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CO_2 emissions of the European heavy-duty vehicle fleet

Analysis of the 2019-2020 reference year data

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Contents

Abstract

CO_2 emissions reduction targets for 2025 and 2030 have been introduced for new heavy lorries sold in the EU. The targets currently apply to the lorry groups that account for around 65 % to 70 % of all heavy-duty vehicles' CO_2 emissions in the EU. The reference against which the reduction is calculated, is the fleet-average CO_2 emissions of newly registered vehicles from July 1st 2019 to June 30th 2020. Artificially increased CO_2 emissions during this reference period would lead to less stringent reduction targets. In this report, the robustness of the reference CO_2 emissions is analysed. In the first part of this study, an overview is provided of the CO_2 emissions and the main characteristics of the European heavy-duty vehicle fleet during this reference period. It was found that vehicles in groups 5 and 10 and the long haul subgroups have the lowest specific CO_2 emissions, expressed in g/t.km.

The CO_2 emissions of a heavy-duty vehicle are determined by simulating the vehicle with the Vehicle Energy consumption Calculation TOol (VECTO). Vehicles simulated with component data derived from predefined values (so-called standard values), have generally higher CO_2 emissions compared to vehicles with component data derived from measurements. Standard values were introduced to reduce the component testing cost. Standard values are more conservative when it comes to energy savings to motivate the use of measured data, which better characterise each individual vehicle. Their usage could artificially increase the reference CO_2 emissions. The second part of this study investigates the share of vehicles with standard values for components and their effect on the reference CO_2 emissions. The study quantified the impact of components with standard values on the reference CO_2 emissions by replacing these components in vehicles with standard values of representative components and recalculating the vehicle's CO_2 emissions and the fleet's reference CO_2 emissions. The use of standard values for certain components instead of measured component data in the simulation tool increases the reference CO_2 emissions between 0.4 % and 1 %.

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Executive summary

Policy context

The European Union (EU) introduced fleet-wide, sales-weighted CO_2 emission reduction targets for certain new heavy-duty vehicles (HDV) sold in the EU, to meet the EU's COP21 commitments and its greenhouse gas emissions reduction objectives. Regulation (EU) 2019/1242 sets a reduction target for the average CO_2 emissions of certain new heavy lorries by 15 % and 30 % for 2025 and 2030, respectively. The reduction targets do not apply to each individual vehicle sold but rather to the average, sales-weighed CO_2 emissions of each vehicle manufacturer, which have to be reduced relative to the reference CO_2 emissions. The latter is defined as the fleet-average CO_2 emissions of newly registered HDVs in the reference period from July 1st 2019 to June 30th 2020.

The CO_2 emissions of new HDVs are determined by simulating the specific vehicle in the Vehicle Energy consumption Calculation TOol (VECTO) over various mission profiles. This simulation-based approach is defined in Regulation (EU) 2017/2400. The resulting CO_2 emissions are reported to the European Environment Agency, as set out in Regulation (EU) 2018/956 and are used to establish the reference CO_2 emissions and the manufacturers' average CO_2 emissions.

There is no regulatory incentive for the vehicle manufacturer to achieve low average CO_2 emissions during the reference period. On the contrary, since the regulation introduces relative reduction targets, higher fleet-average CO_2 emissions during the reference period would lead to less stringent absolute compliance levels in 2025 and 2030. Such an increase in the reference CO_2 emissions could be possibly achieved by exploiting the regulatory margins of the certification procedures in a way that would not be done if the CO_2 emissions targets would already be applicable. This risk only exists during the reference period, as afterwards, there is an incentive for the vehicle manufacturer to achieve the lowest possible average CO_2 emissions. Article 10 of Regulation (EU) 2019/1242 requires the Commission to assess whether the reference CO_2 emissions have been unduly increased and, possibly correct them. The analysis summarised in the present report fulfils this obligation; the report assesses if the reported CO_2 emissions were increased by unduly procedural means, which would not represent a situation where the CO_2 emissions are already regulated.

One possible way to increase CO_2 emissions is the excessive and artificial use of standard values in the simulation tool for certain component properties (e.g. the gearbox or axle efficiency) instead of measured component data. Standard values represent a worst-case performance assumption for a component and include a penalty factor, which lead to increased vehicle CO_2 emissions. Regulation (EU) 2017/2400 offers the possibility to use standard values for components to avoid the cost of testing, particularly in the case of components produced in low numbers. The worst-case performance is applied to incentivise component measurements, considering that the manufacturer would aim for lower, vehicle-representative fuel consumption and CO_2 emissions values for both target compliance and marketing reasons. Once the targets apply, it is expected that their use remains limited to vehicles designed for niche applications since their use makes it more challenging and possibly costly to comply with the reduction targets. If during the reference period more vehicles in the fleet are simulated with standard values than it would be reasonably expected from cost-efficiency considerations and this artificial behaviour has a significant quantitative effect, the reference CO_2 emissions should be considered as artificially increased and should be corrected accordingly.

Another possibility to increase the CO_2 emissions is the use of excessively large and artificial component families. The concept of component families was introduced in Regulation (EU) 2017/2400 to limit the cost of certification. Components with a similar design and performance can be grouped into a family, which is represented by the component with the worst energy-efficiency performance. Only the worst-performing component is tested to incentivise energy efficiency improvement in the family, and its performance is assigned to the entire family. Therefore, a component family with many members would underestimate the performance of many components and increase the CO_2 emissions of vehicles equipped with these components. When the targets apply, it is expected that only components with very similar performance are grouped together in a family. Since Regulation (EU) 2017/2400 specifies detailed provisions for which components can be grouped together in a family, the effect of large components families on the reference CO_2 emissions is not expected to be large.

Key conclusions

The analysis shows that the reference CO_2 emissions are representative of the fleet. Therefore, no ex-post correction is required. The use of standard values for certain vehicle components instead of measured component data in the simulation tool increases the reference CO_2 emissions between 0.4 % and 1 %, a percentage that falls well inside the uncertainty margins of the experimental tests used for quantifying component efficiencies or the complete-vehicle fuel consumption and CO_2 emissions simulation. Therefore, no ex-post correction of the reference values is justifiable.

Continuous monitoring of the VECTO simulation summary data files (sum exec data, which is a VECTO output file not specified in legislation that is described in Annex I below) is recommended to allow for a periodical re-evaluation of the fleet's CO_2 emissions and component properties compared to the reference period. With such an evaluation, any marked difference in component performance or component family size compared to the reference period can be detected and lead to a follow-up investigation of the reference CO_2 emissions.

Main findings

- The majority of all HDVs belong to the regulated vehicle groups, most of which belong to subgroup 5-LH.
- The lowest specific CO_2 emissions are found in vehicle groups 5 and 10 and the long haul subgroups.
- Vehicles with standard values for a component have, in general, higher CO_2 emissions compared to vehicles with only measured components. The worst-case performance of components with standard values is confirmed.
- A limited number of different technologies are applied for the vehicle components (e.g. gearbox types). However, many different component models are present in the fleet. This observation confirms the need for a simulation-based certification approach and suggests sufficiently differentiated component families.
- The use of standard values for components affects only a low share of vehicles and varies depending on the vehicle subgroup
- The impact of components with standard values on the reference CO_2 emissions was quantified for a conservative, an intermediate and a worst-case scenario. The conservative scenario resulted in 0.4 % higher reference emissions due to the application of standard values, the intermediate scenario in 0.6 - 0.7 % and the worst-case scenario 1 % higher emissions, respectively.

1 Introduction

The greenhouse gas emissions from heavy-duty vehicles (HDVs) account for about 5% of the total EU greenhouse gas emissions and about a quarter of the greenhouse gas emissions from road transport [1]. The EU has introduced CO_2 emissions reduction targets for new HDVs with Regulation (EU) 2019/1242 [2]. These targets will help fulfil the EU's Paris Agreement commitments and achieve the EU's overall greenhouse gas emissions reduction objectives [3]. Furthermore, the introduction of the targets will accelerate the uptake of energy-efficient technologies in HDVs, the market introduction of zero-emission vehicles and enable the decarbonisation and modernisation of road transport.

The CO_2 emissions reduction targets for HDVs require a reduction of the average CO_2 emissions of new HDVs by 15 % and 30 % for 2025 and 2030, respectively. These reductions are relative to the reference CO_2 emissions, which are established as the average CO_2 emissions of newly registered HDVs in the reference period from July 1st 2019 to June 30th 2020. Whereas the reduction targets apply to the average CO_2 emissions of each individual vehicle manufacturer, the reference CO_2 emissions are based on the sales-weighted fleet-average emissions. A more detailed description of the reference CO_2 emissions calculation is provided in Section 2 of this report.

The CO_2 emissions of new HDVs are determined with a simulation-based approach established in Regulation (EU) 2017/2400 [4] which accommodates the highly customisable nature of HDVs by taking into account all relevant vehicle properties. Each new vehicle is modelled in the Vehicle Energy consumption Calculation TOol (VECTO) and simulated over various mission profiles. VECTO was first introduced in 2012, and since then it has undergone multiple updates to become the official tool used for the certification of HDV CO_2 emissions in the EU [5,6]. New technologies relevant to VECTO are continuously being monitored [7,8] and developments are ongoing to extend it with new technologies (such as waste heat recovery [9]) and vehicle categories (such as buses and medium lorries [10,11]). More details regarding the simulation tool and its capabilities can be found in Section 3.1 and the VECTO user manual [12].

The CO_2 emissions and other VECTO results of new vehicles are monitored by both the vehicle manufacturers upon vehicle production and the member states upon vehicle registration. The data is reported annually to the European Environment Agency (EEA), as set out in Regulation (EU) 2018/956 [13]. The EEA matches the vehicle manufacturers' data to the member states' registration data to establish the reference CO_2 emissions and the manufacturers' average specific CO_2 emissions in each reporting period. This report used a more detailed dataset to analyse the HDV fleet composition, energy consumption and CO_2 emissions compared to the monitoring data. The additional data consist of the sum exec data VECTO output files of all vehicles simulated between October 1st 2019 and June 30th 2020. A detailed description of the dataset and its comparison to the monitoring data can be found in section 3 of this report.

Currently, Regulation (EU) 2017/2400 [4], as amended by Regulation (EU) 2019/318 [14], covers only certain HDV groups (listed in Table 1). The groups comprise heavy lorries with a technically permissible laden mass (TPMLM) above 7.5 t and with a certain axle configuration. However, work is ongoing to extend its scope to other categories, such as heavy buses and medium lorries. The CO_2 emissions reduction targets currently apply only to HDV groups 4, 5, 9 and 10 (in bold in Table 1). These vehicles make up about 65 % to 70 % of the HDV CO_2 emissions in the EU and have the most significant CO_2 emissions reduction potential. The vehicle groups and categories falling under Regulation (EU) 2019/1242 will be assessed and possibly revised in 2022, together with the reduction targets for 2030 and beyond. This report focuses on HDV groups 4, 5, 9 and 10, since these vehicle groups currently make up the reference CO_2 emissions. However, the CO_2 emissions and component data quality of vehicle groups 1, 2, 3, 11, 12 and 16 are examined for inclusion in the targets' scheme.

There is no regulatory incentive for the vehicle manufacturer to achieve low average CO_2 emissions during the reference period. On the contrary, since the regulation introduces relative reduction targets, higher fleet-average CO_2 emissions during the reference period would lead to less stringent absolute compliance levels in 2025 and 2030. Such an increase of the reference CO_2 emissions could be possible by exploiting the regulatory margins of the certification procedure, which would not be relevant if the CO_2 emissions targets were already applicable. This risk only exists during the reference year as afterwards there is the incentive for the vehicle manufacturer to achieve the lowest possible average CO_2 emissions. Article 10 of Regulation (EU) 2019/1242 requires the Commission to assess whether the reference CO_2 emissions have been unduly increased and, if required to do so, correct them. The analysis summarised in the present report fulfils this obligation; the report assesses if the reported CO_2 emissions were increased by unduly procedural means, which would not represent a situation where the CO_2 emissions are already regulated.

One possible way for increasing CO_2 emissions is the excessive and artificial use of standard values in the simulation tool for certain component properties (e.g. the gearbox efficiency) instead of measured component data. Standard values represent a worst-case performance assumption for a component and lead to increased vehicle CO_2 emissions. Regulation (EU) 2017/2400 offers the possibility to use standard values for components to avoid the cost of testing, particularly in the case of components produced in low numbers. The worst-case performance is applied to incentivise component measurements, considering that the manufacturer would aim for lower, vehicle-representative fuel consumption and CO_2 emissions values for both target compliance and marketing reasons. Once the targets apply, it is expected that their use remains limited to vehicles designed for niche applications since their use makes it more challenging and possibly costly to comply with the reduction targets. Suppose more vehicles in the fleet are simulated with standard values than reasonably expected during the reference period, which would have a significant quantitative effect on the reference emissions; in that case, the reference CO_2 emissions should be considered as artificially increased and should be corrected accordingly.

The study used the sum exec data VECTO output files of the European HDV fleet during the reference period to analyse the fleet's component properties, the extent of standard values use, and create representative components. The impact of components with standard values on the reference CO_2 emissions was quantified by replacing these components in vehicles with standard values by the representative components and recalculating the vehicle's CO_2 emissions and the fleet's reference CO_2 emissions. The results of the reference fleet analysis can be used as a source for comparison in the future when the CO_2 emissions reduction targets are active or as a basis for modelling the European HDV fleet. The calculation of the reference CO_2 emissions of the different vehicle groups is explained in Section 2 of the report, and the source data used for the analysis is elaborated in Section 3. The fleet characteristics are provided in Section 4; the latter comprise fleet composition, the CO_2 emissions of each vehicle group, and their component properties. Based on the fleet data, the number of unique components in the fleet and reference vehicles that represent the European HDV fleet are identified and presented. The use of standard values in the fleet is discussed in Section 4.6. The methodology and the results of the analysis on the representativeness of the reference emissions can be found in Section 5.

Table 1. Vehicle groups. In bold, vehicles categories falling under scope of the Regulation

Axle configuration	**Chassis configuration**	**Technically permissible maximum laden mass [t]**	**Vehicle group**
4x2	Rigid (or Tractor)	> 7.5 - 10	1
		> 10 - 12	2
		> 12 - 16	3
	Rigid	> 16	**4**
	Tractor	> 16	**5**
6x2	Rigid	All weights	**9**
	Tractor	All weights	**10**
6x4	Rigid	All weights	11
	Tractor	All weights	12
8x4	Rigid	All weights	16

Source: Regulation (EU) 2019/1242, 2019.

2 Reference CO_2 emissions calculation

2.1 Vehicle groups 4, 5, 9 and 10

The CO_2 emissions reduction targets apply to HDVs in vehicle groups 4, 5, 9 and 10. The calculation of the reference CO_2 emissions is set out in Regulation (EU) 2019/1242 and summarised in this section.

The reference CO_2 emissions are determined per vehicle subgroup, that further differentiate the vehicle groups based on the vehicle's cabin type and the rated engine power (Table 2). The vehicle subgroups better capture the typical usage and specific technical characteristics than the vehicle groups. This allows the specific driving patterns, annual mileage and payload to be taken into account to calculate the vehicle's CO_2 emissions. Each vehicle is simulated over different mission profiles in VECTO, representing typical vehicle use cases (e.g. the regional delivery of goods), and each mission profile is simulated with a low and a reference payload. The CO_2 emission value of a vehicle ($CO2_v$) is calculated as follows:

$$CO2_v = \sum_{mp} W_{sg,mp} \cdot CO2_{v,mp} \tag{1}$$

With *mp* the mission profiles, $W_{sg,mp}$ the mission profile weights for a vehicle in subgroup *sg* specified in Table 3 and $CO2_{v,mp}$ the CO_2 emissions in g/km of vehicle *v* in subgroup *sg* simulated with VECTO. The reference CO_2 emissions ($rCO2_{sg}$) of each subgroup are expressed in g/t.km to reflect the utility of the vehicle. They are calculated from the individual vehicle CO_2 emissions as follows:

$$rCO2_{sg} = \frac{1}{rV_{sg}} \cdot \sum_{v} \frac{CO2_{v,sg}}{PL_{sg}} \tag{2}$$

Table 2. Vehicle subgroups

Vehicle group	Cabin type	Engine power [kW]	Subgroup
4	All	< 170	4-UD
	Day cab	≥ 170	4-RD
	Sleeper cab	≥ 170 and < 265	
	Sleeper cab	≥ 265	4-LH
5	Day cab	All	5-RD
	Sleeper cab	< 265	
	Sleeper cab	≥ 265	5-LH
9	Day cab	All	9-RD
	Sleeper cab	All	9-LH
10	Day cab	All	10-RD
	Sleeper cab	All	10-LH

Source: Regulation (EU) 2019/1242, 2019.

With v the vehicles in subgroup sg, rV_{sg} the total number of vehicles in subgroup sg, $CO2_{v,sg}$ the CO_2 emissions in g/km for vehicle v in subgroup sg and PL_{sg} the average payload of the vehicle in subgroup sg in tonnes. The average payload per subgroup is determined from the actual payload that the vehicle is simulated with in VECTO over each mission profile and the weights listed in Table 3. The average payload is listed in Table 4.

Table 3. Mission profile weights of the vehicle subgroup

Subgroup	Regional Delivery		Long Haul		Urban Delivery	
	Low	Ref	Low	Ref	Low	Ref
4-UD	0	0	0	0	0.5	0.5
4-RD	0.45	0.45	0.05	0.05	0	0
4-LH	0.05	0.05	0.45	0.45	0	0
5-RD	0.27	0.63	0.03	0.07	0	0
5-LH	0.03	0.07	0.27	0.63	0	0
9-RD	0.27	0.63	0.03	0.07	0	0
9-LH	0.03	0.07	0.27	0.63	0	0
10-RD	0.27	0.63	0.03	0.07	0	0
10-LH	0.03	0.07	0.27	0.63	0	0

Source: Regulation (EU) 2019/1242, 2019.

Table 4. Average payload per vehicle subgroup

Subgroup	Payload [t]
4-UD	2.65
4-RD	3.18
4-LH	7.42
5-RD	10.26
5-LH	13.84
9-RD	6.28
9-LH	13.40
10-RD	10.26
10-LH	13.84

Source: Regulation (EU) 2019/1242, 2019.

2.2 Vehicle groups 1, 2 and 3

The calculation of the reference emissions is only set out for the regulated vehicle groups in Regulation (EU) 2019/1242. A similar approach was followed to calculate the reference emissions of vehicle groups 1, 2 and 3. However, minor differences exist, which are described in this section.

Firstly, there are no vehicle subgroups specified for vehicle groups 1, 2 and 3. Therefore the reference CO_2 emissions can only be determined per vehicle group. The CO_2 emission value of a vehicle ($CO2_v$) is calculated according to Eq. 1, with the subgroup replaced by the group and the mission profile weights listed in Table 5.

Table 5. Mission profile weights of vehicle group 1, 2 and 3

Group	Regional Delivery		Long Haul		Urban Delivery	
	Low	Ref	Low	Ref	Low	Ref
1	0.1	0.4	0	0	0.15	0.35
2	0.06	0.24	0.06	0.14	0.15	0.35
3	0.1	0.4	0	0	0.15	0.35

Source: VECTO manual, 2020.

Secondly, an important distinction exists for the payload applied to vehicles in groups 1, 2 and 3 and vehicles in the other groups. Vehicles in groups 1, 2 and 3 are simulated in VECTO for a given mission profile with a payload that is a function of the vehicle's TPMLM. Vehicles with a higher Technically Permissible Max Laden Mass (TPMLM) within the group are simulated with a higher payload. Vehicles in the other groups are all simulated with a fixed payload per subgroup and per mission profile. Therefore, the group's average payload is not the same as the individual vehicle's payload. The payload variation within a group affects the calculation of the reference CO_2 emissions in g/t.km. The reference CO_2 emissions is calculated from the individual vehicle CO_2 emissions according to Eq. 2, with the average payload of the group PL_g calculated as follows:

$$PL_v = \sum_{mp} w_{v,mp} \cdot PL_{v,mp} \tag{3}$$

$$PL_g = \frac{1}{rV_g} \cdot \sum_{v,g} PL_{v,g} \tag{4}$$

With $PL_{v,g}$ the average payload of vehicle v in group g in tonnes. The average payload of vehicle groups 1, 2 and 3 calculated from the 2019-2020 fleet data is listed in Table 6. It will vary each year depending on the TPMLM of the sold vehicles.

Table 6. Average payload of vehicle group 1, 2 and 3 in 2019-2020 fleet

Subgroup	Payload [t]
1	1.47
2	2.33
3	3.36

Source: JRC, 2022.

2.3 Vehicle groups 11, 12 and 16

The calculation of the reference emissions of vehicle groups 11, 12 and 16 is analogous to the calculation for vehicle groups 4, 5, 9 and 10. Equations (1 and (2 were applied to the CO_2 emissions value of a vehicle and the reference CO_2 emissions, respectively. The mission profiles weights listed in Table 7 and the average payload listed in Table 8 were used.

Table 7. Mission profile weights of vehicle groups 11, 12 and 16

Group	Regional Delivery		Construction	
	Low	Ref	Low	Ref
11	0.15	0.35	0.15	0.35
12	0.21	0.49	0.09	0.21
16	0	0	0.30	0.70

Source: VECTO manual, 2020.

Table 8. Average payload of vehicle groups 11, 12 and 16

Group	Payload [t]
11	5.39
12	9.81
16	9.81

Source: VECTO manual, 2020.

2.4 Fleet-average CO_2 emissions

Regulation (EU) 2019/1242 defines the calculation of the reference CO_2 emissions on the vehicle subgroup level. To be able to evaluate the representativeness of the reference CO_2 emissions on the fleet level, the fleet-average CO_2 emissions ($CO2_{fleet}$) are calculated as follows in this study:

$$CO2_{fleet} = \sum_{sg} share_{sg} \cdot MPW_{sg} \cdot rCO2_{sg} \qquad (5)$$

With $share_{sg}$ the share of subgroup sg in the fleet, MPW_{sg} the mileage and payload weighting factor of subgroup sg, defined in Table 9 and $rCO2_{sg}$ the reference CO_2 emissions of each subgroup expressed in g/t.km. The calculation is analogous to the calculation of the average specific CO_2 emissions of a manufacturer, defined in Regulation (EU) 2019/1242, without the zero- and low-emission factor. The MPW_{sg} is defined as the product of the assumed annual mileage per subgroup and the average payload per subgroup, normalised to the respective value for vehicle subgroup 5-LH.

Table 9. Mileage and payload weighting factor per vehicle subgroup

Subgroup	MPW_{sg} [-]
4-UD	0.10
4-RD	0.15
4-LH	0.45
5-RD	0.50
5-LH	1.00
9-RD	0.29
9-LH	0.90
10-RD	0.43
10-LH	0.92

Source: Regulation (EU) 2019/1242, 2019.

