenger cars.**

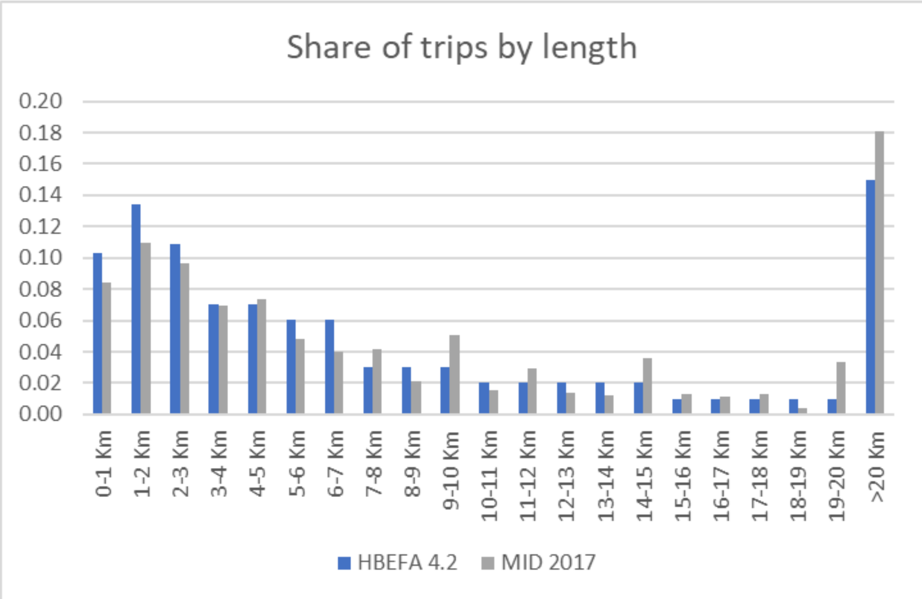


Figure by ifeu

For trucks the trip length distribution was derived based on two sources:

- for HGVs < 12 t: MID 2017 (see above)
- for HGVs >= 12 t: the survey Traffic of European Trucks by the KBA[49] for the year 2022

MID 2017 considers the vehicle category truck (in German "LKW") whereas no info about the type of trucks is given. But as MID covers all kind of trips and in the German vehicle register trucks also include LGVs it is assumed, that MID will rather represent smaller trucks.

KBA VE includes trucks with a payload above 3.5 tonnes. Therefore, it is assumed, that this dataset represents bigger trucks. As the survey differentiates only the distance classes 0-25 km, 26-50 km, and so on, whereas the HBEFA differentiates only distance up to 20 km. The share of trips below 20 km was derived based on own assumptions and distributed equally to each class.

The trucks in MID, here used for trucks <12 t, have about 70% of trips below 20 km, while for the bigger trucks almost 70 % of the trips cover a distance of 20 km or longer. The average trip length for trucks <12 t therefore is around 25 km and for trucks >= 12 t 91 km per trip (Figure), whereas the trips longer than 20 km have in average 69 km and 129 km, respectively.

[49] "Verkehr europäischer Lastkraftfahrzeuge (VE)", see https://www.kba.de/DE/Statistik/Kraftverkehr/europaeischerLastkraftfahrzeuge/verkehreurop%C3%A4ischer_node.html

Figure 33: Share of trips by distance classes (left) and average trip length (right) for HGVs.