3 Source data

The data used for the analysis are the VECTO simulation results of vehicles that fall within the scope of Regulation (EU) 2017/2400 and that were simulated between October 1st 2019 and June 30th 2020 by the vehicle manufacturer. A more detailed VECTO output file (the sum exec data file) was used, compared to the monitoring data described in Regulation (EU) 2018/956 [13] that are reported to the EEA and that are used to establish the reference CO_2 emissions and the manufacturers' average specific CO_2 emissions. It should be noted that the source data differs from the monitoring data, because it covers only a part of the monitoring period, which runs from July 1st 2019 to June 30th 2020, and because the simulation date was used in this work and not the vehicle registration date. Therefore, the results in this work may differ from the official reference CO_2 emissions results. However, it was concluded that these differences do not significantly impact the findings in this work. A description of the data used for the analysis and a comparison with monitoring data is presented in this section.

3.1 VECTO

The CO_2 emissions of new HDVs are determined with the simulation tool VECTO. Each new vehicle is modelled in VECTO and simulated over various mission profiles. The mission profiles are characterised by a distance-based target speed and a vehicle payload that are representative of typical HDV use cases. The mission profiles are simulated with both a reference payload and a low payload that depend on the vehicle group. The main vehicle properties such as mass, air drag, tyre rolling resistance, axle and gearbox torque loss maps (torque loss as a function of input torque and speed), and engine maps (maximum torque, motoring torque and fuel consumption) are required as input. These vehicle and component properties are determined from standardised tests set out in Regulation (EU) 2017/2400 [4]. The vehicle manufacturer can choose not to measure the components but use standard values instead which are defined in Regulation (EU) 2017/2400. To promote the use of measured component properties and to avoid an underestimation of the CO_2 emissions, the standard values represent a worst-case performance for a certain component and include a penalty factor. It is not allowed to use standard values for the internal combustion engine, due to its key role on CO_2 emissions.

The vehicle's longitudinal dynamics are simulated over the different mission profiles based on the vehicle's technical properties and a driver model. The instantaneous engine power is calculated from the power demand at the wheels, the efficiency of each component in the drivetrain and the power demand of the auxiliaries. The engine speed is determined from the engaged gear, the powertrain gear ratios and the dynamic tyre radius. The fuel consumption is calculated through interpolation in the fuel consumption map, using the instantaneous engine torque and speed. The CO_2 emissions are calculated based on the fuel properties. Specific CO_2 emissions in g/km, g/t.km and g/m^3.km are provided as aggregated results for each mission profile.

The simulation results are written in different output files generated by VECTO, each with their own purpose: the customer information file, the manufacturer's records file, the monitoring file, the cycle results file and the sum exec data file. The sum exec data file contains aggregated simulation results per simulated mission profile and payload condition and was used for the analysis in this work. An overview of all variables listed in the sum exec data file is provided in Annex 1. The most important variables are those related to the energy use of each component over the mission profile. This enables establishing the energy balance of the vehicle over the cycle and modelling the performance of specific components. It is then possible to replace certain components in some vehicles and recalculate their CO_2 emissions. This methodology was used to assess the potential need of corrections to the reference CO_2 emissions.

3.2 Scope

The analysis is limited to vehicles that fall under the scope of Regulation (EU) 2017/2400 and that were simulated between October 1st 2019 and June 30th 2020 by the vehicle manufacturer. The considered fleet comprises N2 vehicles with a TPMLM exceeding 7.5 t and N3 vehicles [15]. Excluded from the analysis are:

- vehicles that do not fall within the scope of Regulation (EU) 2017/2400 (e.g. special purpose vehicles [15])
- vocational vehicles, as defined in Regulation (EU) 2017/2400 [4]
- vehicles not belonging to one of the vehicle groups listed in Table 1.

The vehicle manufacturer decided the vocational purpose of vehicles at the time of simulation and could only be attributed to vehicles in groups 4, 5, 9 and 10. Duplicate sum exec data files were removed and the file with the latest simulation date was kept. The following vehicle manufacturers provided the sum exec data files:

- DAIMLER TRUCK AG
- DAF NV
- FORD OTOMOTIV SANAYI AS
- ISUZU MOTORS LTD
- IVECO MAGIRUS-AG
- IVECO SPA
- MAN TRUCK AND BUS SE
- MITSUBISHI FUSO TRUCK AND BUS CORPORATION
- RENAULT TRUCK SA
- SCANIA CV AB
- VOLVO TRUCK CORPORATION

3.3 Data integrity

The data integrity of the CO_2 determination process relies on cryptographic hashing of the different files: each file, from the component files to the final manufacturer's records file, contains a hash value. The hash value is a unique identifier calculated from the data in the file. The manufacturer's records file contains the hash values of all components and the hash of the manufacturer's records file is added to the vehicle's certificate of conformity. This allows tracing back the data integrity from the final CO_2 emissions values to the component files. The sum exec data file is also hashed, but its hash value is not part of the manufacturer's records file and can therefore not be verified.

The data integrity of the sum exec data file was verified by recalculating the hash value of each file from its data and comparing it to the hash value found in the sum exec data file. All hash values matched. This ensures that no data was modified compared to the original VECTO output. However, this does not ensure that the sum exec data files belong to the actual vehicle. A specific vehicle could be simulated with different input data, resulting in different CO_2 emissions. Therefore, the CO_2 emissions in the sum exec data files were compared to those in the monitoring database based on the vehicle's VIN. The vehicles that were present in both databases had the same CO_2 emissions in both databases. The combination of both verification steps gives confidence that the data in the sum exec data files have not been modified.

3.4 Monitoring data comparison

The representativeness of the dataset used in this analysis is verified by comparing the fleet composition and CO_2 emissions of the reference vehicle subgroups to those from the monitoring database as published in Decision (EU) 2021/781 [16] for the 2019 reporting period. Table 10 lists the number of vehicles per subgroup (column 2) and the share of each vehicle subgroup in the fleet (Fleet share dataset) in the dataset used for the analysis. The subgroup shares of the monitoring database, which spans an entire year, are listed in column 4 (Fleet share monitoring) of Table 10. The total number of vehicles in the dataset is about 73 % of the vehicles registered during the monitoring period, which corresponds to missing data from the third quarter of 2019. This confirms that the quarterly vehicle sales remained constant. The fleet shares of the subgroups are similar to those of the monitoring period, especially for subgroup 5-LH, which makes up the majority of the fleet. A difference of 1.2 and 2.0 percentage points can be observed for vehicle groups 4-RD and 9-RD, respectively. This could be caused by vehicles that were registered as vocational but not simulated as such. Thereby they were not considered in the monitoring data. Table 10 also contains the subgroup shares of vehicles simulated in the third and fourth quarter of 2019, as published in an ACEA study [17]. Similar shares are found for subgroups 4-RD and 9-RD. Since this dataset is also based on the information available at the time of simulation, it confirms the hypothesis of vocational vehicles not simulated as vocational. Moreover, this implies that adding the data of vehicles simulated in the third quarter of 2019 to the database would not significantly change the findings.

The average CO_2 emissions per subgroup are listed in Table 11 for the dataset (CO_2 dataset), together with those from the monitoring database (CO_2 monitoring). The discrepancy between the datasets is within one percentage point for all subgroups, except for subgroup 4-LH with 3 % lower average CO_2 emissions than the monitoring data. However, it should be noted that subgroup 4-LH makes up only 2 % of the entire fleet, and this discrepancy will not significantly alter the findings of this analysis. Combining the findings from the comparison of the fleet compositions and the average CO_2 emissions, it can be concluded that the dataset is adequate for evaluating the reference emissions.

Table 10. Fleet shares of the reference subgroups

Subgroup	Vehicles [-]	Fleet share dataset (Q4 2019 – Q2 2020) [%]	Fleet share monitoring[1] (Q3 2019 – Q2 2020) [%]	Fleet share ACEA[2] (Q3 2019 – Q4 2019) [%]
4-UD	413	0.3	0.4	0.4
4-RD	10324	8.3	7.1	7.9
4-LH	2419	2.0	2.7	1.9
5-RD	1151	0.9	0.7	0.8
5-LH	76504	61.7	61.8	62.8
9-RD	9822	7.9	5.9	7.2
9-LH	11445	9.2	10.8	9.2
10-RD	150	0.1	0.1	0.1
10-LH	11751	9.5	10.4	9.7
Total number of vehicles	**123979**	**-**	**170351**	**102290**

[1] Commission Implementing Decision (EU) 2021/781 [16]
[2] CO_2 emissions from heavy-duty vehicles Preliminary CO_2 baseline (Q3-Q4 2019) [17]
Source: JRC, 2022.

Table 11. Average CO_2 emissions per subgroup

Subgroup	Fleet share dataset [%]	CO_2 dataset [g/t.km]	CO_2 monitoring[1] [g/t.km]	Difference [%]
4-UD	0.3	305.6	307.2	-0.5
4-RD	8.3	197.8	197.2	+0.3
4-LH	2.0	102.6	106.0	-3.2
5-RD	0.9	84.7	84.0	+0.8
5-LH	61.7	56.4	56.6	-0.4
9-RD	7.9	110.8	111.0	-0.2
9-LH	9.2	64.6	65.2	-0.9
10-RD	0.1	82.7	83.3	-0.7
10-LH	9.5	58.4	58.3	+0.2

[1] Commission Implementing Decision (EU) 2021/781 [16]
Source: JRC, 2022.

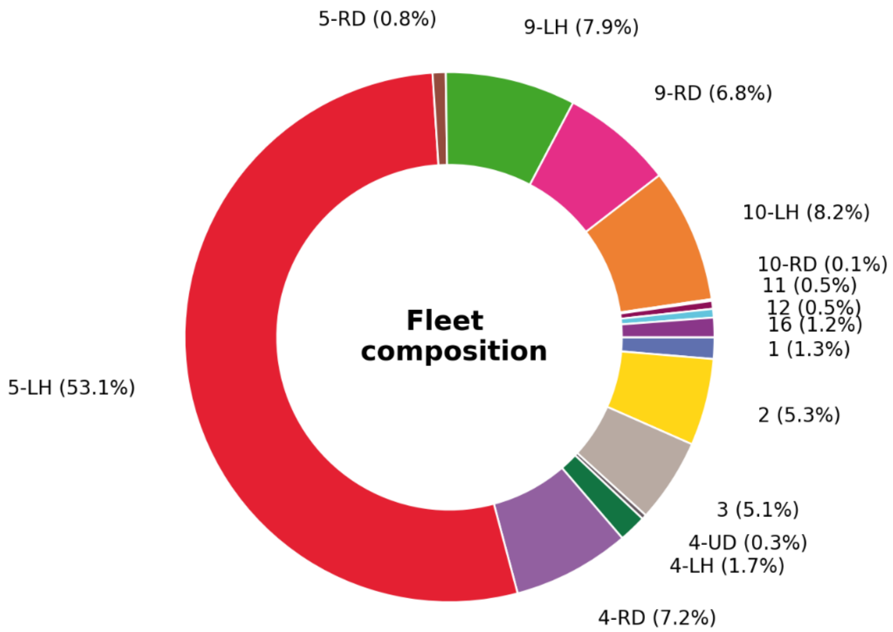
4 Reference fleet

An in-depth analysis of the HDV fleet is provided in this section: the fleet's composition, the CO_2 emissions of the different vehicle subgroups, the main component properties and the number of unique components. Based on the data, representative HDVs are generated for each vehicle subgroup. Finally, the use of standard values for components is discussed.

4.1 Fleet composition

The composition of the fleet is listed in Table 10 for the subgroups considered in the calculation of the reference CO_2 emissions. The majority of the HDVs belong to subgroup 5-LH. The long haul subgroup has a larger market share than the regional delivery subgroup of vehicle groups 5, 9 and 10, with the exception of vehicle group 4. The subgroup shares of all vehicle groups considered in this study is shown in Figure 1. The majority of all HDVs still belong to subgroup 5-LH. When considering all vehicle groups, the subgroups considered for the reference emissions make up about 86 % of the fleet, while vehicle groups 1, 2 and 3 make up 12 % and vehicle groups 11, 12 and 16 make up the remaining 2 %.

Figure 1. Shares of the vehicle subgroups in the fleet



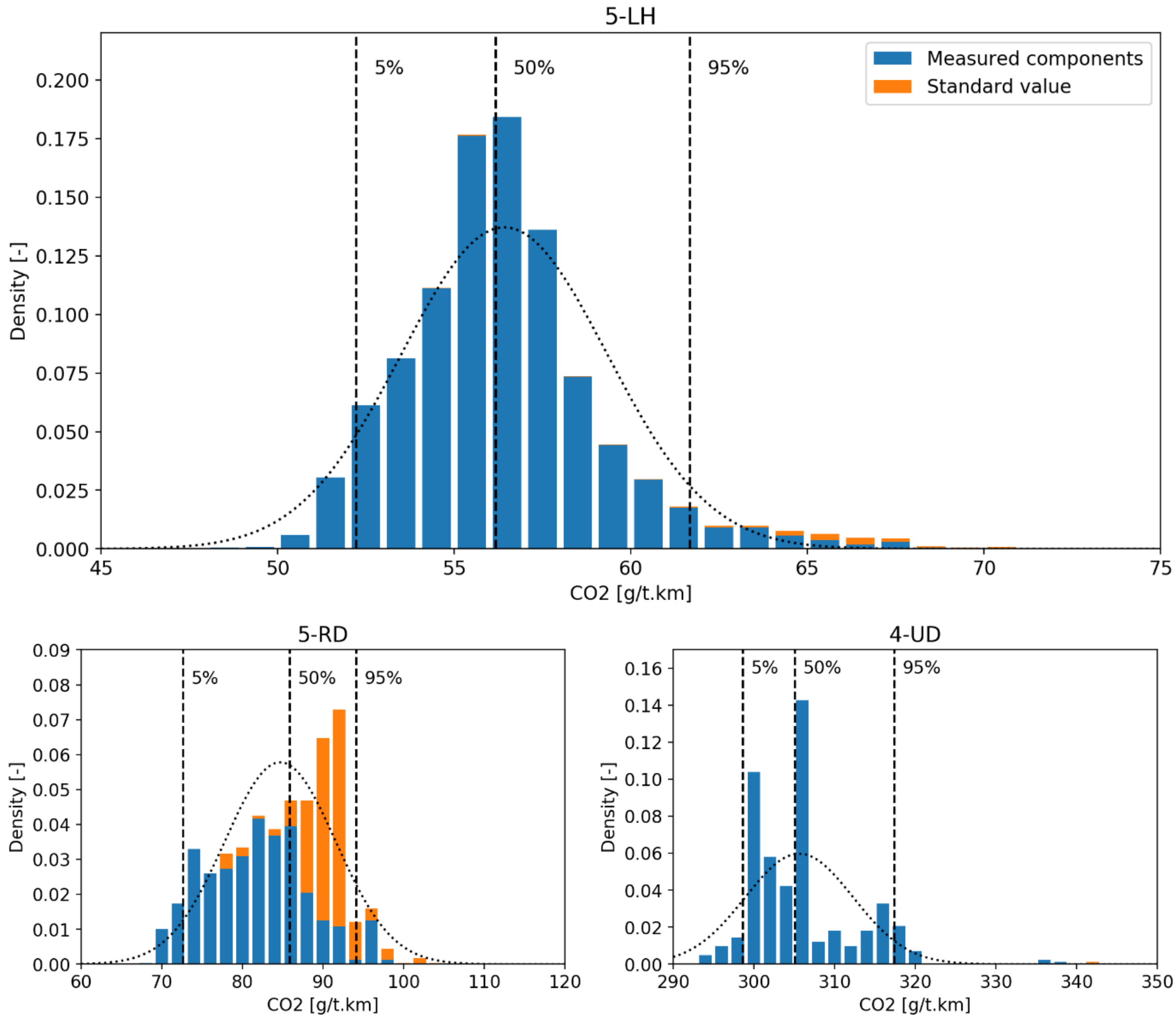
Source: JRC, 2022.

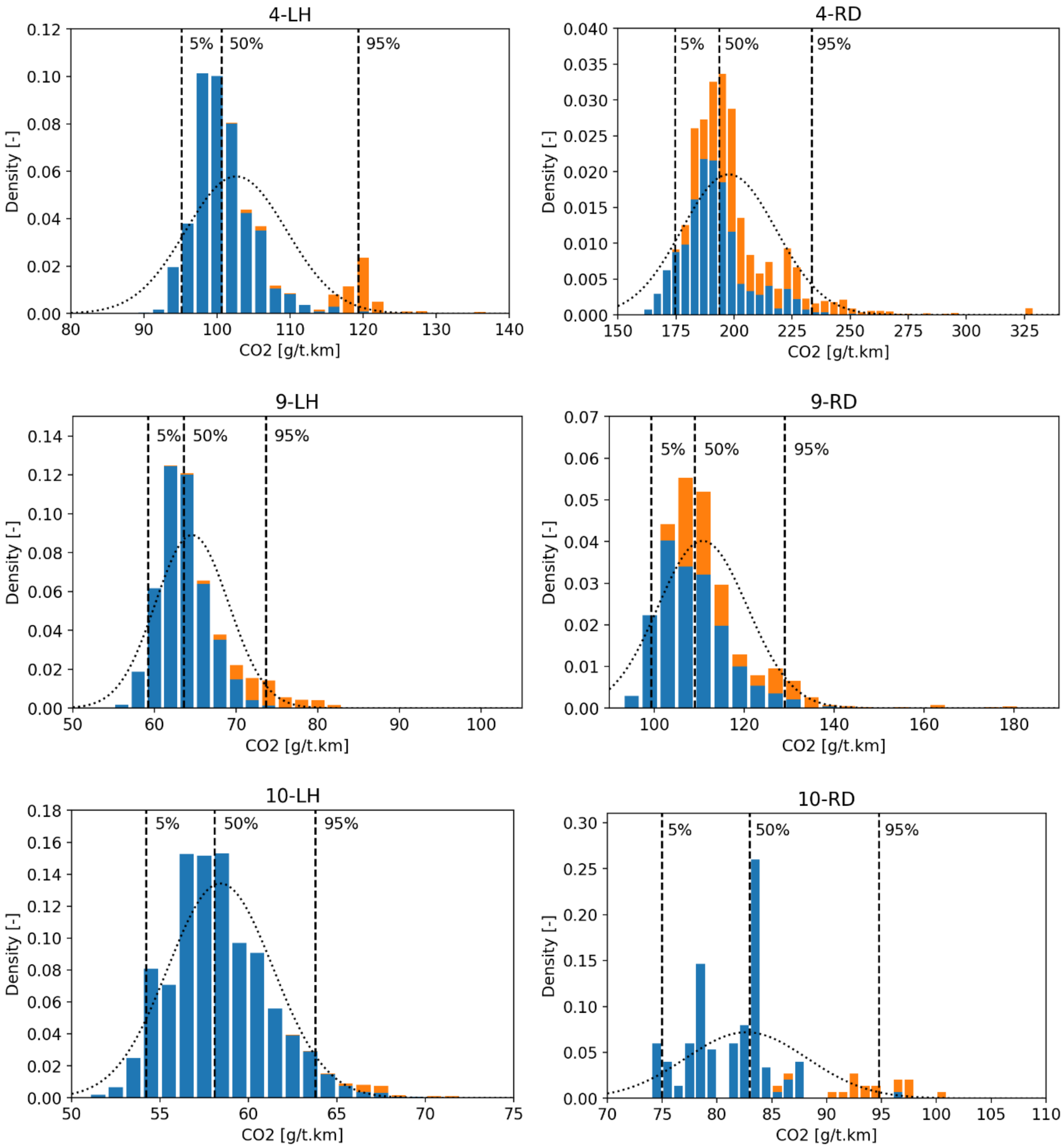
4.2 CO_2 emissions

The average CO_2 emissions per subgroup are presented in Table 11 for the subgroups considered in the calculation of the reference CO_2 emissions. These were calculated according to Eq. 2. Lower specific CO_2 emissions (expressed in g/t.km) are found for the tractors (groups 5 and 10) compared to the rigid lorries (groups 4 and 9). Analogously, lower specific CO_2 emissions are found for the long haul subgroups compared to regional delivery and urban delivery subgroups. The large difference can mostly be attributed to the different simulated payload (listed in Table 4), since vehicles with a higher payload have lower specific CO_2 emissions.

The CO_2 emissions distribution of the different vehicle subgroups is shown in Figure 2. The blue bars represent vehicles with only measured components and the orange bars vehicles that are equipped with at least one component with standard values. The bars are stacked, which means that the outline of the stacked bars represents the entire vehicle subgroup. The dotted line illustrates the normal distribution and the dashed vertical lines mark the 5, 50 and 95 percentiles. Vehicles left of the 5 % line have lower CO_2 emissions than 95 % of the vehicles in the subgroup. The numerical values of the 5, 50 and 95 percentiles are listed in Table 12. The vehicles with standard values for certain components can be mostly found at the right-hand tail of the distribution, as they have in general higher CO_2 emissions compared to vehicles with only measured components. This confirms the worst-case performance of components with standard values and the hypothesis that the application of standard values can increase the reference CO_2 emissions. Whereas standard values and the resulting impact on the average CO_2 emissions are limited for subgroup 5-LH, other subgroups (e.g. 4-LH) have more standard values. This has a more significant effect on the shape of the distribution.

Figure 2. Distribution of CO_2 emissions in g/t.km per vehicle subgroup of vehicles with only measured components (blue bars) and vehicles with standard values (orange bars)





Source: JRC, 2022.

Table 12. CO_2 emissions per subgroup

Subgroup	Mean CO_2 [g/t.km]	Median CO_2 [g/t.km]	p_{05} CO_2 [g/t.km]	p_{95} CO_2 [g/t.km]
4-UD	305.6	305.1	298.6	317.4
4-RD	197.8	193.8	174.7	233.6
4-LH	102.6	100.6	95.1	119.4
5-RD	84.7	85.9	72.7	94.1
5-LH	56.4	56.2	52.2	61.7
9-RD	110.8	109.0	99.3	129.1
9-LH	64.6	63.6	59.2	73.7
10-RD	82.7	83.0	75.0	94.8
10-LH	58.4	58.1	54.2	63.8

Source: JRC, 2022.

Other vehicle groups

The average CO_2 emissions and the 5, 50 and 95 percentiles of the vehicle groups not considered in the calculation of the reference CO_2 emissions are listed in Table 13. The CO_2 emissions (in g/t.km) of vehicles in groups 1, 2 and 3 are calculated with the simulated CO_2 emissions (in g/km) and the average payload of the group, as described in Section 2.2. This is not the same payload as the one that the vehicle was simulated with. The lowest CO_2 emissions of vehicles in groups 1, 2 and 3 can be found in group 3, which corresponds to the groups with the highest payload (Table 6). The same holds true for vehicle groups 11, 12 and 16.

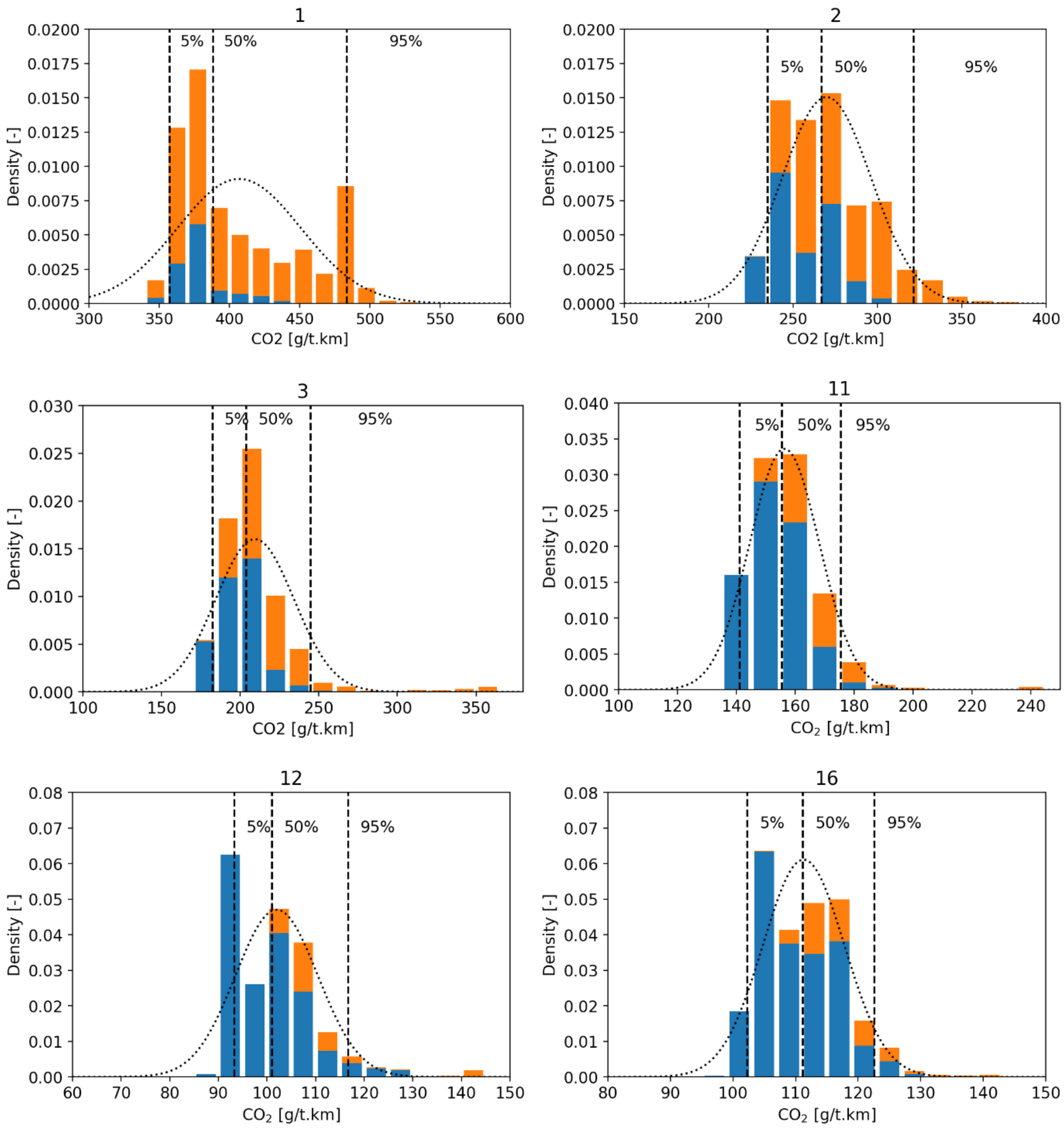
Table 13. CO_2 emissions of the non-reference groups

Subgroup	Mean CO_2 [g/t.km]	Median CO_2 [g/t.km]	p_{05} CO_2 [g/t.km]	p_{95} CO_2 [g/t.km]
1	406.8	388.2	357.3	483.5
2	269.8	266.7	234.8	321.5
3	209.3	203.9	182.4	244.7
11	156.3	155.5	141.1	175.4
12	102.0	101.0	93.3	116.7
16	111.3	111.2	102.3	122.6

Source: JRC, 2022.

The CO_2 emissions distribution of the vehicle groups not considered in the calculation of the reference CO_2 emissions is shown in Figure 3. The blue bars represent vehicle equipped with only measured components and the orange bars vehicles equipped with at least one component with standard values. The vehicles with standard values for certain components have generally higher CO_2 emissions compared to vehicles with only measured components. Many vehicles have components with standard values in groups 1, 2 and 3. This could be caused by the fact that these vehicle groups are not subject of the CO_2 performance standards and do not share components with vehicles in the reference subgroups.

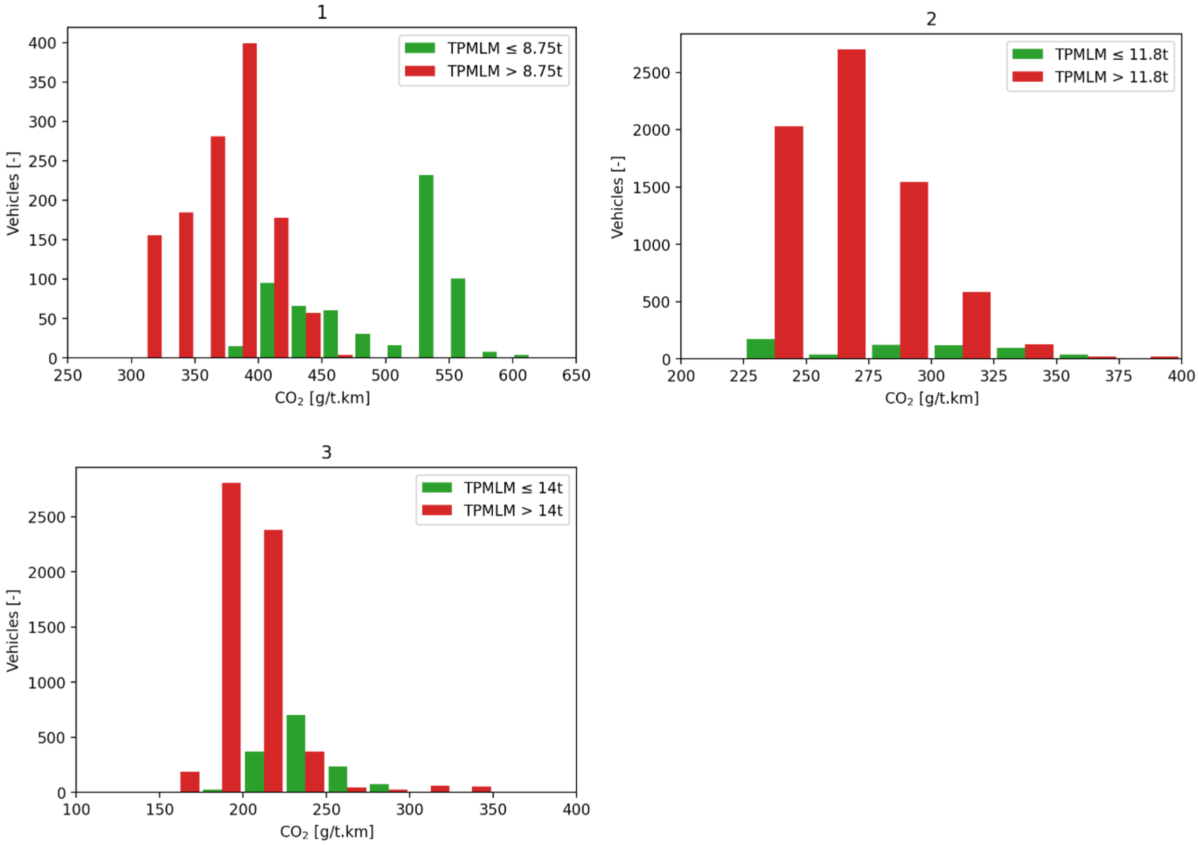
Figure 3. Distribution of the CO_2 emissions in g/t.km of the non-reference groups of vehicles with only measured components (blue bars) and vehicles with standard values (orange bars)



Source: JRC, 2022.

An important distinction exists between the payload applied to vehicles in groups 1, 2 and 3 and the payload applied to vehicles in the other groups. Vehicles in groups 1, 2 and 3 are simulated in VECTO for a given mission profile with a payload that is a function of the vehicle's TPMLM. Vehicles with a higher TPMLM within the group are simulated with a higher payload. Vehicles in the other groups are all simulated with a fixed payload per subgroup and mission profile. The variation of the payload within a group affects the calculation of the specific CO_2 emissions. For this reason, the CO_2 emissions were also calculated with the simulated CO_2 emissions (in g/km) and the simulated payload, rather than the average payload as presented in Figure 3. The distribution of these CO_2 emissions of vehicle groups 1, 2 and 3 is shown in Figure 4. The distribution shape is much wider than the distribution of the CO_2 emissions with the average payload. The green bars represent vehicles with a low TPMLM in the vehicle group and the red bars represent vehicles with a high TPMLM. Since the simulated payload is a function of the vehicle's TPMLM, the figure also illustrates the effect of the payload on the CO_2 emissions. The average value is similar for both calculation approaches. However, the approach with the actual payload would penalise vehicles with a lower TPMLM within the group because of the lower reference for normalizing the CO_2 emissions. A vehicle with a lower TPMLM is simulated with a lower payload, resulting in lower specific CO_2 emissions, compared to a vehicle with a higher TPMLM.

Figure 4. Distribution of the CO_2 emissions in g/t.km with the actual payload of groups 1, 2 and 3 of vehicles with a low TPMLM (green bars) and vehicles with a high TPMLM (red bars)

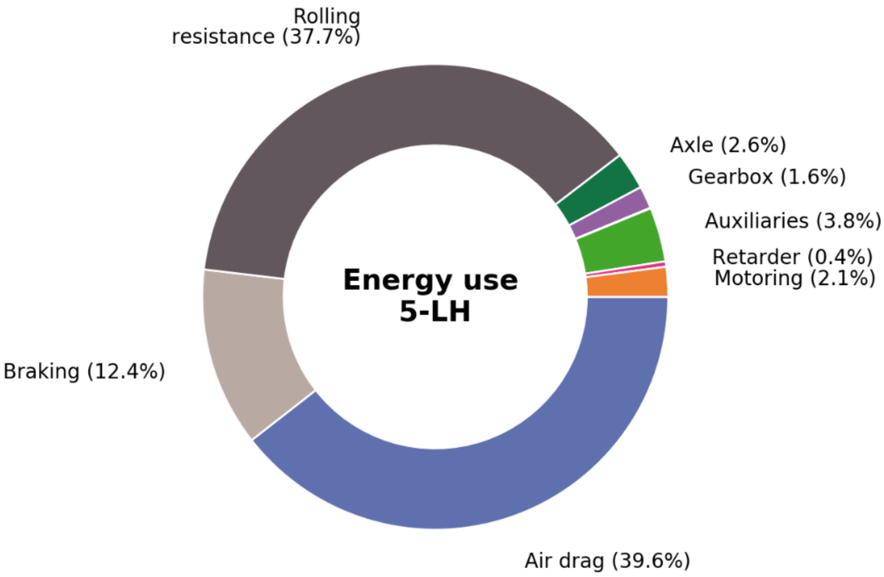


Source: JRC, 2022.

4.3 Component analysis

The average distribution of the energy use of a 5-LH vehicle[1] over the long haul mission profile with a reference payload is shown in Figure 5. The largest part of the energy is used to overcome the road resistances (air drag and rolling resistance) or is lost during braking. Due to individual component losses, about 10% of the energy is lost in the powertrain. The main component and vehicle properties that affect these losses are discussed in this section: air drag, curb mass (braking and rolling resistance), tyre rolling resistance, axle, gearbox, retarder, engine (motoring) and auxiliaries. Consequently, the components that are responsible for a large part of the losses also have an important effect on the vehicles' fuel consumption and CO_2 emissions. It should be noted that the energy distribution will differ slightly depending on the vehicle subgroup and the mission profile. E.g. vehicles designed for mainly regional or urban driving will be less aerodynamically optimised and will exhibit higher air drag losses over the long haul mission profile. The share of the air drag will also be reduced over mission profiles with less high-speed driving.

Figure 5. Energy use of 5-LH vehicles over the long haul mission profile



Source: JRC, 2022.

4.3.1 Air drag

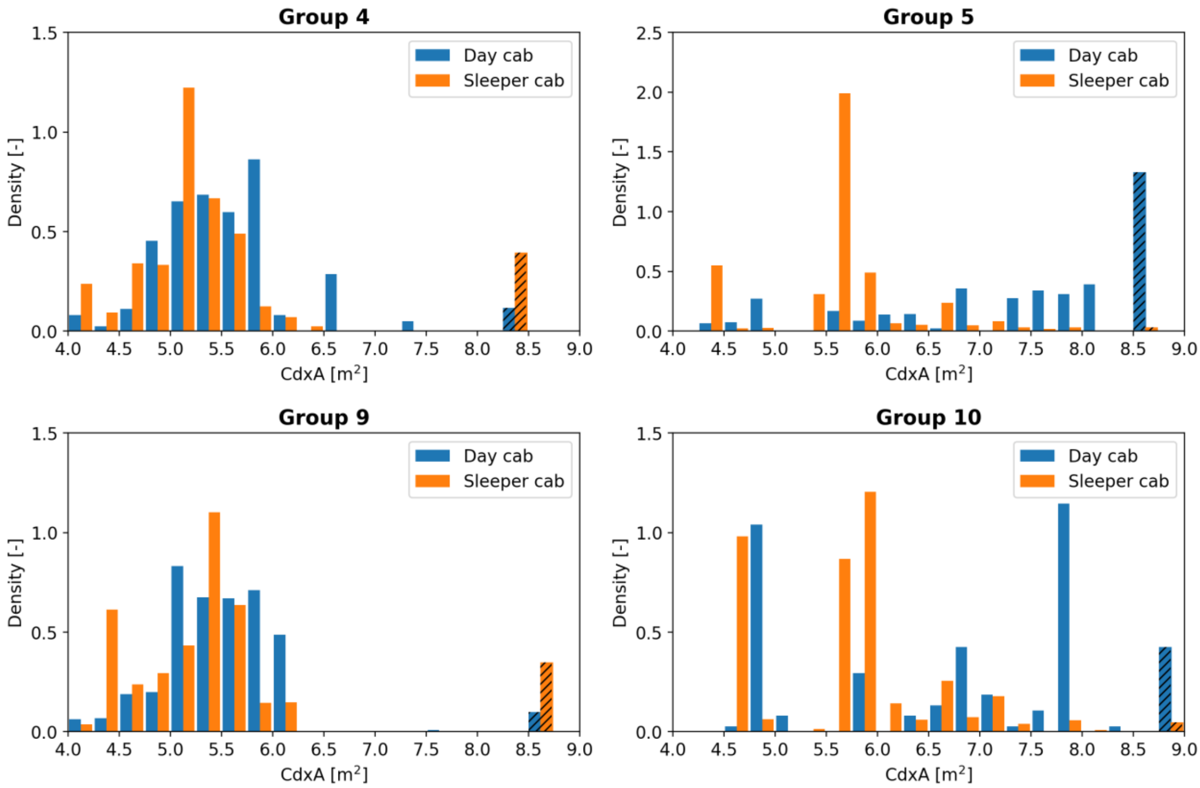
The largest part of the energy consumed by the vehicle over a long haul mission profile is to overcome the aerodynamic resistance or air drag. The vehicle drag area (CdxA) is the vehicle characteristic that defines the magnitude of the aerodynamic resistance together with the vehicle speed. The CdxA is defined as the product of the vehicle's frontal area and its aerodynamic coefficient, which depends on the vehicle's shape. The CdxA of a vehicle's cabin is determined with a constant speed test, during which the vehicle is equipped with a semi-trailer or body with standardised dimensions. The distribution of the CdxA is shown in Figure 6 for each vehicle group. The blue bars represent vehicles with a day cabin and the orange bars vehicles with a sleeper cabin. A sleeper cabin has a sleeping compartment behind the driver's seat and a day cabin lacks such a compartment. The presence of a sleeper cabin is also a criterion for the classification of the subgroups together with the rated engine power: vehicles with a sleeper cabin are generally categorized in the LH subgroup and vehicles with a day cabin in the RD subgroup. It should be noted that both distributions are normalised to visualise the shape of the distributions best. This means that the height of the bars can only be compared within the distribution and not between cabin types; there are far more vehicles with a sleeper cabin than a day cabin in group 5.

The presence of a sleeping compartment does not significantly increase the vehicle's CdxA, as the CdxA range is similar for both cabin types. Although it can be expected that more vehicles with a sleeper cabin are equipped with air drag-reducing components (e.g. roof spoiler or side skirts) to reduce fuel consumption since these vehicles are optimised for long haul operation. Tractors (vehicle groups 5 and 10) exhibit a larger spread of

[1] The vehicle group 5-LH is used as an example because it is the most widely used vehicle subgroup.

CdxA compared to the rigid lorries (groups 4 and 9), but they have a distribution skewing more to the low side. This indicates that tractors are more aero optimised compared to rigid lorries. The bars in Figure 6 with a black striped pattern are vehicles that use standard values for the air drag. The standard values represent a worst-case behaviour, especially for the rigid lorries where there is a big difference with the measured CdxA. Given the important contribution of the air drag on the overall vehicle energy consumption, the use of standard values for the CdxA can significantly affect the vehicle's CO_2 emissions and the reference CO_2 emissions.

Figure 6. Distribution of the CdxA (in m^2) per vehicle group of vehicles with a day cab (blue bars), a sleeper cab (orange bars) and standard value (hashed bars)

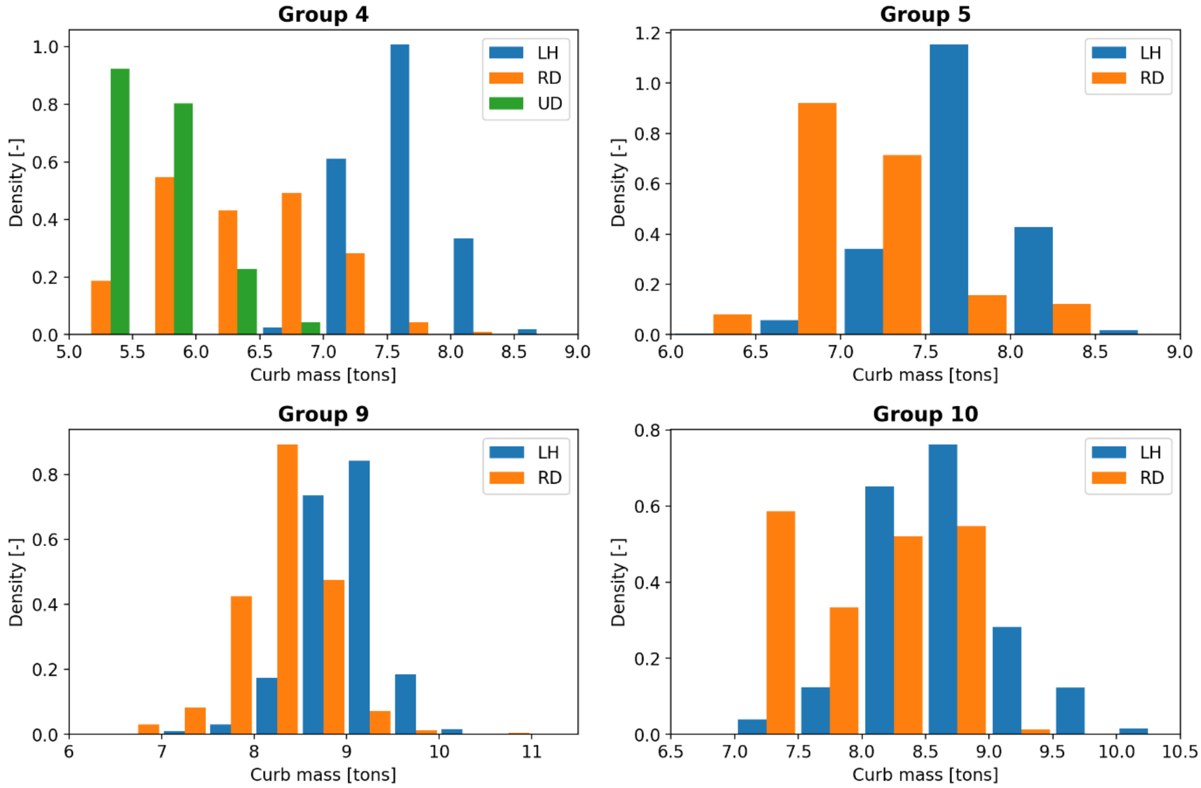


Source: JRC, 2022.

4.3.2 Curb mass

The vehicle curb mass is defined as the 'actual mass of the vehicle' in Regulation (EC) 1230/2012 [18], except with the tanks filled to at least 50% of their capacity and without superstructure (body or trailer). The mass of the superstructure is taken into account in the simulation as a generic value that depends on the vehicle group and the mission profile. The curb mass affects the energy consumed during acceleration, braking and overcoming the rolling resistance. The distribution of the curb mass of the different subgroups is shown in Figure 7, with the bars of different colours representing the different vehicle subgroups within a group. The vehicles in the RD and UD subgroups have a lower curb mass compared to the vehicles in the LH subgroups. Similarly, vehicles with 3 axles (groups 9 and 10) have a higher mass compared to their 2-axled variant (groups 4 and 5). Standard values cannot be used for the curb mass.

Figure 7. Distribution of the vehicle curb mass (in tons) per vehicle group of vehicles in the long haul (blue bars), regional delivery (orange bars) and urban delivery (green bars) subgroups



Source: JRC, 2022.

4.3.3 Rolling resistance

The rolling resistance that the vehicle has to overcome is a function of the vehicle's mass and the tyres' rolling resistance. The tyre's rolling resistance is quantified by the dimensionless rolling resistance coefficient (RRC), which is determined from a standardised test procedure. The tyre's RRC is also used to establish the tyre fuel efficiency classes, according to Regulation (EU) 2020/740 [19]. HDVs are equipped generally with C3 class tyres, based on their load capacity index. Within the C3 class, tyres with an RRC of less than 4.0 N/kN fall in fuel efficiency class A, while tyres with an RRC of more than 7.1 N/kN fall in fuel efficiency class E. The allowed RRC values associated with each fuel efficiency class are listed in Table 14.

Table 14. RRC per tyre fuel efficiency class

Fuel efficiency class	RRC [N/kN]
A	RRC ≤ 4.0
B	4.1 ≤ RRC ≤ 5.0
C	5.1 ≤ RRC ≤ 6.0
D	6.1 ≤ RRC ≤ 7.0
E	7.1 ≤ RRC

Source: Regulation (EU) 2020/740, 2020.