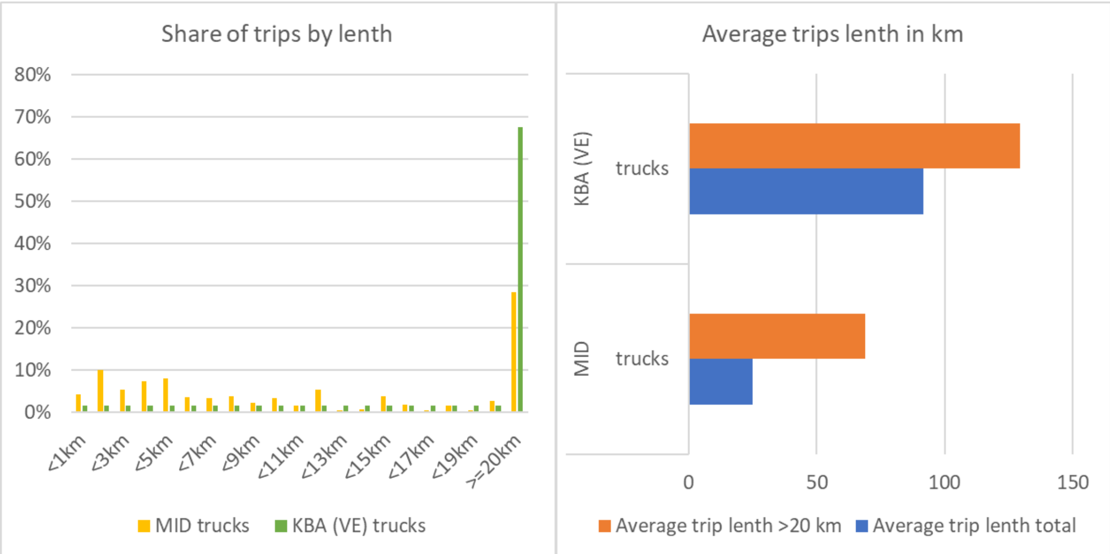


Figure by ifeu

Parking time

There was no new data available for parking times. Therefore, the parking time distribution was not updated and the existing parking time data for passenger cars was used for all vehicle categories.

Traffic distributions over the day

New data on traffic distributions over the day was taken from MID 2017 (see section on trip lengths). There on starting times from ~ 366,000 passenger cars and ~ 1.300 trucks available. The traffic distributions are given in Figure .

Figure 34: percentage of starts of passenger cars and trucks over the daytime according to MID 2017.

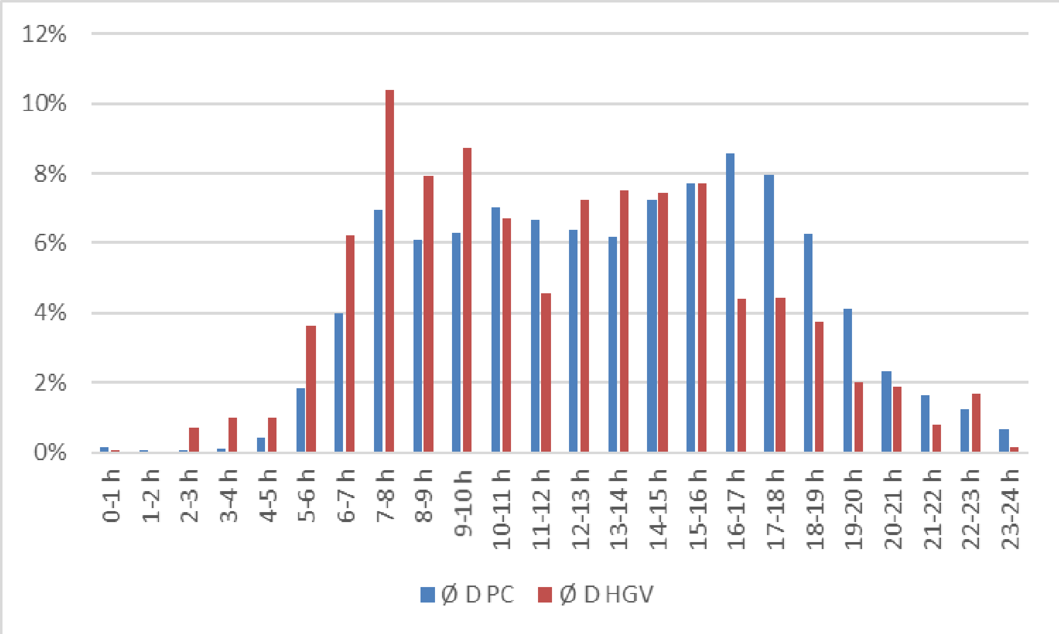


Figure by ifeu

Climate data

For the update of the climate data historical hourly data on air temperature and relative humidity from the German Weather Service DWD (open data[50]) from 1 January 2019 up to and 31 December 2023 was used. Only data from weather stations that provided temperature and humidity values or were active over the entire observation period were analyzed. The values of each year and station were weighted to mean values per hour of the day for Germany and the four meteorological seasons. With the updated values the annual mean temperature is 10,1 degrees Celsius and 77 % humidity.

5.7. Sweden

5.7.1. Vehicle stock

The vehicle stock in Sweden has been updated in HBEFA 5.1 up to 2024 with registry data supplied by the Swedish Transport Authority. The same data, but with a lower level of detail, is

[50] https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/hourly/air_temperature/historical/

available from Transport Analysis[51]. New registration data from 2025 to 2060 are based on assumptions by the Swedish Transport Administration.

5.7.2. Traffic activity (mileage, starts/stops)

Traffic activity (mileage) has been updated based on odometer data of Swedish vehicles[52] and road goods transport in Sweden by foreign lorries[53]. The latter is updated from 2009 to 2023 due to changes in methodology. Allocation of mileage between different technologies has been updated for passenger cars from 2001 to 2024. Age-dependent mileage has been updated for petrol and dieses PCs and LCV from 2016 to 2024. Mileage for motorcycle & mopeds have been updated between 1996 and 2024, due to revised data for mopeds from the national travel survey[54].

5.7.3. Energy efficiency

Energy use per km has been calibrated for CNG and PHEV passenger cars to better align with WLTP g CO_2/km. Energy use per km for LCV Petrol and LCV Diesel segments is updated with the same methodology but using TNO data for the excess fuel estimate[55]. LCV FFV and CNG are updated to be aligned with calibration of petrol and diesel LCVs due to lack of data.

5.7.4. Sub-technology scenarios (high-emitter shares, software updates, utility factors etc)

No new data is available on the share of software updates and utility factors compared to HBEFA 4.2. For the share of high-emitters (tampered and malfunctioning vehicles), see Chapter 5.3.1.

5.7.5. Traffic and ambient conditions

Average trip length and traffic distribution over the day was updated for heavy goods vehicles, assuming the same distributions as Germany. Light duty vehicle, bus and coach traffic conditions are unchanged compared to HBEFA 4.2

[51] https://www.trafa.se/en/road-traffic/vehicle-statistics/
[52] https://www.trafa.se/en/road-traffic/driving-distances-with-swedish-registered-vehicles/
[53] https://www.trafa.se/en/road-traffic/international-road-goods-transport/
[54] https://www.trafa.se/en/transportation-trends/passenger-and-goods-transport/
[55] https://publications.tno.nl/publication/34639300/erZOUs/TNO-2022-R10409.pdf

5.8. Norway

Norway's country data are updated in HBEFA 5.1 resulting in significant changes in estimated consumption and emissions.

5.8.1. Vehicle stock

The method used to separate busses in urban bus and coach are changed from year 1998, resulting in higher number of urban buses on behalf of coaches. The Register of Vehicles at the Directorate of Public Roads is used as source.

LCV now include PHEV in the vehicle stock.
New registration data has been updated to project time series from 2025 to 2050.

5.8.2. Traffic activity (mileage, starts/stops)

Average mileage has been updated according to changes on the vehicle stock and the national statistics on road traffic volumes is used as source.

The allocation of LOS in traffic situations has been updated from 2020, based on estimates from Google Maps data.

Age dependency of annual mileage by road category is updated from 2015 to 2050. An average from 2018 to 2023 is used in the updates.