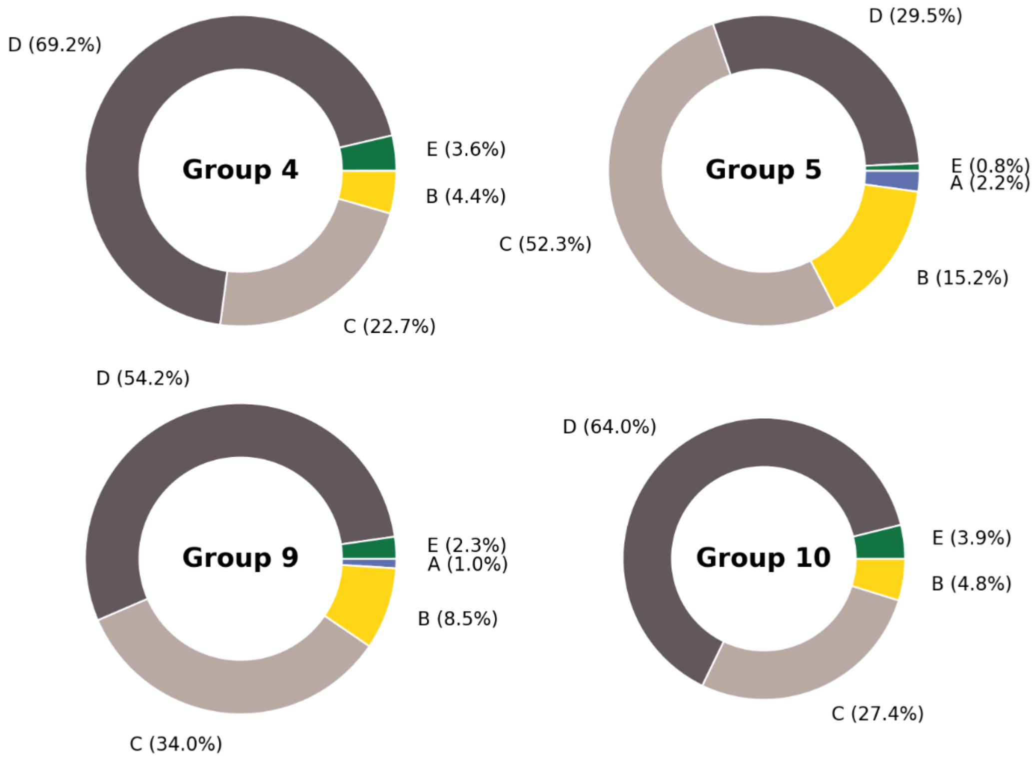
In VECTO the vehicle's rolling resistance coefficient is calculated from the tyre RRC and the load on each axle according to Eq. 6.

$$RRC = \sum_i s_i \cdot RRC_{ISO,i} \cdot \left(\frac{s_i \cdot m \cdot g}{w_i \cdot F_{zISO,i}}\right)^{-0.1} \tag{6}$$

With *RRC* the vehicle's rolling resistance coefficient, s_i the relative axle load of axle *i*, $RRC_{ISO,I}$ the tyre RRC on axle *i* determined with a standardized test, *m* the mass, *g* the earth gravitational constant, w_i the number of tyres on the axle and $F_{zISO,i}$ the test load on the tyre used to determine RRC_{ISO}. The fuel efficiency class based on the vehicle's RRC without trailer over the long haul mission profile with a reference load is shown in Figure 8 for the different vehicle groups. The class is not the same as the individual tyre's fuel efficiency class, since it is based on a weighted average of the different tyres.

The vast majority of the vehicles have tyres with a fuel efficiency class of C or D. Most tractors are equipped with C class tyres and most rigid lorries with D class tyres. Vehicles in group 5 have the lowest share of class E and the highest share of class A tyres. This indicates that this vehicle group is the most optimised for a low rolling resistance, but progress can still be made. Since the measurement of the tyre RRC is mandatory for all tyres on the market that are mounted on HDVs in practise, no standard values were used for the tyre RRC.

Figure 8. Tyre fuel efficiency class per vehicle group



Source: JRC, 2022.

4.3.4 Axle

A part of the energy transferred from the engine to the wheels is lost in the axle. The distribution of the axle efficiency of the different vehicle subgroups is shown in Figure 9. The axle efficiency was determined as the average value over a representative mission profile. The representative mission profile is the long haul mission profile for vehicles in the LH subgroups, regional delivery for vehicles in the RD subgroups and urban delivery for vehicles in the UD subgroups. The blue bars represent vehicles where the efficiency of the axles was measured and the orange bars vehicles where a standard value was used for the axle efficiency. Because of the low share of vehicles with standard values, no common normalisation was applied, to be able to visualise both distributions. Hence the height of the bars cannot be used to compare the share of vehicles with measured axles and axles with standard values. The share of vehicles with measured or standard values for the axle is discussed in Section 4.6. The axle efficiency of vehicles in the LH subgroups is higher compared to vehicles in the RD and UD subgroups. The axle efficiency is very similar for vehicles in the LH subgroups, but the tractors have a slightly higher efficiency compared to the rigid lorries for vehicles in the RD subgroups. It is not visualised, but few vehicles in the LH subgroups have axles with standard values, whereas more vehicles in the RD subgroups use axles with a standard value. The standard values also exhibit the worst-case performance, illustrated by the separate distribution at a lower efficiency. Axles that use standard values also have a distribution, not a single value, since the standard value is an efficiency, based on the gear ratio and axle type.

4.3.5 Gearbox

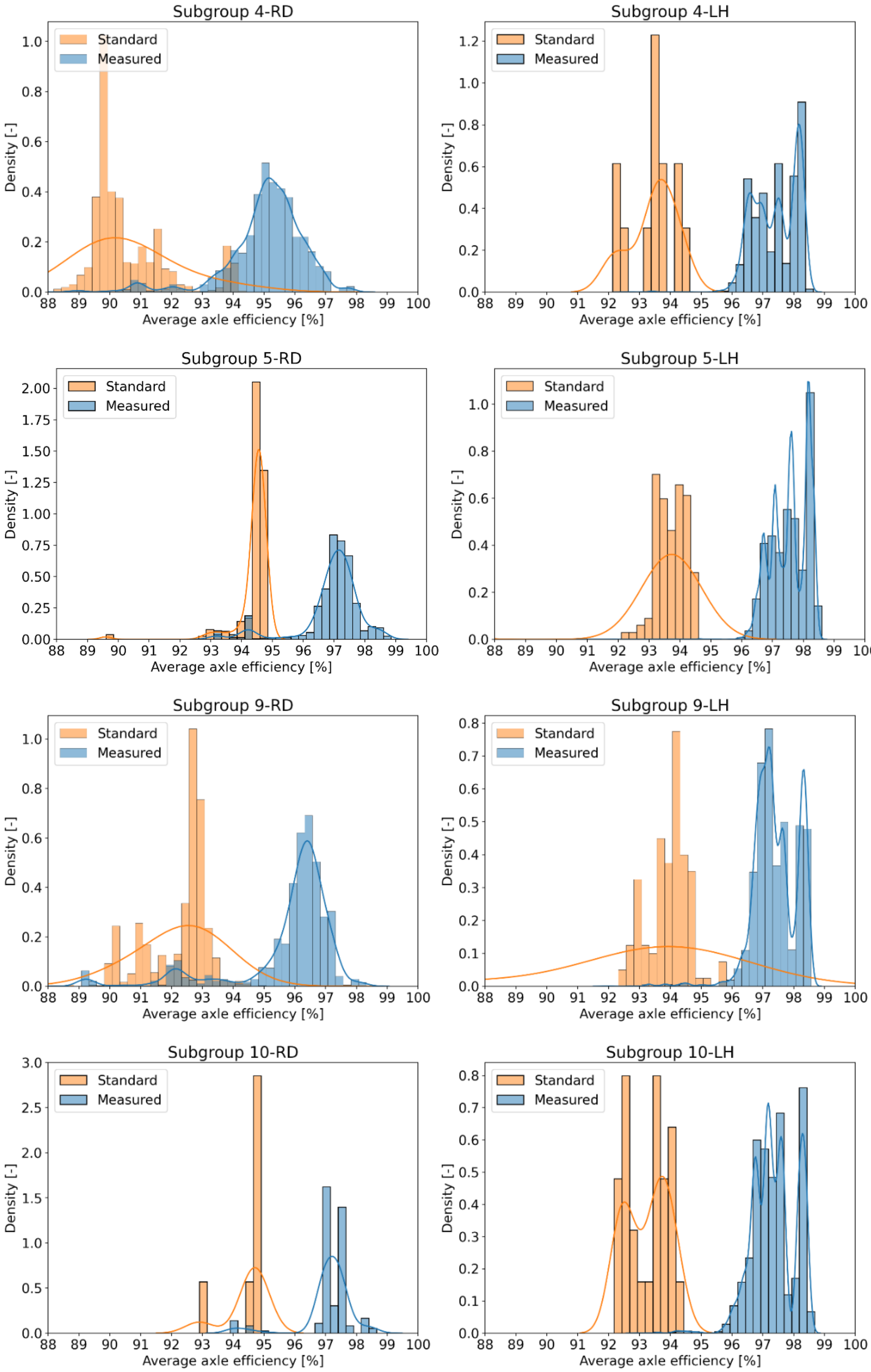
HDVs are equipped with different types of transmission based on their use case. Three types of transmissions can be distinguished:

1. **Manual Transmission** (MT): a manually operated transmission with two or more selectable speed ratios that are obtained using synchronisers.
2. **Automated Manual Transmission** (AMT): an automatically shifting transmission with two or more selectable speed ratios that are obtained using tooth clutches (un-/synchronised).
3. **Automatic Powershifting Transmission** (AT): an automatically shifting transmission with more than two friction clutches and several selectable speed ratios that are obtained mainly by the use of those friction clutches. A serial configuration has the torque converter in series with the transmission (non-power split).

The share of the transmission types per vehicle group is shown in Figure 10. The vast majority of HDVs is equipped with an AMT. Smaller shares of rigid lorries (groups 4 and 9) are equipped with MT and AT type transmissions, whereas tractors (groups 5 and 10) are equipped almost exclusively with an AMT.

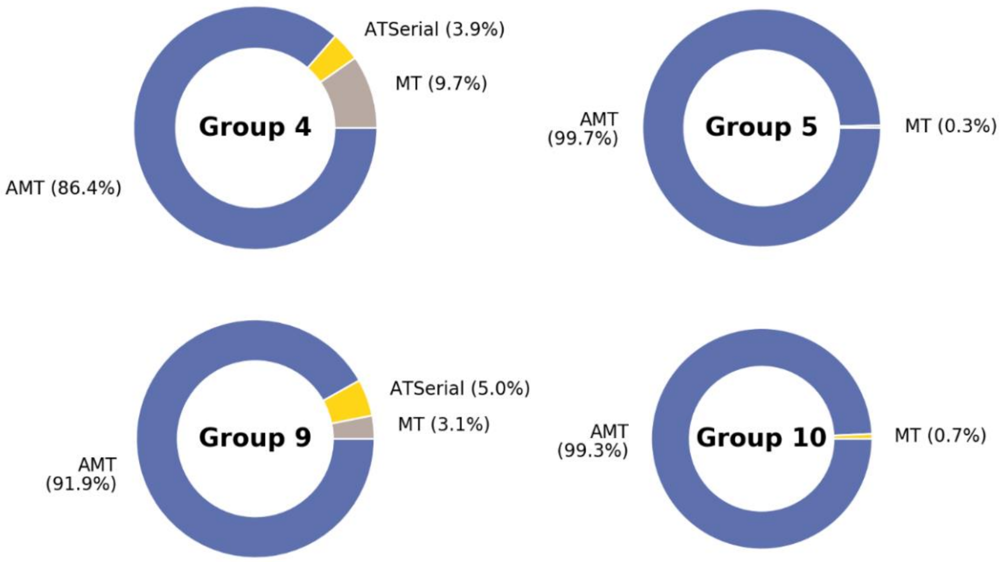
Similar to the axle, a part of the energy transferred from the engine to the wheels is lost in the gearbox. The distribution of the gearbox efficiency of the different vehicle subgroups is shown in Figure 11. The gearbox efficiency is the average value over a representative mission profile of the LH, RD and UD subgroups. The blue bars represent vehicles equipped with an AMT, the orange bars vehicles equipped with an MT and the green bars vehicles equipped with an AT. It should be noted that all three distributions are normalised to best visualise the shape of the distributions. This means that the height of the bars can only be compared for a certain transmission type and not between transmission types.

Figure 9. Distribution of the average axle efficiency per vehicle subgroup over the representative mission profile of vehicles equipped with a measured axle (blue bars) and axle with standard values (orange bars)



Source: JRC, 2022.

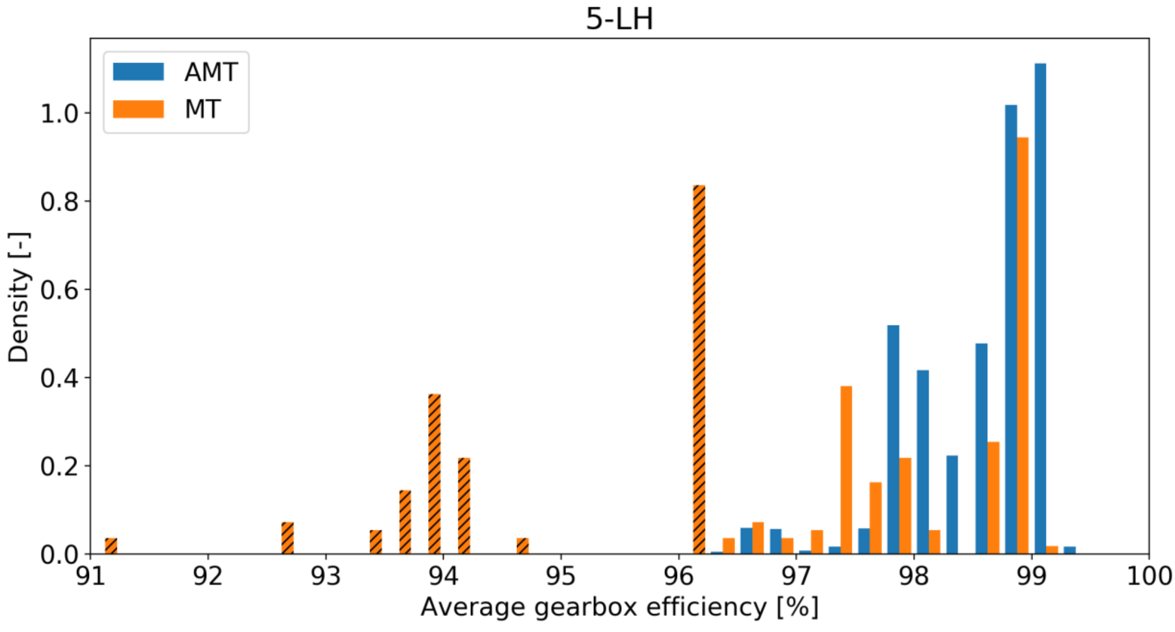
Figure 10. Share of the transmission types per vehicle group

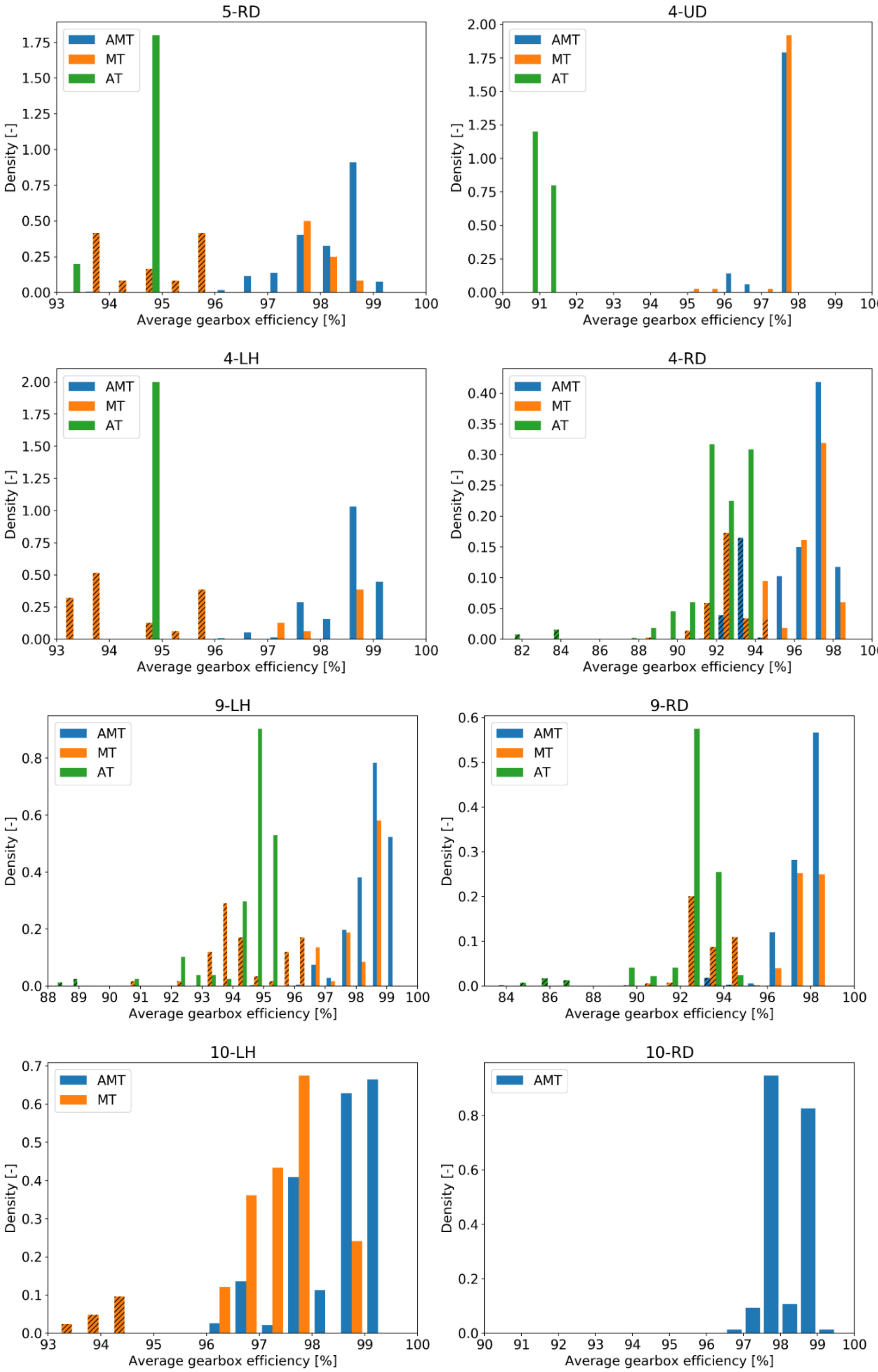


Source: JRC, 2022.

A similar efficiency is found for AMTs and MTs, although a larger share of vehicles has an AMT with a high efficiency than an MT with a high efficiency. The lowest efficiency is observed for ATs, which is on average about 4 percentage points lower than an AMT or MT. Fortunately, only a small fraction of the fleet is equipped with an AT, which consists mostly of rigid lorries. The highest efficiency transmissions can be found in 5-LH and 10-LH vehicles and the largest part of the vehicles are equipped with those transmissions. The bars in Figure 11 with a black striped pattern are vehicles that use standard values for the gearbox efficiency. Almost all AMTs have been certified, with only a small share of vehicles in subgroup 4-RD making use of an AMT with standard values. A larger share of MTs make use of standard values. Also for the transmissions, the standard values represent the worst-case performance, illustrated by the separate distribution at a lower efficiency. Similar to the axles, the standard value is not a single value, since it is an efficiency for every gear, based on the gear ratio, rated input torque and transmission type.

Figure 11. Distribution of the gearbox efficiency per vehicle subgroup over the representative mission profile of vehicles equipped with an AMT (blue bars), MT (orange bars) and AT (green bars) gearbox



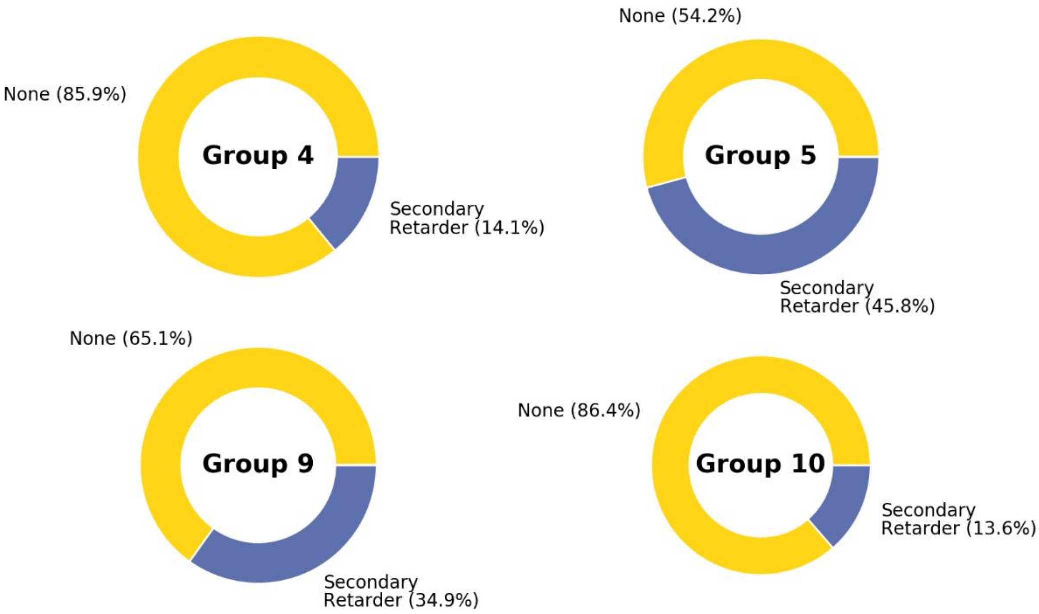


Source: JRC, 2022.

4.3.6 Retarder

A retarder is a braking device in a vehicle powertrain used for permanent braking (e.g. when driving down a hill). The share of vehicles equipped with a retarder is shown in Figure 12. A significant share of the fleet is equipped with a retarder. As illustrated by Figure 5, the retarder is only responsible for a small part of the energy losses in the vehicle (0.4%). Therefore, its efficiency is not further discussed.

Figure 12. Share of vehicles with retarder per vehicle group



Source: JRC, 2022.

4.3.7 Engine

Only vehicles powered by an internal combustion engine are considered in the reference period. The engine fuel type is listed in Table 15 for the different vehicle groups. The vast majority of vehicles have a compression ignition (CI) engine fuelled with diesel. Among the alternative fuels, compressed natural gas (CNG) is the most common fuel in the regional delivery subgroups and liquefied natural gas (LNG) in the long haul subgroups. Both of these fuels are for engines with positive ignition (PI). A small share of vehicles is equipped with a CI ethanol fuelled engine.

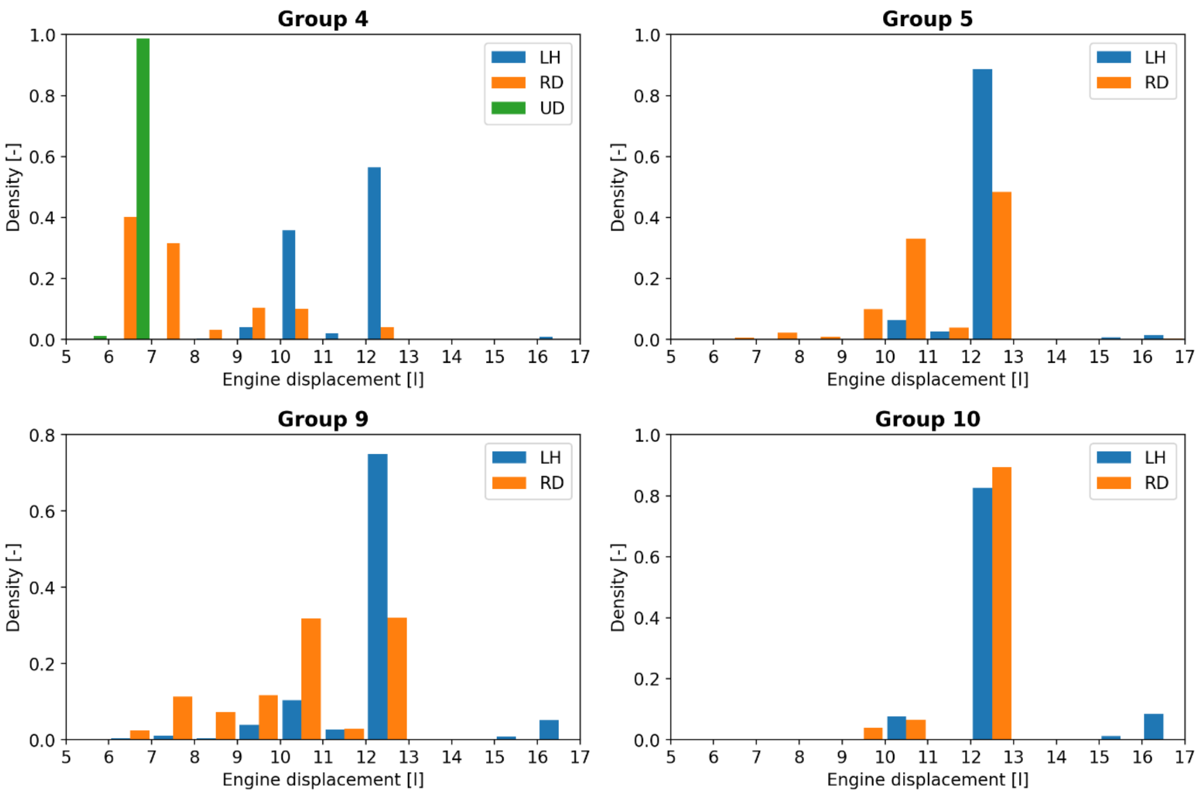
The distribution of the engine displacement and rated power are shown in Figure 13 and Figure 14 for the different vehicle groups. The bars represent the different vehicle subgroups in the group: LH (blue), RD (orange) and UD (green). Vehicles in subgroup 4-UD are all powered by similar engines in terms of displacement and rated power. Vehicles in the LH subgroups are equipped with larger and more powerful engines compared to the vehicles in the RD subgroups. The majority of vehicles are equipped with a 12l rated at 300 to 350 kW. Standard values cannot be used for the engine.

Table 15. Engine fuel type per subgroup

Subgroup	Diesel CI [%]	CNG PI [%]	LNG PI [%]	Ethanol CI [%]
4-UD	98.79	1.21	0.00	0.00
4-RD	97.55	2.30	0.10	0.06
4-LH	99.42	0.04	0.54	0.00
5-RD	90.88	8.51	0.52	0.09
5-LH	96.75	0.87	2.36	0.02
9-RD	96.30	3.46	0.18	0.05
9-LH	97.72	1.45	0.77	0.06
10-RD	100.00	0.00	0.00	0.00
10-LH	99.10	0.82	0.09	0.00

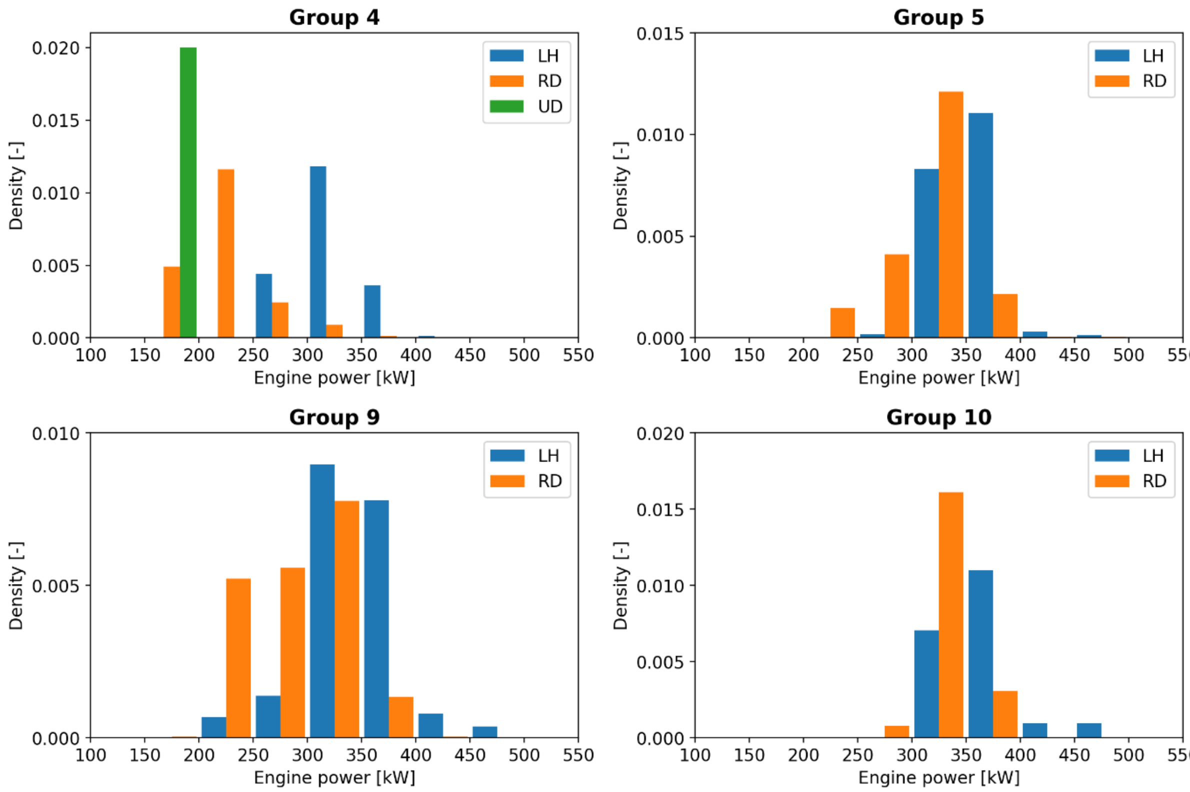
Source: JRC, 2022.

Figure 13. Distribution of the engine displacement (in litres) per vehicle group of vehicles in the long haul (blue bars), regional delivery (orange bars) and urban delivery (green bars) subgroups



Source: JRC, 2022.

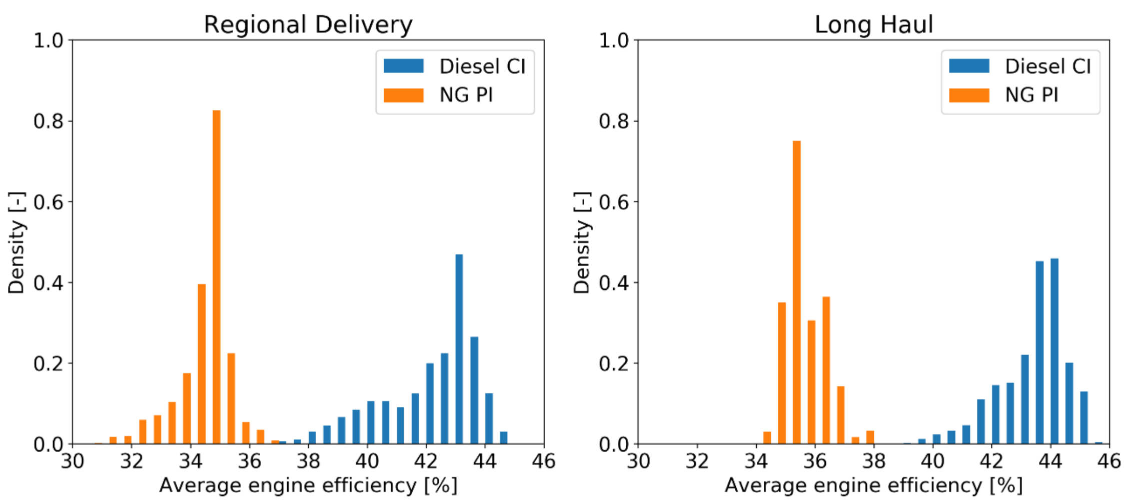
Figure 14. Distribution of the rated engine power (in kW) per vehicle group of vehicles in the long haul (blue bars), regional delivery (orange bars) and urban delivery (green bars) subgroups



Source: JRC, 2022.

The distribution of the average engine efficiency over the regional delivery and the long haul cycle is shown in Figure 15. The blue bars represent the vehicles with a Diesel CI engine and the orange bars vehicles with either a CNG PI or LNG PI engine. The average engine efficiency is higher over the long haul cycle compared to the regional delivery cycle since the engine is operated over a narrower range of conditions. CI engines exhibit a higher average efficiency compared to PI engines over both cycles. The distribution of the Diesel CI engine could be split up based on the engine displacement, since engines with a displacement larger than 10l achieve a higher efficiency compared to engines with a smaller displacement.

Figure 15. Distribution of the average engine efficiency of vehicles with a Diesel CI (blue bars) and a natural gas (orange bars) over the regional delivery and long haul cycle.



Source: JRC, 2022.

4.3.8 Auxiliaries

A significant part of the energy is required to power the auxiliaries in an HDV. In VECTO, a generic power demand is considered for the different auxiliaries based on their technology. The following technologies are considered:

(a) Pneumatic system

(b) Engine cooling fan

(c) Steering pump

(d) Electric system

(e) Air Conditioning system

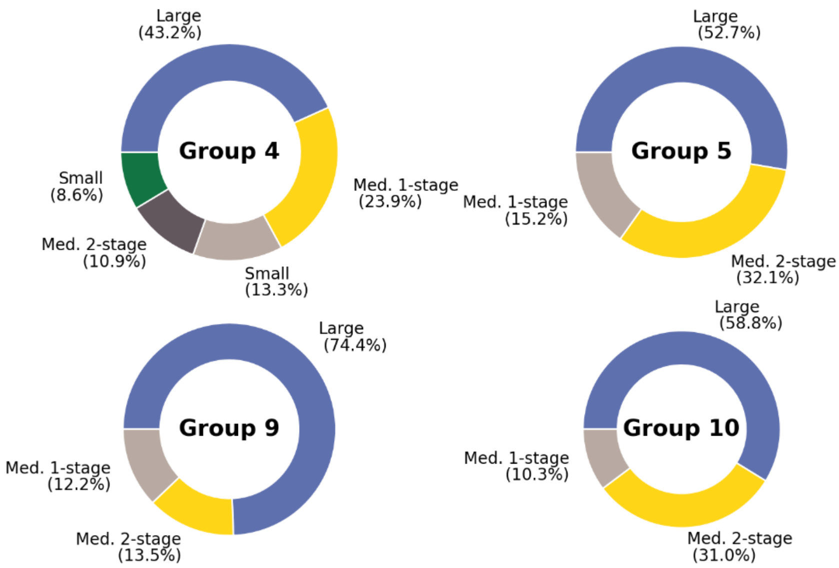
(f) Power take-off

The shares of the different auxiliary technologies are shown in Figure 16 per vehicle group and auxiliary. It should be noted that technologies with a share of less than 1% are not shown in the figures for the sake of clarity. For the same reason, the pneumatic system technologies are grouped based on their compressor displacement and stages, regardless of the presence of energy-saving systems or optimized air regeneration. The steering pump technology for vehicles with 3 axles (groups 9 and 10) is split up if two steerable axles are installed on the vehicle.

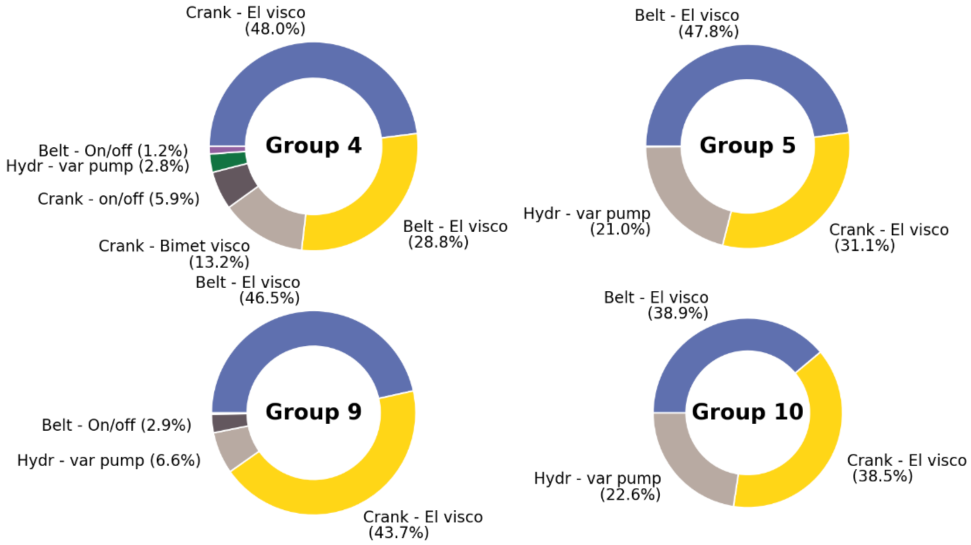
Similar technologies and shares can be observed for vehicles in groups 5, 9 and 10, whereas a larger number of technologies are used for vehicles in group 4. Analogously, the technology shares are similar for the long haul and regional delivery subgroups per vehicle group. The exception is power take-off (PTO), where the regional delivery subgroup has double the share of vehicles with PTO installed compared to the long haul subgroup.

Figure 16. Share of different auxiliary technologies per vehicle group and auxiliary type

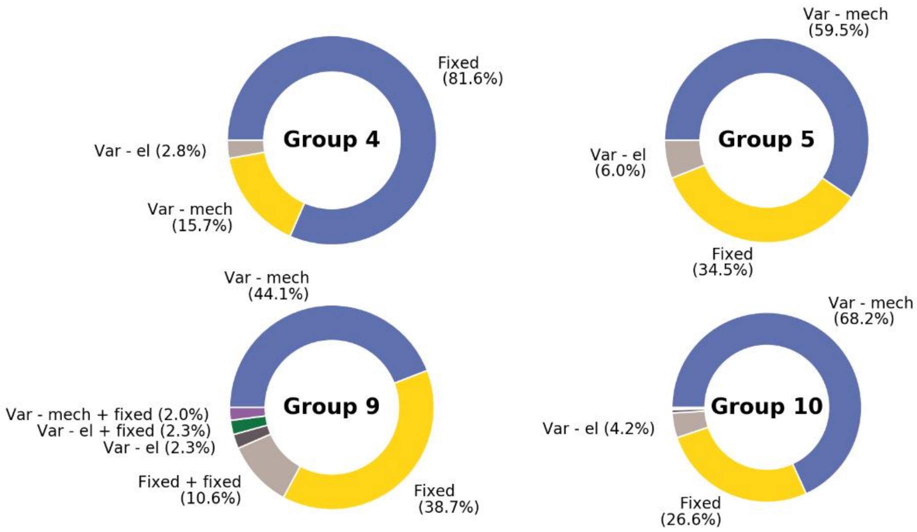
(a) Pneumatic system



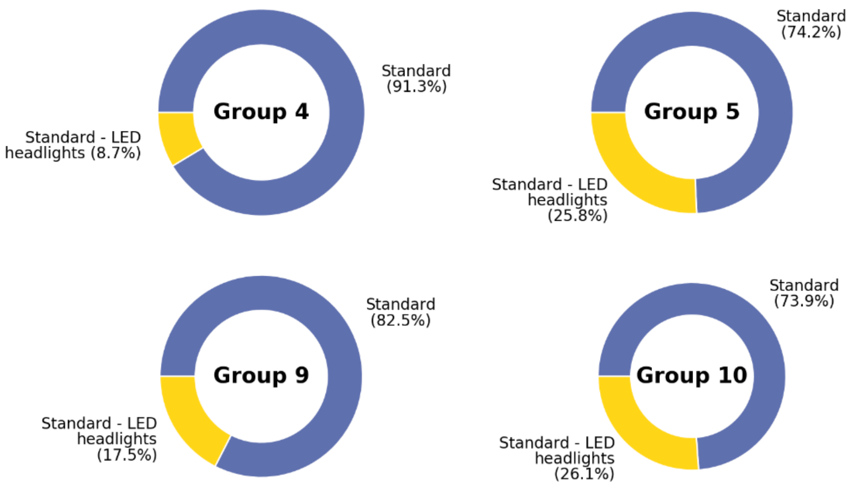
(b) Engine cooling fan



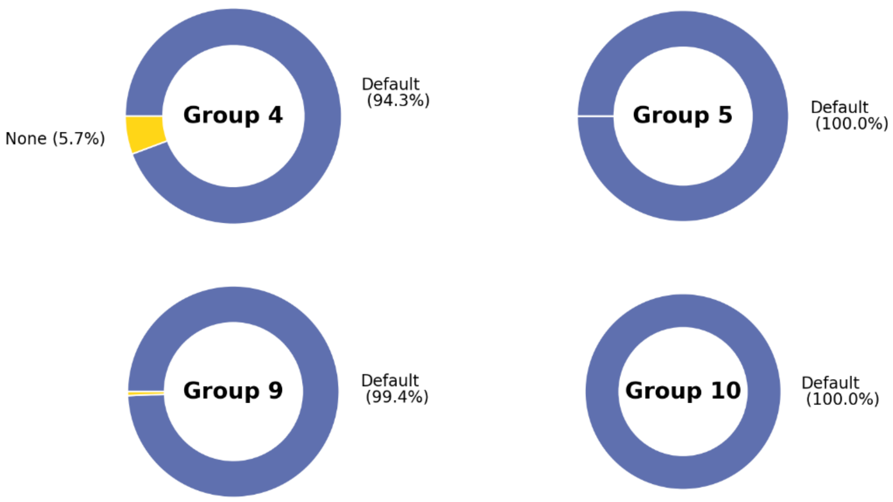
(c) Steering pump



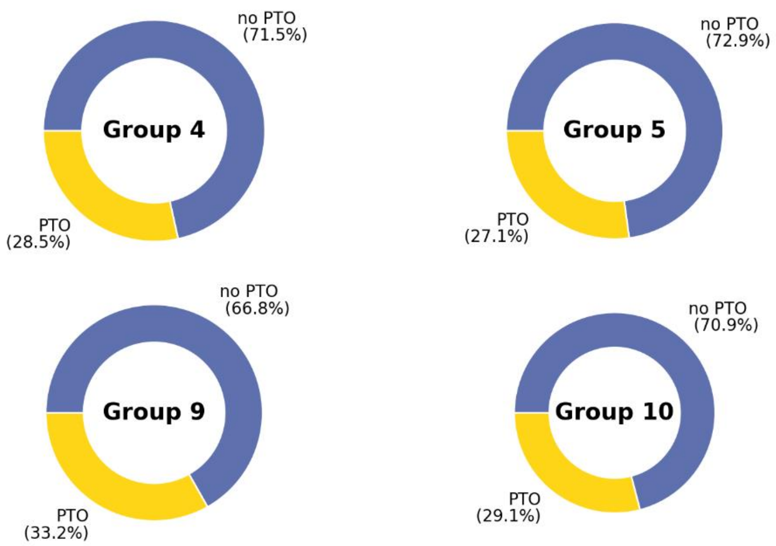
(d) Electric system



(e) Air Conditioning system



(e) Power take-off (PTO)



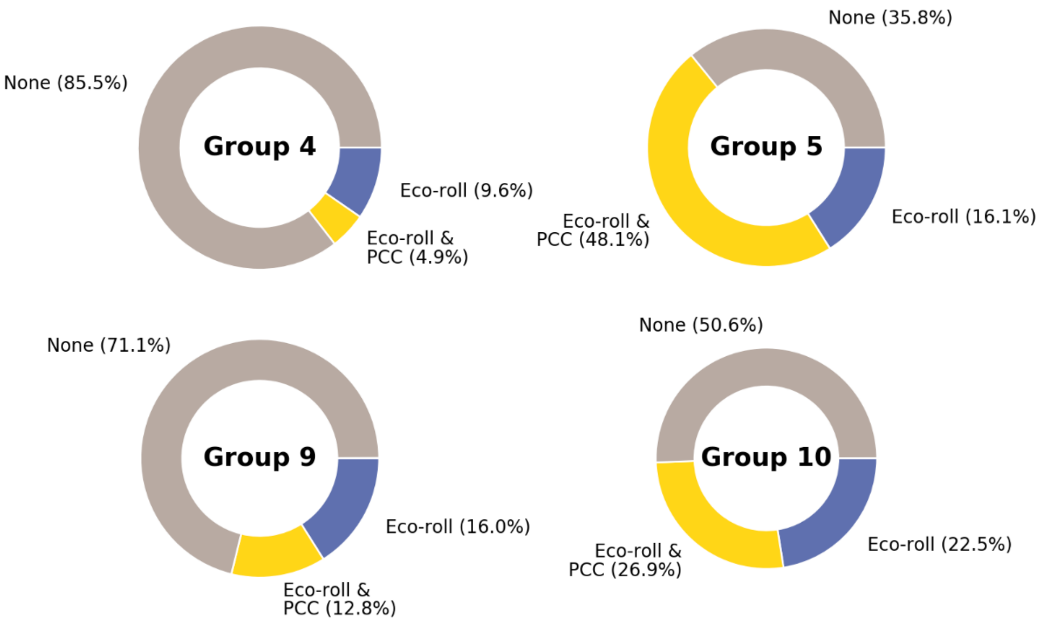
Source: JRC, 2022.

With the introduction of amending Regulation (EU) 2019/318 [14], it became possible to simulate advanced driver assistance systems. The systems include:

- Engine stop-start, which automatically shuts down and restarts the internal combustion engine during vehicle stops to reduce engine idling time.
- Eco-roll, which automatically decouples the internal combustion engine from the drivetrain during specific downhill driving conditions with a low negative gradient. The internal combustion engine is idling during eco-roll.
- Eco-roll with engine stop-start, which automatically decouples and switches off the internal combustion engine during eco-roll.
- Predictive cruise control (PCC), which optimises the usage of potential energy based on a preview (>1km) of the road gradient by crest coasting, accelerating without power or dip coasting.

The shares of different advanced driver assistance systems are shown in Figure 17 per vehicle group. Engine stop-start is not present on any of the vehicles, neither stand-alone nor in combination with eco-roll. All PCC systems are capable of crest coasting, acceleration without engine power and dip coasting.

Figure 17. Advanced driver assistance systems per vehicle group



Source: JRC, 2022.