5.8.3. Energy efficiency

Energy efficiency assumptions for light duty vehicles are improved based on NEDC and WLTP data (average laboratory) for newly registered vehicles from the register of vehicles at the Directorate of Public Roads and the European Environment Agency. The data is adjusted for real-world data (vehicle manufacturers).

5.8.4. Sub-technology scenarios (high-emitter shares, software updates, utility factors etc)

Software update shares on diesel passenger cars are revised based on shares from the Swedish Environmental Research Institute.

Norway does not have data on tampered/high-emitting shares on vehicles. The estimated shares for heavy goods vehicles in Norway are based on a country specific share of Central Eastern European vehicles (average of CZ and SK) and Western European vehicles (represented by Germany); see Chapter 5.3.1.

5.8.5. Traffic and ambient conditions

Trip length and parking time distributions are updated for all vehicle categories. Due to lack of data for Norway, the distributions are based on data from Switzerland.

5.9. France

The French country data are not yet final at this point. This chapter will be written and updated as soon as they are final.

5.9.1. Vehicle stock

5.9.2. Traffic activity (mileage, starts/stops)

5.9.3. Energy efficiency

5.9.4. Sub-technology scenarios (tampering, software updates, utility factors etc)

High emitter shares: see Chapter 5.3.1

5.9.5. Traffic and ambient conditions

6. Open issues and outlook

Several questions and open issues have arisen during the development of HBEFA 5.1 that could not be finally resolved within this project. In these regards, HBEFA 5.1 contains the best possible solution based on the available data and knowledge. The respective methodology will be refined in future HBEFA versions.

Such issues include:

- Non-exhaust emission factors:
  - Curves have a major impact on tyre wear – it is much higher in curves than on a straight road. The curve impact is currently considered on average; however, the impact of the exact location of curves in the driving cycles assigned to the traffic situations is not yet taken into account.
  - The effects of winter tires are not yet considered.
  - The effects of Euro-7 reduction targets that were not yet known at the time of work are not yet considered.
- Cold start:
  - The availability of input data on driving behaviour (such as trip length or parking time distributions) for HDV is still low. Further empirical data need to be searched for or researched for future HBEFA versions.
  - The effect of parking inside garages (with temperature distributions differing from those outdoor) is not yet considered
- SCR tampering and malfunctions:
  - The share of high emitters is currently differentiated by vehicle type and Euro standard. However, there are indications high emitter shares also increase with vehicle age. It seems plausible that a decision to tamper a vehicle may often be taken after the first SCR disfunction: Instead of having the vehicle repaired, the operator decides to disable the SCR catalyst instead and save money on AdBlue and possible future repairs. However, there is currently not sufficient data to quantify such an age dependency of tampering shares – most available data on high emitter shares are from around 2020 and include mostly older Euro-V, and newer Euro-VI vehicles. A refinement regarding the age dependency of SCR tampering and malfunctions is therefore on the agenda for future HBEFA versions.
- PN high-emitters: PTI tests show a significant share of defect or manipulated particle filters. This is not only the case for HDV, but also or even more so for passenger cars. However, the data comes along with high uncertainty so far and the topic needs more research work. Consequently, the implementation of a share for high-emitters with respect to particle emissions has been deferred to the next HBEFA version.