4.4 Unique components

HDVs offer a high degree of customisation to meet the customers' needs. Oftentimes different variants of a component can be chosen to optimise the vehicle for its intended application. The number of unique components in the fleet is analysed in this section. Unique components were identified based on their manufacturer, model name and main characteristics (e.g. the cabin name and its CdxA-value). The number of unique components per subgroup and in the fleet is listed in Table 16 for the main vehicle components. The highest count of unique components can be found for the cabin, engine and axle in the subgroups with the highest sales volumes. It should be noted that the components are shared between subgroups and their count is therefore not additive. A large number of different components is present in the fleet and in each subgroup. This supports the decision for a simulation-based approach to determine the CO_2 emissions of new HDVs. The large number of different vehicle variations that exist based on these different components, would make a certification approach based on vehicle testing time intensive.

The number of unique components that a vehicle manufacturer has in its portfolio per subgroup for the air drag, engine, axle and gearbox is shown in Figure 18. The boxplot illustrates the variation in unique components between the nine vehicle manufacturers, with the number of unique components per vehicle manufacturer on the y-axis The horizontal orange line indicates the median number of unique components that a vehicle manufacturer has in its portfolio, the box ranges from the first to the third quartile and the whiskers indicate 1.5 times the inter-quantile distance. Outliers are represented by dots. A large variation between vehicle manufacturers can be observed for all components and in almost all subgroups. This indicates that the number of unique components offered by the vehicle manufacturer and/or the differentiation applied in the VECTO input data varies a lot by the vehicle manufacturer. E.g. in the 5-LH subgroup one vehicle manufacturer applies 50 different cabin models, whereas another vehicle manufacturer applies only 4. A smaller variation is present in subgroups 4-UD, 5-RD and 10-RD that have a smaller market share and with less vehicle manufacturers present.

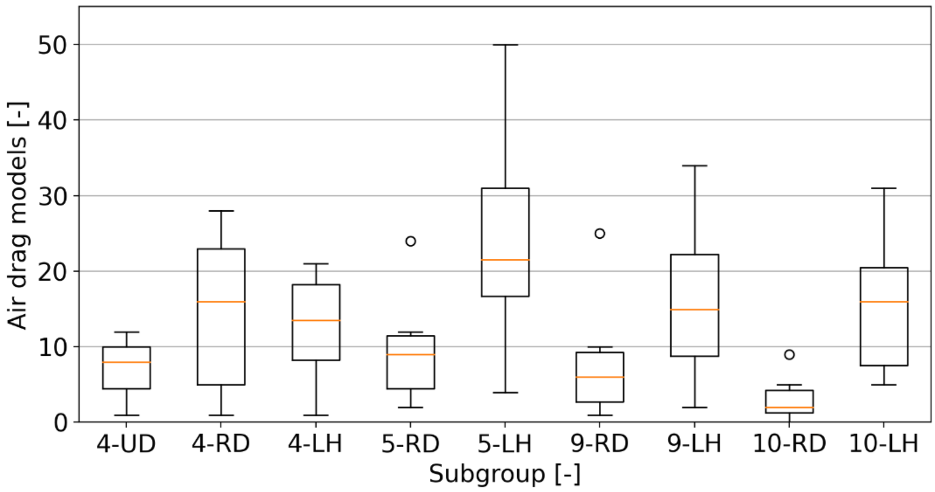
Table 16. Number of unique models per component and subgroup

Subgroup	Cabin models	Engine models	Axle models	Gearbox models	Torque converter models	Retarder models
4-UD	21	3	12	7	1	1
4-RD	121	110	148	44	8	9
4-LH	101	86	82	28	2	6
5-RD	67	92	80	27	3	5
5-LH	190	116	124	36	1	5
9-RD	56	117	125	45	13	11
9-LH	126	137	128	45	8	9
10-RD	19	28	24	11	0	3
10-LH	108	72	94	33	1	5
Fleet	**631**	**179**	**193**	**56**	**16**	**11**

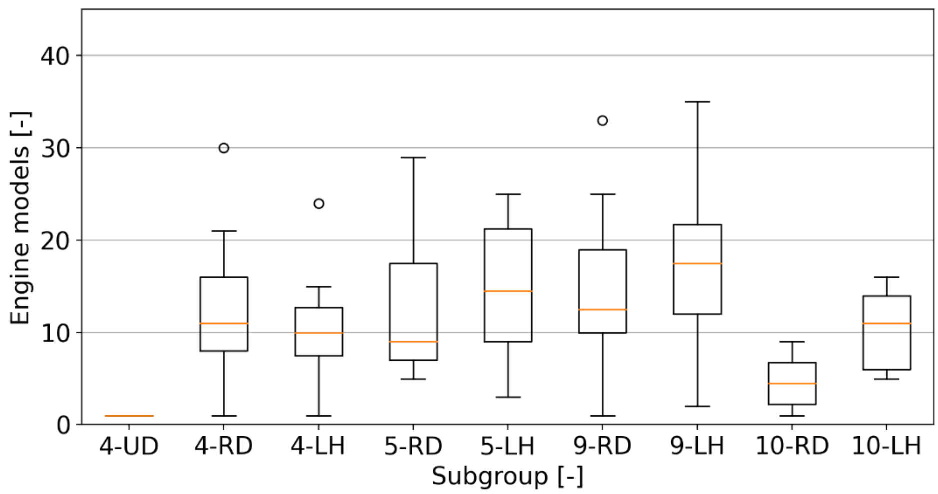
Source: JRC, 2022.

Figure 18. Unique component models applied by each vehicle manufacturer per subgroup

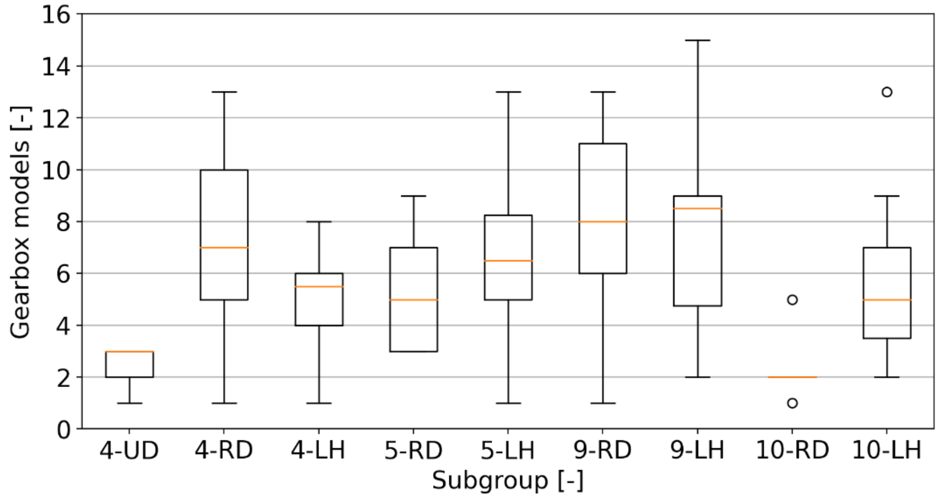
(a) Air drag



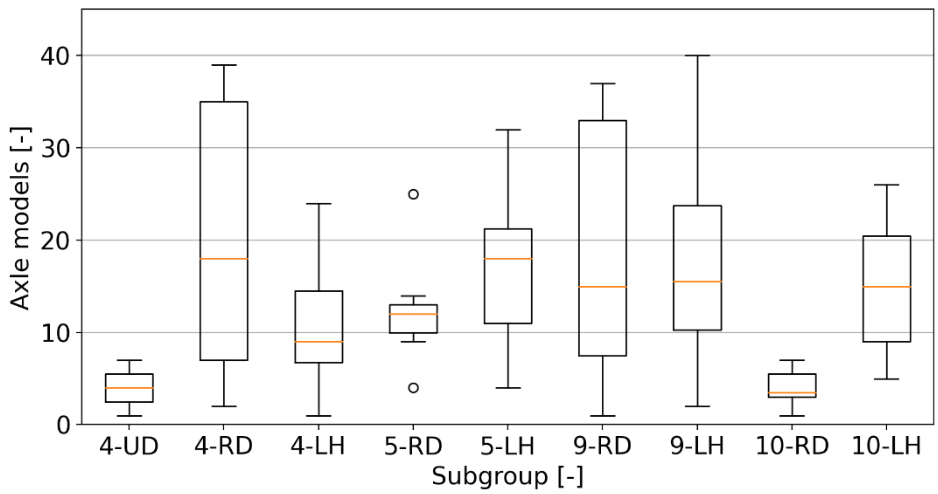
(b) Engine



(c) Gearbox



(d) Axle



Source: JRC, 2022.

Because of the large number of different components, the concept of component families was introduced in Regulation (EU) 2017/2400 to limit the cost of certification. Components with a similar design and performance can be grouped together into a family, which is represented by the component with the worst performance. Only the worst-performing component is tested and its performance is assigned to the entire family. A component family comprising of many different variants would therefore underestimate the performance of many components and increase the CO_2 emissions of vehicles equipped with them. When the targets apply, it is expected that only components with very similar performance are grouped together in a family. Since Regulation (EU) 2017/2400 specifies detailed provisions for which components can be grouped together in a family, the effect of large components families on the reference CO_2 emissions is not expected to be large.

The number of members in a component family cannot be derived unequivocally from the sum exec data used in this analysis. The sum exec data contains the component certificate number, but lacks the component family name. Since a component certificate can comprise of multiple component families and members, it does not allow identifying component families. Therefore, the number of unique components per component certificate were identified. The minimum, median and maximum number of unique components per component certificate is listed in Table 17. Although some component certificates contain many unique components, the majority contain only 1 or 2. This indicates that large component families are not commonly used. The evaluation of the number of unique components and the number of unique components per component certificate with time, gives an idea of the number of component families. Therefore, it is recommended to continuously monitor the sum exec data to periodically evaluate the number of unique component models in the fleet.

Table 17. Number of unique models per component certificate of each component type

	Minimum	**Median**	**Maximum**
Cabin	1	2	15
Engine	1	1	8
Axle	1	2	9
Gearbox	1	1	4
Torque converter	1	1	1
Retarder	1	1	1

Source: JRC, 2022.

4.5 Reference vehicles

Based on the component analysis, reference vehicles can be created that enable modelling of the HDV fleet for the reference year. The sales-weighted average component properties and most common component technologies are listed in Table 18. The average was used for properties with a continuous value (e.g. CdxA) and the median for properties with discrete a value (e.g. number of gears). All component properties were derived from the measured components alone. The engine properties were derived from diesel engines only and the gearbox properties from AMTs only since these are the most prevalent technologies. The efficiencies and fuel consumption are the weighted averages over the different mission profiles, according to the weights in Table 3.

Similarly, the best component properties can be identified to model the top-runners of the reference year fleet. The properties of the top 5% components are listed in Table 19. The component properties again were derived from the measured components alone. The engine properties were derived from diesel engines only and the gearbox properties from AMTs only since these are the most prevalent technologies. The efficiencies and fuel consumption are the weighted averages over the different mission profiles, according to the weights in Table 3.

Table 18. Average and most common vehicle properties per subgroup

	4-RD	4-LH	5-RD	5-LH	9-RD	9-LH	10-RD	10-LH
CdxA [m^2]	5.45	5.16	6.62	5.63	5.47	5.15	6.50	5.68
Curb mass [kg]	6328	7675	7093	7747	8245	9009	8041	8638
Rated power [kW]	224	323	311	354	289	345	332	367
Engine capacity [l]	8.04	11.9	11.5	12.6	10.6	12.4	12.4	13.0
Engine CF [-]	1.02	1.01	1.02	1.01	1.02	1.01	1.02	1.01
Dynamic tyre radius [m]	0.4922	0.4922	0.5223	0.4922	0.5223	0.4922	0.4922	0.4922
RRC axle 1 [-]	0.0057	0.0052	0.0056	0.0052	0.0057	0.0054	0.0057	0.0055
RRC axle 2 [-]	0.0064	0.0058	0.0062	0.0057	0.0064	0.0061	0.0064	0.0057
RRC axle 3 [-]	-	-	-	-	0.0057	0.0054	0.0062	0.0060
Number of gears	12	12	12	12	12	12	12	12
Trans. ratio final gear	0.86	0.98	0.97	0.99	0.93	0.97	0.98	0.98
Axle ratio	3.97	2.56	2.94	2.53	3.36	2.72	2.74	2.62
Retarder type	None	None	None	None	None	None	None	None
Engine cooling fan	Crankshaft - El. Contr. visco clutch	Crankshaft - El. Contr. visco clutch	Crankshaft - El. Contr. visco clutch	Belt / trans. - El. Contr. visco clutch	Belt / trans. - El. Contr. visco clutch	Belt / trans. - El. Contr. visco clutch	Crankshaft - El. Contr. visco clutch	Belt / trans. - El. Contr. visco clutch
Steering pump	Fixed displ.	Variable displ. mech. contr	Fixed displ.	Variable displ. mech. contr	Fixed displ.	Variable displ. mech. contr	Fixed displ.	Variable displ. mech. contr
AC system	Default	Default	Default	Default	Default	Default	Default	Default
Electric system	Std. tech.	Std. tech.	Std. tech.	Std. tech.	Std. tech.	Std. tech.	Std. tech.	Std. tech.

Pneumatic system	Large Supply + ESS + AMS	Large Supply + ESS + AMS	Large Supply + ESS + AMS	Medium Supply 2-stage + ESS + AMS	Large Supply + ESS + AMS	Large Supply + ESS + AMS	Large Supply + mech. clutch + AMS	Large Supply + mech. clutch + AMS
Axle efficiency [%]	94.83	97.10	96.70	97.37	95.60	97.17	96.89	97.17
Gearbox efficiency [%]	96.74	98.42	98.11	98.48	97.35	98.39	98.19	98.37
Engine efficiency [%]	39.90	43.14	42.78	43.53	41.21	43.48	43.52	43.43
FC [l/100km]	24.01	29.11	33.63	29.87	26.54	33.06	32.41	30.92

Source: JRC, 2022.

Table 19. Properties of the best performing components

	4-RD	**4-LH**	**5-RD**	**5-LH**	**9-RD**	**9-LH**	**10-RD**	**10-LH**
CdxA [m^2]	4.56	4.19	4.79	4.48	4.66	4.29	4.89	4.58
Curb mass [kg]	5408	7148.8	6548	7118	7438	8263	7274	7842
RRC [-] axle 1	0.0049	0.0040	0.0047	0.0040	0.0047	0.0040	0.0050	0.0040
RRC [-] axle 2	0.0052	0.0049	0.0050	0.0040	0.0053	0.0043	0.0050	0.0045
RRC [-] axle 3	-	-	-	-	0.0049	0.0040	0.0050	0.0046
Axle efficiency [%]	96.62	98.11	98.06	98.20	97.16	98.27	98.09	98.25
Gearbox efficiency [%]	98.28	99.14	98.98	99.18	98.73	99.19	98.92	99.18
Engine efficiency [%]	41.59	44.15	43.98	44.78	42.66	44.73	44.28	44.71
FC [l/100km]	21.23	27.00	29.22	27.69	23.83	30.36	29.40	28.70

Source: JRC, 2022.

4.6 Standard values

The vehicle and component properties used in VECTO can either be certified data obtained from measurements or by applying standard values defined in regulation (EU) 2017/2400. Standard values are not allowed for the engine, but can be applied for:

- Gearbox
- Torque converter
- Axle
- Other torque transferring components or additional driveline components
- Air drag
- Tyres

To promote the use of measured component properties and avoid overestimating a component's performance, the standard values represent a worst-case performance for a certain component and include a penalty factor. This is illustrated in Figure 6, Figure 9 and Figure 11 for the CdxA, axle efficiency and gearbox efficiency respectively. The worse performance results in higher CO_2 emissions, as shown in Figure 2 and Figure 3 for the different vehicle groups.

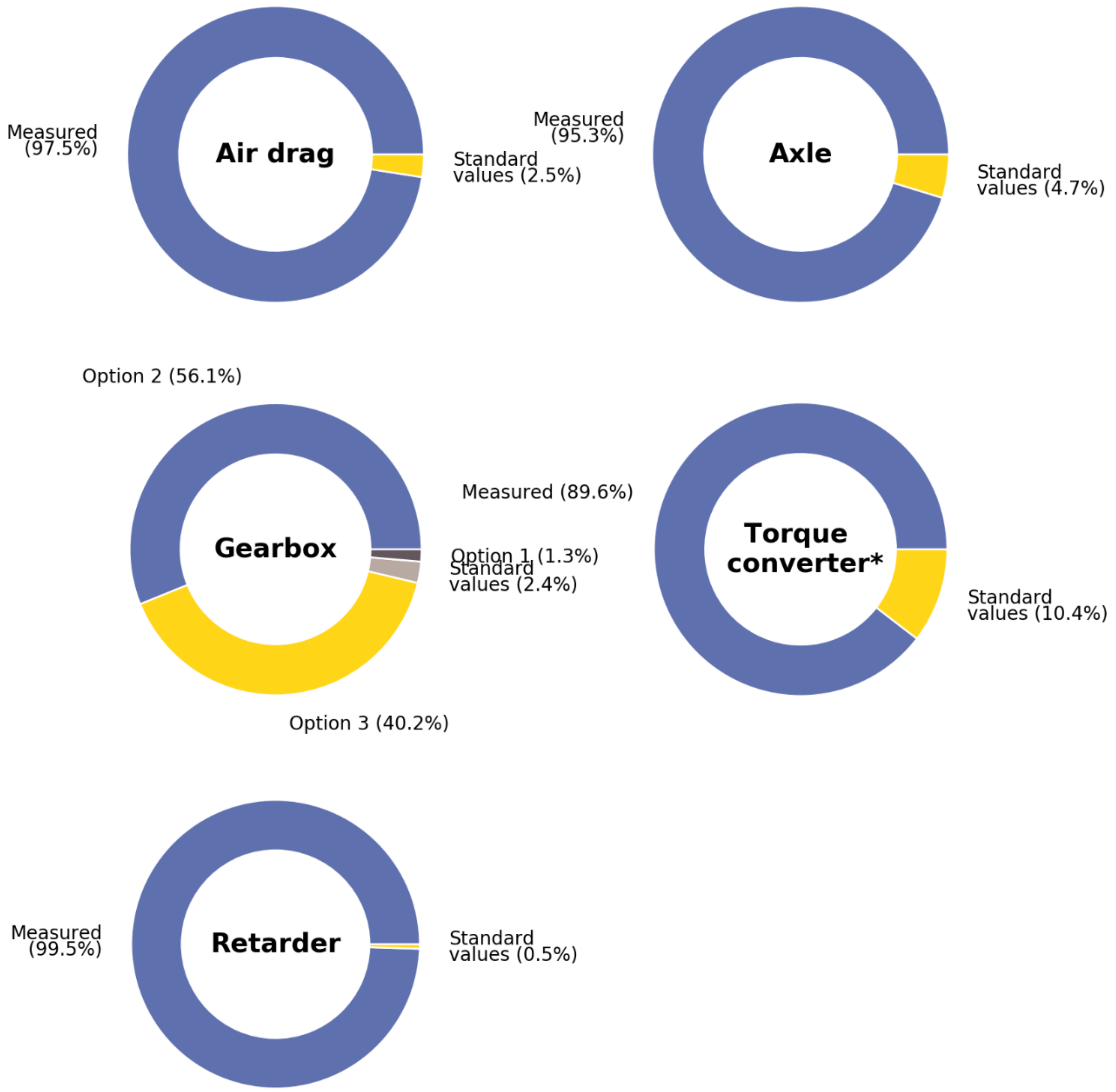
The share of measured and standard values used in the fleet for each component is shown in Figure 19. The number of vehicles in the fleet equipped with the component is taken into account. The gearbox certification method is split up into three allowed measurement methods for determining the torque losses:

1. Option 1: Measurement of the torque independent losses, calculation of the torque dependent losses.
2. Option 2: Measurement of the torque independent losses, measurement of the torque loss at maximum torque and interpolation of the torque dependent losses based on a linear model.
3. Option 3: Measurement of the total torque loss.

All options require measuring the gearbox losses, with increasing measurement requirements, and resulting model accuracy, when going from option 1 to option 2 and from option 2 to option 3. Almost all gearboxes have a measured efficiency determined with option 2 or 3. Also, the majority of other components in the fleet have certified properties. The low share of vehicles with a standard value gives confidence in the accuracy of the reference CO_2 emissions. This is especially true for the air drag, which has the largest impact on the vehicle's CO_2 emissions. Larger use of standard values can be observed for the torque converter. However, it should be noted that a torque converter is only installed in vehicles equipped with an automatic transmission (AT) and the market share of this transmission type is less than 1.3%. Hence, the use of standard values for torque converters has a limited impact on the reference CO_2 emissions. The share of each certification method per gearbox type is shown in Figure 20. The more accurate measurement methods (options 2 and 3) are used for the most common gearbox type (AMT), whereas the least accurate measurement method (option 1) and standard values are used for MT and AT gearboxes.

The distribution of the components with standard values over the different vehicle subgroups is shown in Table 20. It lists the share of vehicles per subgroup that are equipped with at least one component that uses a standard value. A large difference can be observed between the different subgroups. Whereas subgroups 4-UD, 5-LH and 10-LH have very few vehicles with standard values, subgroups 4-RD, 5-RD and 9-RD have a large share of vehicles with standard values. It should be noted that the 5-LH and 10-LH subgroups make up the majority of the fleet and that subgroups 4-RD, 5-RD and 9-RD have a smaller market share (Figure 1).

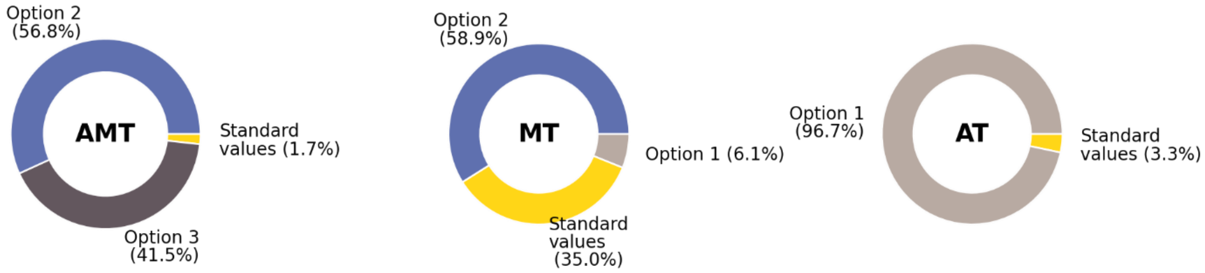
Figure 19. Share of standard values per component



** Vehicles equipped with AT*

Source: JRC, 2022.

Figure 20. Share of each certification method per gearbox types



Source: JRC, 2022.

Table 20. Share of vehicles with at least one standard value

Subgroup	Fleet share with standard values [%]
4-UD	0.2
4-RD	43.5
4-LH	10.7
5-RD	35.5
5-LH	1.3
9-RD	30.8
9-LH	10.6
10-RD	12.0
10-LH	1.4

Source: JRC, 2022.

The number of components per vehicle that have a standard value are listed in Table 21. It can be observed that 91.5% of all vehicles in the HDV fleet are equipped with measured components only. Moreover, the vehicles that are equipped with components with standard values, generally only have one component with a standard value and are equipped with measured components otherwise. Consequently, if a correction of the reference CO_2 emissions were to be applied, only a limited number of vehicles would need to be corrected. Additionally, the interaction of multiple components with standard values would not significantly increase the error of the correction, since very few vehicles are equipped with multiple components with standard values.

Table 21. Share of vehicles with the amount of components with standard values

Number of components with standard value	Fleet share [%]
0	91.5
1	7.4
2	1.1
3	0.0

Source: JRC, 2022.

Other vehicle groups

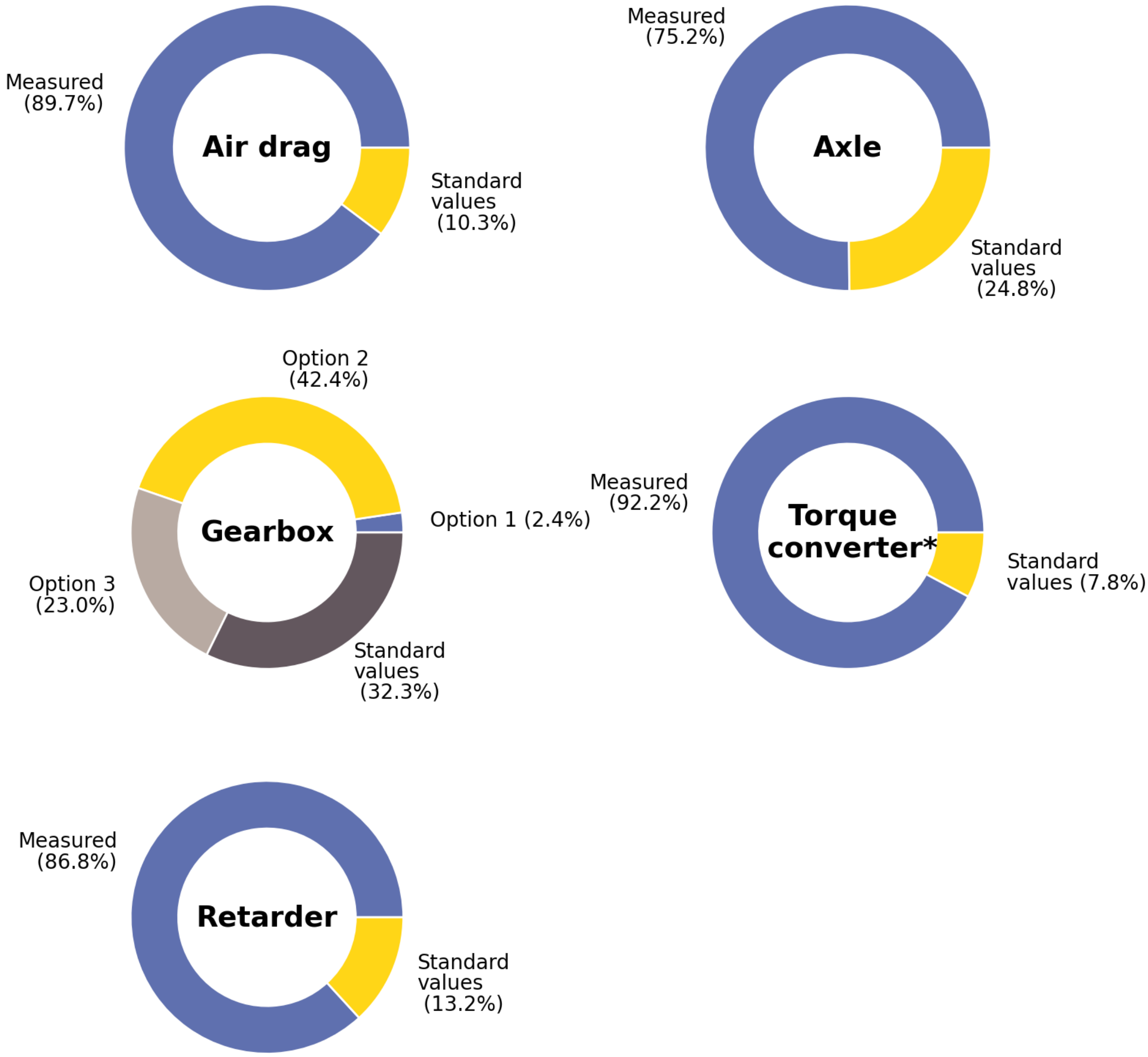
The share of measured and standard values for each component of vehicles in the non-reference vehicle groups is shown in Figure 21. The air drag certification method of vehicles in group 16 was not considered in the analysis, since all vehicles are simulated with a generic CdxA value. A much larger share of vehicles is equipped with components with a standard value compared to the vehicles in the reference groups. The increase is the most noticeable for the axle, the retarder and the gearbox. This indicates that an effort was undertaken to certify the components of vehicles in the regulated groups, which contradicts an intention of inflating the reference CO_2 emissions. The share vehicles per group that are equipped with at least one component that uses a standard value is listed in Table 22. Standard values are mostly used in vehicle groups 1, 2 and 3. Possibly, because these vehicles share fewer components with the vehicles in the reference groups.

Table 22. Share of vehicles in the non-reference groups with at least one standard value

Group	Fleet share with standard values [%]
1	82.7
2	61.0
3	48.3
11	24.3
12	15.2
16	17.3

Source: JRC, 2022.

Figure 21. Share of standard values per component for the other vehicle groups



** Vehicles equipped with AT*

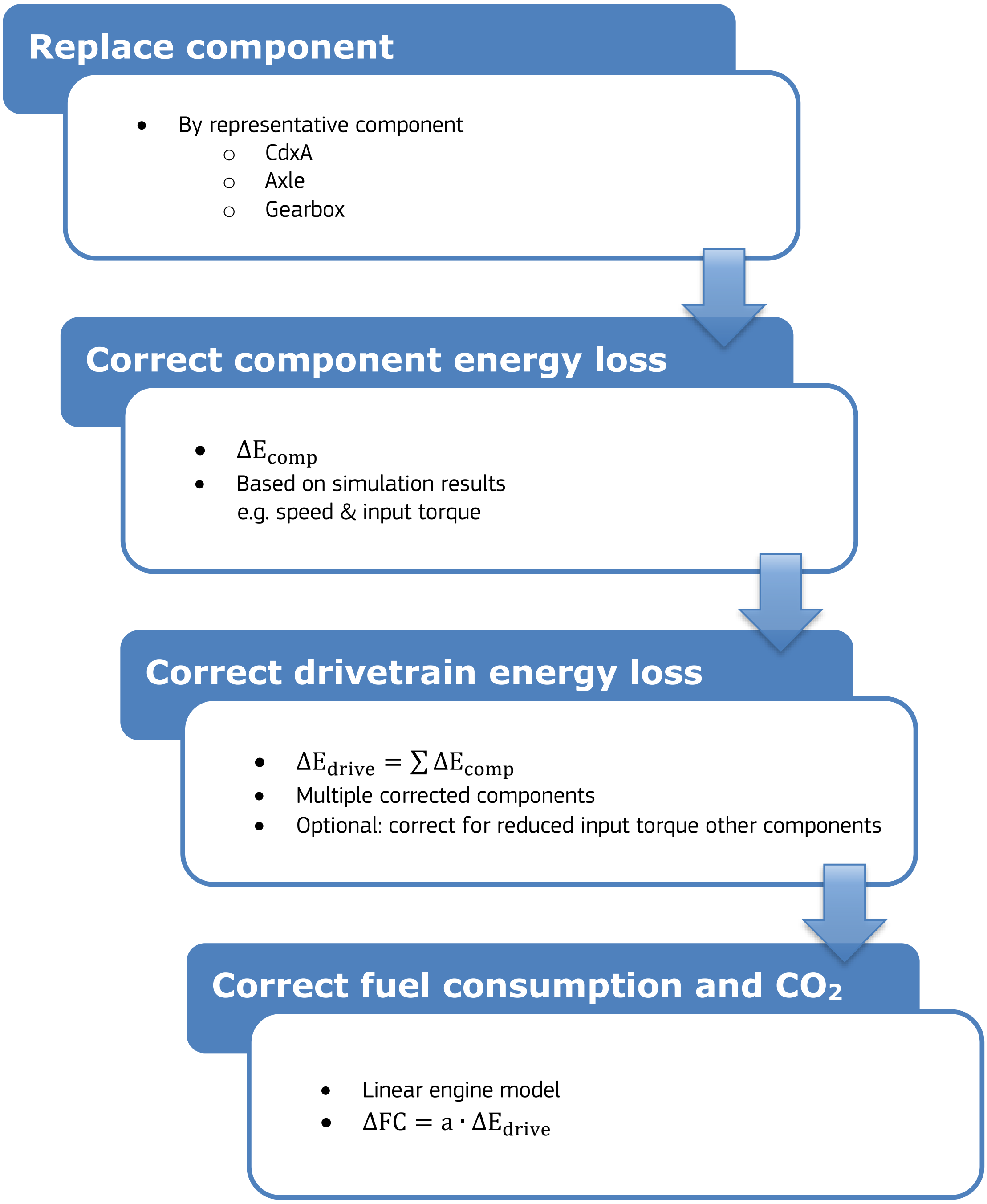
Source: JRC, 2022.

5 Correction of the reference CO_2 emissions

5.1 Principle

Previous chapters demonstrated that components using a standard value have worse efficiency than measured ones resulting in higher vehicle CO_2 emissions, as shown in Figure 2 and Figure 3. This section investigates the impact of components with standard values on the reference CO_2 emissions. The components with standard values are replaced by representative components in each vehicle and the vehicle's fuel consumption and CO_2 emissions are corrected over each mission profile based on its energy use with the representative component. The reference CO_2 emissions are then recalculated with the corrected vehicles' CO_2 emissions. A similar approach was followed in [20] to evaluate the 2016 HDV fleet. The principle of the vehicle's fuel consumption correction follows the schema below:

Figure 22. Fuel consumption correction flowchart



Source: JRC, 2022.

Each component that has a standard value is replaced by a representative component. The representative component has a property (e.g. CdxA or efficiency) or a model (e.g. torque loss as a function of the input torque and speed) derived from representative measured components in the fleet. Only the air drag, axle and gearbox were considered in the correction. The torque converter and retarder were not considered because of their low market share and share of standard values, respectively. The engine component was not corrected because its fuel consumption map is always measured. The energy loss of the representative component is calculated based on its properties and its cycle-average inputs (e.g. torque and speed). The difference in energy loss ΔE_{comp} between the corrected component and the original component (with standard value) is considered. These energy losses are summed up over all corrected components in the vehicle's drivetrain to obtain ΔE_{drive}. The engine fuel consumption was modelled with a linear Willans model and the difference in fuel consumption ΔFC was determined from ΔE_{drive}. Finally, the vehicle's corrected CO_2 emissions are calculated from uncorrected CO_2 emissions, ΔFC and the fuel's chemical properties. This correction process was repeated for each mission profile and all vehicles with components with standard values.

An additional step was to model also the components without standard values upstream of the corrected component in the drivetrain. Their energy loss with the reduced energy input required by the corrected downstream component is calculated. However, the secondary effects this additional step considers have only a small impact on the overall results. The correction of the energy losses in the drivetrain is visualised in Figure 23. The orange boxes indicate the components with standard values that were replaced by a representative component. Their energy loss was corrected based on the property in the yellow box. The green boxes represent the vehicle energy losses that were not corrected and the blue boxes show the aggregated energy losses that were corrected.

5.2 Component models

5.2.1 Air drag

The energy lost to overcome the air drag is corrected for vehicles that were simulated with a standard value for CdxA. A reference CdxA value ($CdxA_{corr}$) was determined for each vehicle subgroup, based on the vehicles with a measured CdxA. The difference in energy (ΔE_{air}) is determined from the reference CdxA according to two different methods.

Method 1

In method 1, the ΔE_{air} is calculated according to Eq. 7, with the assumption that the air drag is proportional to the CdxA.

$$\Delta E_{air} = E_{air,ori} \cdot \left(\frac{CdxA_{corr}}{CdxA_{ori}} - 1\right) \quad (7)$$

With $E_{air,ori}$ and $CdxA_{ori}$ the vehicle's uncorrected air drag and CdxA, respectively.

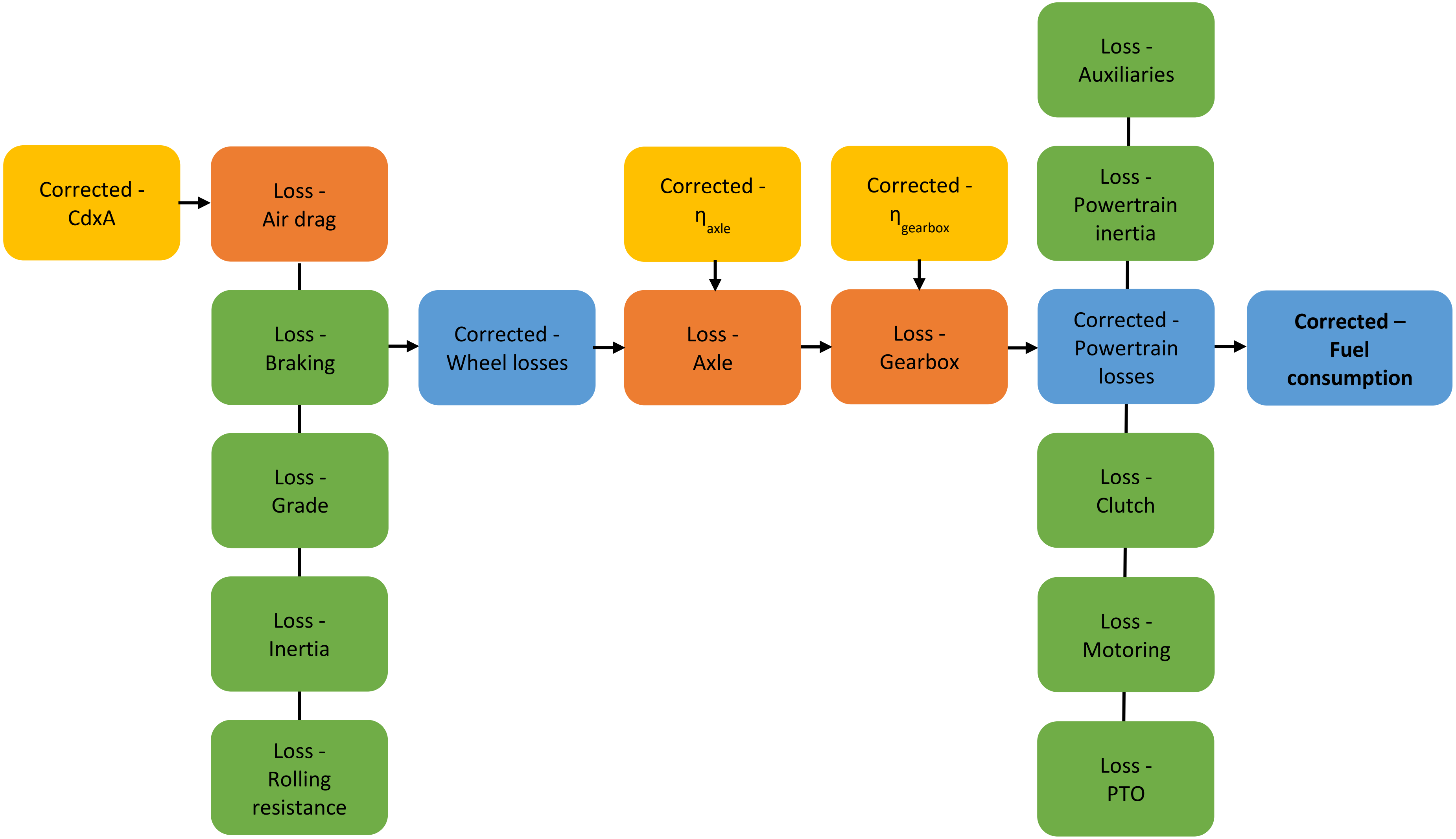
Method 2

In method 2, the ΔE_{air} is calculated according to Eq. 8, with a linear model of the power to overcome the air drag based on the reference CdxA.

$$\Delta E_{air} = (a_1 \cdot CdxA_{corr} \cdot v^3 + a_2) \cdot t_{cycle} - E_{air,ori} \quad (8)$$

With a_1 and a_2 the model coefficients obtained per vehicle group and mission profile, v the vehicle's average speed over the driving cycle and t_{cycle} the duration of the driving cycle. It is assumed that the vehicle's average speed and the cycle duration remain the same with the reference CdxA. The model coefficients were obtained by fitting the model in Eq. 8. with the uncorrected CdxA to the uncorrected E_{air} simulated in VECTO of all vehicles in the fleet per vehicle group and mission profile

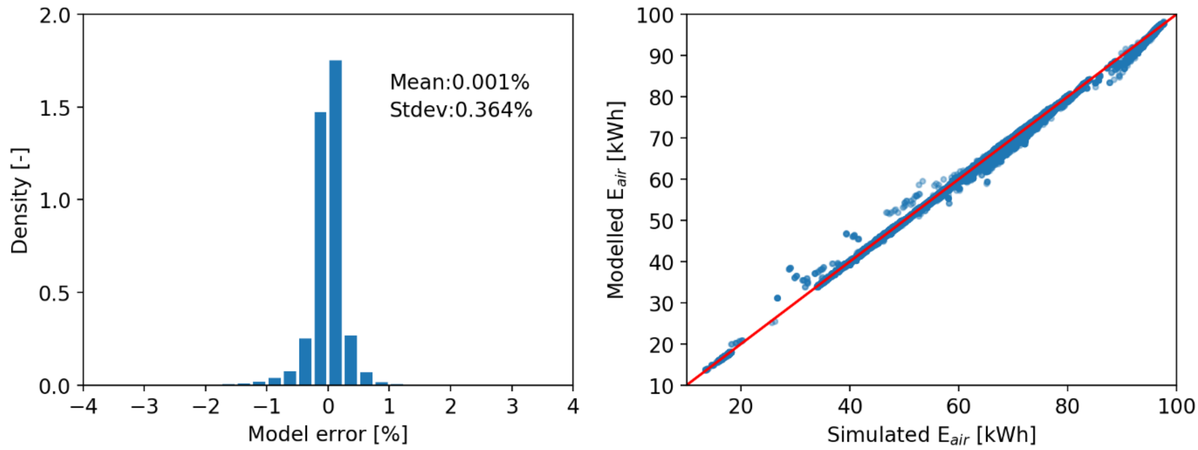
Figure 23. Schematic overview of the powertrain energy losses correction



Source: JRC, 2022.

Method 2 was validated by comparing for each vehicle in the fleet, the E_{air} simulated in VECTO to the modelled E_{air} with the uncorrected CdxA. The distribution of the model error and the relation between the modelled and VECTO simulated E_{air} are shown in Figure 24. A good correlation can be observed with a model error centred around zero.

Figure 24. Error of the modelled air drag



Source: JRC, 2022.

5.2.2 Axle

The energy lost in the vehicle's axle is corrected for vehicles that were simulated with a standard axle torque loss map. The energy loss in the axle is corrected by either applying a reference efficiency (method 1) or by applying a reference torque loss map (method 2). Both the reference efficiency and the reference torque map, were derived from vehicles with measured axle losses.

Method 1

In method 1, the difference in energy loss in the axle (ΔE_{axle}) was calculated from the uncorrected axle loss ($E_{axle,ori}$) and the energy at the wheels (E_{wheel}), with the reference axle efficiency (η_{axle}) according to Eq. 9.

$$\Delta E_{axle} = \left(\frac{1}{\eta_{axle}} - 1\right) \cdot E_{wheel} - E_{axle,ori} \tag{9}$$

The reference axle efficiency was determined per vehicle subgroup, mission profile and payload from vehicles with a measured axle. In case the air drag was corrected, E_{wheel} was corrected accordingly.

Method 2

In method 2, the difference in energy loss in the axle was calculated with a linear model of the axle torque loss ($T_{axle\ loss}$) and the uncorrected axle loss, according to Eq. 10.

$$\Delta E_{axle} = T_{axle\ loss} \cdot \frac{2 \cdot n_{axle,in} \cdot \pi}{60} \cdot t_{cycle} - E_{axle,ori} \tag{10}$$

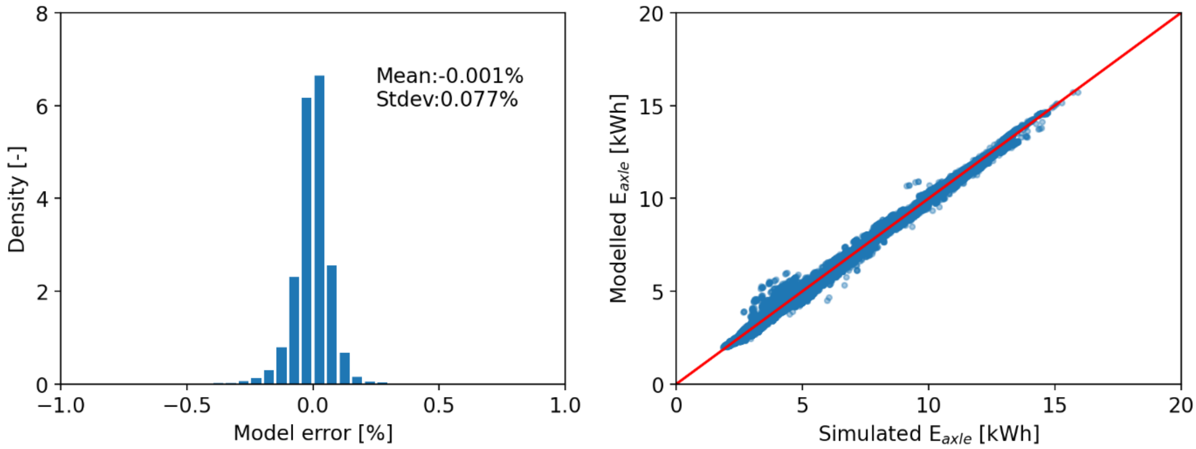
$$T_{axle\ loss} = a_1 + a_2 \cdot T_{axle,in} + a_3 \cdot n_{axle,in} \tag{11}$$

With a_1, a_2 and a_3 the model coefficients per vehicle subgroup, $n_{axle,in}$ the average input speed of the axle over the cycle and $T_{axle,in}$ the average input torque of the axle over the cycle. Model coefficients were obtained for each unique axle in the fleet, by fitting the model in Eq. 11 with the uncorrected $T_{axle,in}$ to the uncorrected $T_{axle\ loss}$ simulated in VECTO for all vehicles in the fleet. Then representative model coefficients a_1, a_2 and a_3 were selected per subgroup based on the individual axle models.

Since $T_{axle,in}$ is upstream of the axle, but calculated from the energy at the wheels and the torque loss in the axle, the calculation was repeated until the $T_{axle\ loss}$ reached a constant value for a given output torque of the axle. In case the air drag was corrected, the output torque of the axle was corrected accordingly based on the corrected E_{wheel}.

Method 2 was validated by comparing for each vehicle in the fleet, the E_{axle} simulated in VECTO to the modelled E_{axle} with the uncorrected axle loss map. The distribution of the axle efficiency's absolute model error and the relation between the modelled and VECTO simulated E_{axle} are shown in Figure 25. A good correlation can be observed with a model error centred around zero.