Glossary

Abbreviation	Description
2S	2 stroke petrol engine
4S	4 stroke petrol engine
a	Acceleration
AC	Air conditioning
ACR	Active carbon reduction (for reducing the HC evaporation emissions)
API	Application Programming Interface: a set of rules and protocols that allows different software systems to communicate and exchange data. In the case of HBEFA, the HBEFA server provides an API that the main front-end can communiate with.
AT	Articulated truck
BAB	German motorway driving cycle (Bundesautobahn)
BAFU	Swiss Federal Office for the Environment (FOEN), Bundesamt für Umwelt
BEV	Battery-electric vehicle
Case	User-defined parameter combination for calculating emission factors
Cat	Catalytic converter
CH	Switzerland
CH4	Methane
CNG	Compressed natural gas
CO	Carbon monOxide
CO2	Carbon dioxide
CSEE	Cold start extra emissions
D	Diesel
DP	Driving profile
DPF	Diesel Particle Filter
DT	Distance travelled, mileage
ECE	Economic Commission for Europe
EEA	Exhaust Emissions Act. In the context of the Handbook, this term refers to Swiss regulations: EEA 1 = Light motorised vehicles, EEA 2 = Heavy motorised vehicles, EEA 3 = Motorcycles, EEA 4 = Mopeds
EF, EFA, E-Factor	Emission factor
EFA_weighted	Emission factor, weighted (according to fleet compositions)
EGR	Exhaust Gas recirculation
EMPA	Federal Materials Testing and Research Institute, Dübendorf
EU	European Union
EURO-1, -2, -3 etc	European emission standards for light duty vehicles
EURO-I, -II, -III etc	European emission standards for heavy duty vehicles (exception: for Euro-7, also the HDV standards carry an arabic number)
FEA	Federal Environmental Agency (=UBA: Umweltbundesamt)
FFV	Flex-fuel vehicle
HC	Hydrocarbons
HGV	Heavy goods vehicles {= general term for trucks, truck trailers (TT) and articulated trucks (AT)}
HDV	Heavy duty vehicle {= vehicles > 3.5 t total weight; = general term for heavy goods vehicles (HGV), coaches (RBus) and urban buses (LBus)}
HEV	Hybrid electric vehicle. Note that within HBEFA 5.1, HEVs are only differentiated from ICE vehicles for HDVs. For LDVs, HEV are included with ICE vehicles, since most modern ICE vehicles exhibit hybridisation to some degree.
IBA	In built-up area

Abbreviation	Description
IUFC	INRETS Urbain Fluide Court, driving cycle used to produce empirical input data for cold start extra emissions up to HBEFA 4.2.
Lbus	Bus, urban bus, public transport bus (also “city bus” (CB) or in German: Linienbus)
LEV	Low Emission Vehicle
LCV	Light commercial vehicle <3,5t (small buses, trucks, camper vans, other motor vehicles)
LDV	Light duty vehicle, general term for passenger cars and light commercial vehicles
LNG	Liquefied natural gas
MC	Motorcycle
NEDC	New European Driving Cycle. Driving cycle for LDV type approval tests in Europe until 2018, when it was replaced by the WLTP (Worldwide Harmonized Light Vehicles Test Procedure)
NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gases
NOx	Nitrogen oxide
OBA	Outside built-up area
Pb	Lead
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate matter (weight)
PN	Particle number
PC	Passenger car
Rbus	Coach (German: Reisebus)
RPA	Relative positive acceleration[1]
RVP	Reid vapour pressure. Absolute vapor pressure exerted by a liquid at 100°F (37.8°C); a measure of a fuel's volatility, indicating how readily it evaporates at a specific temperature.
SCR	Selective catalytic reduction (for NOx-reduction)
SO2	Sulphur dioxide
TLEV	Transient Low Emission Vehicle
TLS	Traffic light system
Truck	Truck
TS	Traffic situation
TT	Truck-trailer, Trailer truck
TTW	Tank-to-wheel. Term for emissions from energy provision.
TUG	Technical University of Graz
TWV	Two-wheeled vehicle
UBA	Umweltbundesamt (Germany, Austria), Federal Environment Agency
ULEV	Ultra Low Emission Vehicle
v	Speed, velocity (in km/h)
VDA	Verband der Automobilindustrie e.V.
VOC	Volatile Organic Compounds
VS	Vehicle segment
WLTP	Worldwide Harmonized Light Vehicles Test Procedure. Type approval test procedure for LDV used in Europe since 2019.
WTT	Well-to-tank. Term for emission from vehicle operation/use
WTW	Well-to-wheel. Total emissions from energy provision and vehicle operation.
ZEV	Zero Emission Vehicle

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