Figure 25. Error of the modelled axle



Source: JRC, 2022.

5.2.3 Gearbox

An analogous approach as for the axle was applied to the gearbox. The energy lost in the vehicle's gearbox is corrected for vehicles that were simulated with a standard gearbox torque loss map. The energy loss in the gearbox is corrected by either applying a reference efficiency (method 1) or by applying a reference torque loss map (method 2). Both the reference efficiency and the reference torque map were derived from vehicles with measured gearbox losses.

Method 1

In method 1, the difference in energy loss in the gearbox (ΔE_{gbx}) was calculated from the uncorrected gearbox loss ($E_{gbx,ori}$), the energy at the wheels (E_{wheel}) and the energy loss in the axle (E_{axle}), with the reference gearbox efficiency (η_{gbx}) according to Eq. 12.

$$\Delta E_{gbx} = \left(\frac{1}{\eta_{gbx}} - 1\right) \cdot (E_{wheel} + E_{axle}) - E_{gbx,ori} \tag{12}$$

The reference gearbox efficiency was determined per vehicle subgroup, gearbox type, mission profile and payload from vehicles with a measured gearbox. In case the air drag or gearbox were corrected, E_{wheel} and E_{axle} were corrected accordingly.

Method 2

In method 2, the difference in energy loss in the gearbox was calculated from a linear model of the gearbox torque loss (T_{loss}) and the uncorrected gearbox loss, according to Eq. 13.

$$\Delta E_{gbx} = T_{gbx\ loss} \cdot \frac{2 \cdot n_{gbx,in} \cdot \pi}{60} \cdot t_{cycle} - E_{gbx,ori} \tag{13}$$

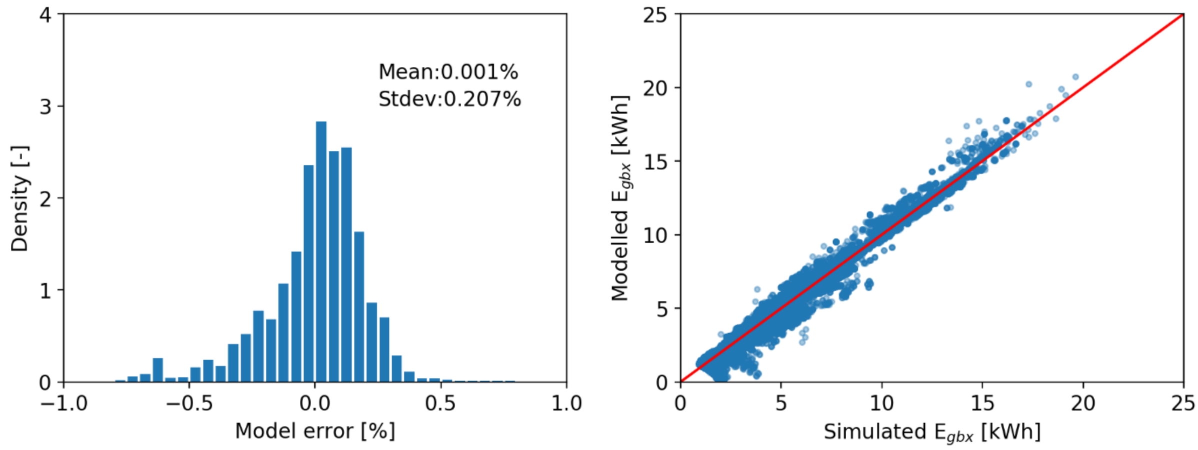
$$T_{gbx\ loss} = a_1 + a_2 \cdot T_{gbx,in} + a_3 \cdot n_{eng} \tag{14}$$

With a_1, a_2 and a_3 the model coefficients obtained per vehicle subgroup and gearbox type, n_{eng} the average engine speed and $T_{gbx,in}$ the average input torque of the gearbox over the cycle.

Model coefficients were obtained for each unique gearbox in the fleet, by fitting the model in Eq. 14 with the uncorrected $T_{gbx,in}$ to the uncorrected $T_{gbx\ loss}$ simulated in VECTO for all vehicles in the fleet. Then representative model coefficients a_1, a_2 and a_3 were selected per subgroup and gearbox type based on the individual gearbox models. Since $T_{axle,in}$ is upstream of the gearbox, but calculated from the energy at the wheels and the torque loss in the axle and in the gearbox, the calculation was repeated until $T_{gbx\ loss}$ reached a constant value for a given output torque of the gearbox. In case the air drag or axle were corrected, the output torque of the gearbox was corrected accordingly based on the corrected E_{wheel} and E_{gbx}.

Method 2 was validated by comparing for each vehicle in the fleet, the E_{gbx} simulated in VECTO to the modelled E_{gbx} with the uncorrected gearbox loss map. The distribution of the gearbox efficiency's absolute model error and the relation between the modelled and VECTO simulated E_{gbx} are shown in Figure 26. A good correlation can be observed with a model error centred around zero.

Figure 26. Error of the modelled gearbox



Source: JRC, 2022.

5.2.4 Engine

The fuel consumption was corrected for vehicles that were simulated with a standard value for the CdxA, a standard axle torque loss map or a standard gearbox torque loss map. The difference in fuel consumption was determined from the difference in energy losses of these components, according to two different methods.

Method 1

In method 1, the difference in fuel consumption rate in g/h (ΔFC) was calculated from the difference in engine work, according to Eq. 15.

$$\Delta FC = \frac{\Delta E_{air} + \Delta E_{axle} + \Delta E_{gbx}}{\eta_{eng} \cdot t_{cycle} \cdot LHV} \tag{15}$$

With η_{eng} the average engine efficiency over the driving cycle, t_{cycle} the duration of the driving cycle and *LHV* the fuel's lower heating value. The difference in engine work comes from the air drag loss (ΔE_{air}), axle energy loss (ΔE_{axle}) and gearbox energy loss (ΔE_{gbx}), if those components were corrected. The average engine efficiency is the one simulated in VECTO with the specific vehicle for each driving cycle and payload with the uncorrected engine work. It is assumed that the average engine efficiency remains the same with the corrected engine work.

Method 2

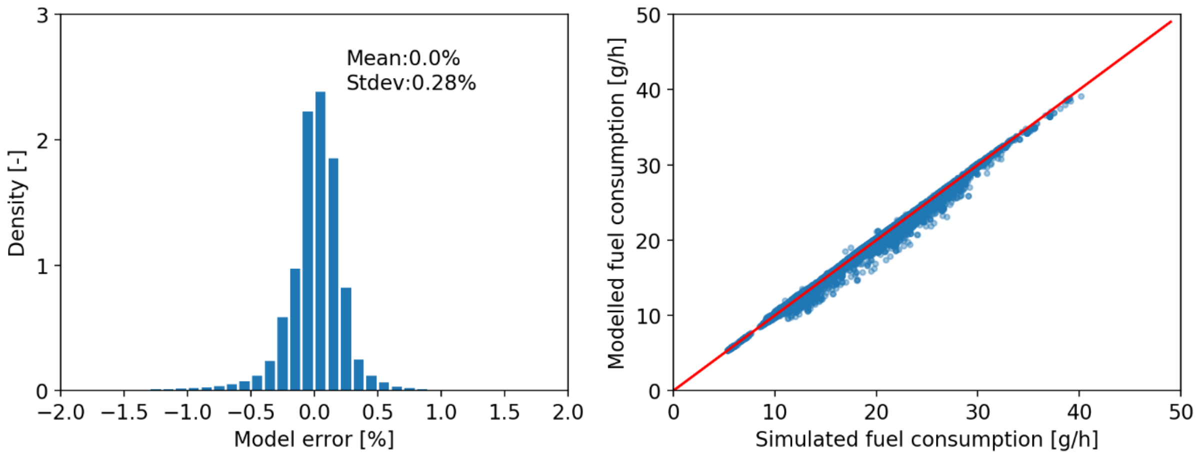
In method 2, the difference in fuel consumption rate was calculated with a linear model of the fuel consumption and the difference in engine work, according to Eq. 16.

$$\Delta FC = a_1 \cdot \frac{\Delta E_{air} + \Delta E_{axle} + \Delta E_{gbx}}{t_{cycle}} \tag{16}$$

$$FC = a_1 \cdot \frac{E_{eng}}{t_{cycle}} + a_2 \cdot n_{eng} \tag{17}$$

With a_1 and a_2 the model coefficients per engine obtained from fitting Eq. 16 to all unique engines with E_{eng} the uncorrected engine work and *FC* the uncorrected fuel consumption rate in g/h from the VECTO simulation results. Method 2 was validated by comparing for each vehicle in the fleet, the fuel consumption simulated in VECTO to the modelled fuel consumption with the uncorrected engine work. The distribution of the fuel consumption's absolute model error and the relation between the modelled and VECTO simulated fuel consumption are shown in Figure 27. A good correlation can be observed with a model error centred around zero.

Figure 27. Error of the modelled engine



Source: JRC, 2022.

For both methods, the *ΔFC* was integrated over the cycle duration and added to the original fuel consumption simulated by VECTO for each simulation to achieve the corrected fuel consumption. The corrected fuel consumption was then converted to CO_2 emissions based on the fuel properties and the corrected reference CO_2 emissions of each subgroup were finally calculated according to Eqs. 1 and 2.

5.3 Results

The effect of the use of standard values on the reference CO_2 emissions was investigated by evaluating 3 different scenarios: a conservative, an intermediate and a worst-case scenario.

Scenario 1 (conservative) assumed that standard values were only used for the worst-performing components. The components with standard values were replaced by representative components that are in the bottom 5th percentile of air drag, axle efficiency or gearbox efficiency. This keeps the conservative performance of these components but removes the performance penalty associated with standard values. For each component, the method of correction with the smallest corrective effect was applied. This scenario can be considered conservative since the reference CO_2 emissions are changed the least.

Scenario 2 (intermediate) assumed that standard values were used for components with varying performance. The components with standard values were replaced by representative components that represent the median performance. In **Scenario 2a** the method of correction with the smallest corrective effect was applied to each component and in **Scenario 2b** the method of correction with the largest corrective effect was applied. This scenario can be considered as more realistic than scenarios 1 and 2, and the two variants provide a lower and upper limit to the change in the reference CO_2 emissions.

Scenario 3 (worst-case) assumed that standard values were only used for the best performing components. The components with standard values were replaced by representative components that are in the top 5th percentile of air drag, axle efficiency or gearbox efficiency. For each component, the method of correction with the largest corrective effect was applied. This scenario changes the reference CO_2 emissions the most and can be considered a 'worst-case' from a regulator's perspective, since it would have the highest inflating effect in the reference CO_2 emissions. It assumes that the vehicle manufacturers actively increase the reference CO_2 emissions.

Table 23 lists the change in reference CO_2 emissions per vehicle subgroup, for the entire fleet, and for each scenario. The fleet average CO_2 emissions were calculated as described in Section 2.4, according to Eq. 5. The change in reference CO_2 emissions varies a lot per subgroup and depends on the share of vehicles with standard values. The reference CO_2 emissions do not change much in the 5-LH subgroup for all scenarios due to its low share of vehicles with standard values. The conservative scenario estimates that the reference CO_2 emissions are 0.4% too high by the application of standard values. In the intermediate scenario, this increases to 0.6-0.7%, depending on the modelling method and in the worst-case scenario it increases to 1%.

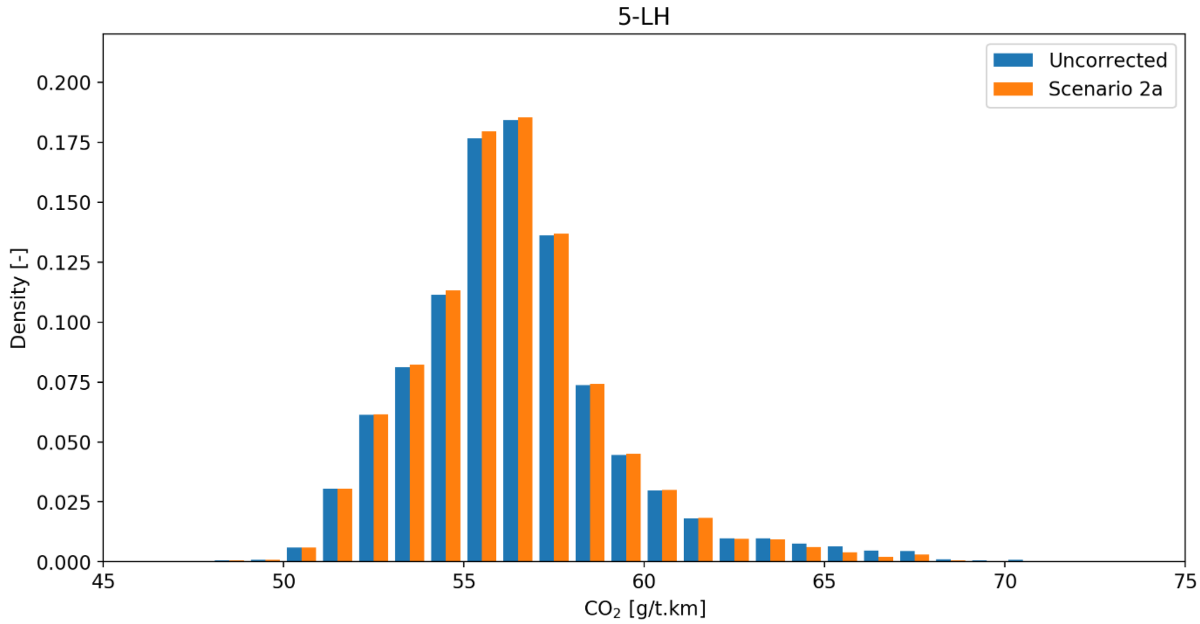
Table 23. Change in reference CO_2 emissions after correction

Subgroup	Scenario 1 [%]	Scenario 2a [%]	Scenario 2b [%]	Scenario 3 [%]
4-UD	0.0	0.0	0.0	0.0
4-RD	-1.7	-2.6	-3.1	-5.1
4-LH	-1.5	-2.0	-2.3	-3.1
5-RD	-0.8	-3.8	-4.5	-8.5
5-LH	-0.1	-0.2	-0.2	-0.3
9-RD	-0.8	-1.9	-2.3	-3.0
9-LH	-1.4	-1.7	-2.0	-2.6
10-RD	-0.5	-1.2	-1.4	-2.8
10-LH	-0.1	-0.2	-0.3	-0.4
Fleet	**-0.38**	**-0.60**	**-0.71**	**-1.02**

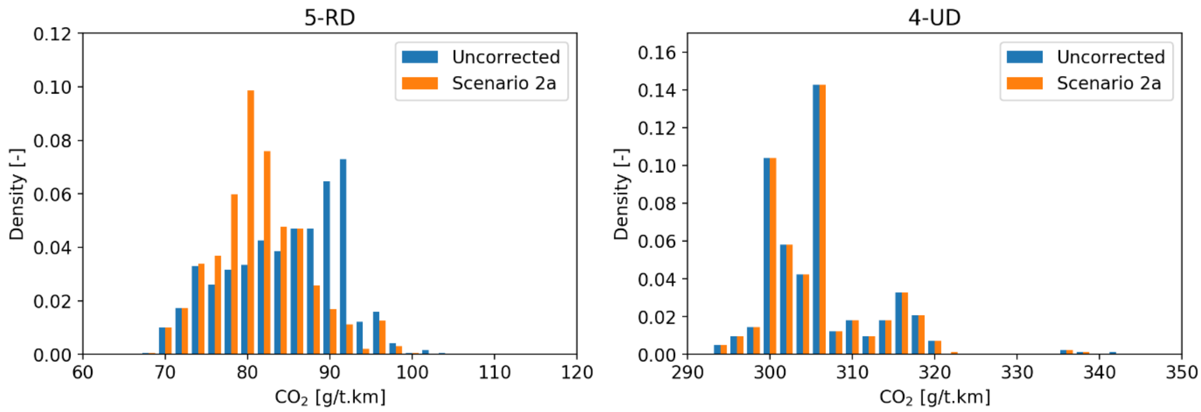
Source: JRC, 2022.

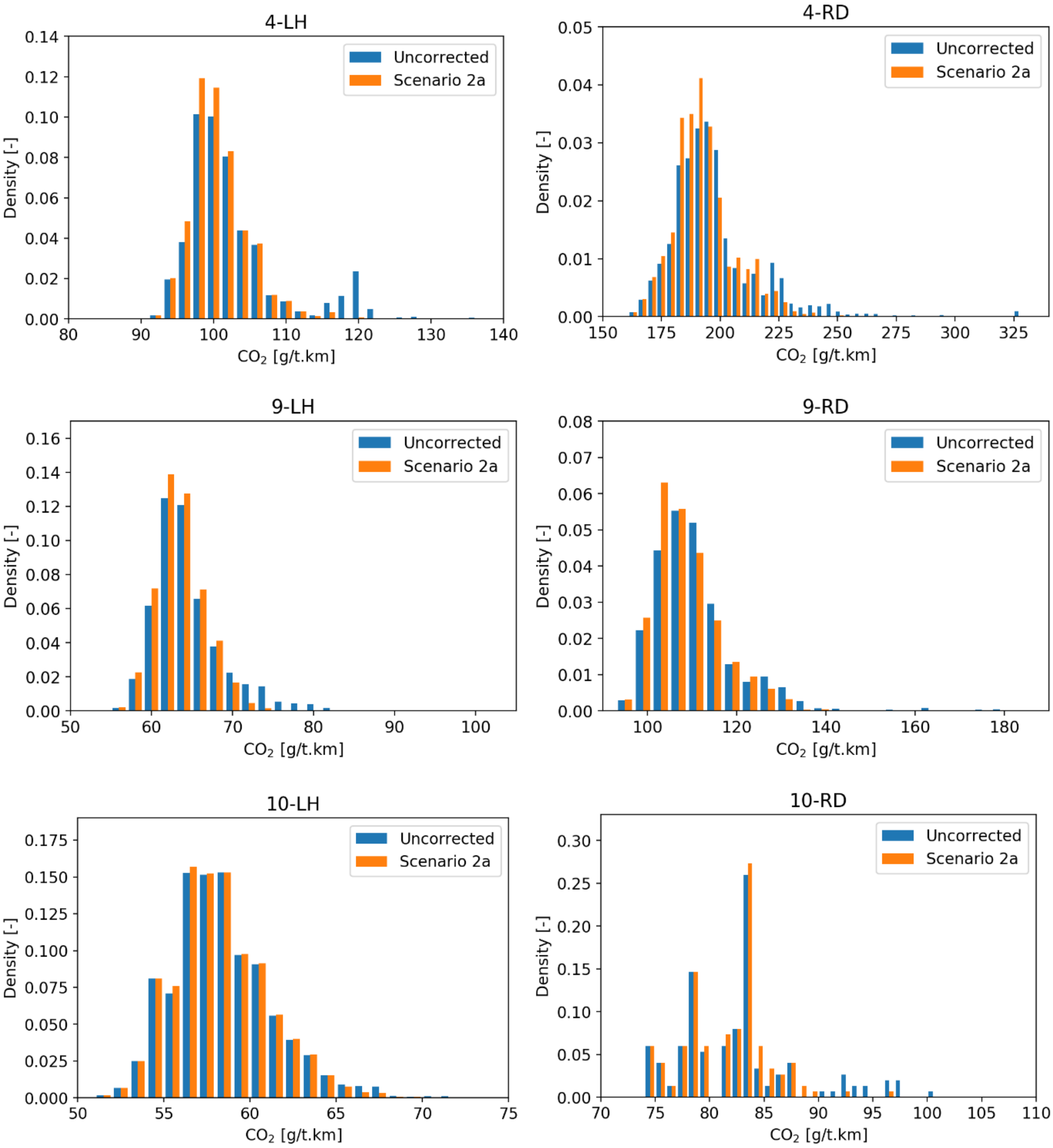
The effect of the correction on the reference CO_2 emissions according to scenario 2a (as an example) is illustrated with Figure 28. It shows the corrected and uncorrected CO_2 emissions distribution of the different vehicle subgroups. The uncorrected distribution is represented by the blue bars and the corrected distribution according to scenario 2a is represented by the orange bars. The difference is quite small for subgroup 5-LH, where a number of vehicles with CO_2 emissions exceeding 63 g/t.km are moved to the median of the distribution. In other vehicle subgroups (e.g. 4-RD, 9-LH and 10-RD), on the other hand, the tail end of the distribution is completely removed and attributed to the median. This significantly reduces the spread of the results.

Figure 28. Distribution of CO_2 emissions in g/t.km per vehicle subgroup without correction (blue bars) and with correction according to scenario 2a (orange bars)



Source: JRC, 2022.





Source: JRC, 2022.

6 Conclusions

The report presented the CO_2 emissions and the main characteristics of the European HDV fleet during the reference period. The source data for the analysis was the detailed VECTO output file of vehicles that were simulated between October 1st 2019 and June 30th 2020 by the vehicle manufacturers. Verification of the files' hash value and comparison of the monitoring data showed that the files were not modified between the original simulation run and their provision to the European Commission. The assessment performed showed that the dataset was adequate for the evaluation of the reference emissions, as demonstrated by a comparison of the fleet composition and the average CO_2 emissions to the official $CO_{2=}$ monitoring data collected by the EEA.

The majority of all HDVs belong to the regulated vehicle groups and subgroup 5-LH has the largest vehicle share. The lowest specific CO_2 emissions (expressed in g/t.km) are found for the tractors (groups 5 and 10) compared to the rigid lorries (groups 4 and 9) and for the long haul, subgroups compared to regional delivery and urban delivery subgroups. The large difference can mostly be attributed to the different simulated payload. Vehicles with standard values for a component have in general higher CO_2 emissions compared to vehicles with only measured components. This finding together with the component analysis confirms the worst-case performance of components with standard values and the hypothesis that an artificially exaggerated application of standard values could potentially increase the reference CO_2 emissions.

A large spread of the components' performance can be observed. However, the best component performance can typically be found in subgroup 5-LH. The number of different technologies (e.g. transmission type or auxiliary technology) used in the fleet for a certain component is limited. This is especially true for vehicle groups 5 and 10, whereas more different technologies are used in vehicle groups 4 and 9. However, a large number of different component models are present in the fleet. This supports the decision for a simulation-based approach to determine the CO_2 emissions of new HDVs, as opposed to a vehicle testing-based approach. A large difference can be observed in the number of unique component models that a vehicle manufacturer has in its portfolio. The unique model count and component family size should be monitored and analysed periodically to identify whether artificial component families affect the fleet CO_2 emissions.

The analysis of standard value showed that only a low share of vehicles makes use of components with standard values and that few vehicles have a standard value for the air drag. Larger use of standard values can be observed for the torque converter. However, a torque converter is only installed in vehicles equipped with an automatic transmission (AT), which has a market share of less than 1.3%. The use of standard values varies a lot between the vehicle subgroups. Whereas subgroups 4-UD, 5-LH and 10-LH have very few vehicles with standard values, subgroups 4-RD, 5-RD and 9-RD have a large share of vehicles with standard values. It should be noted that the 5-LH and 10-LH subgroups make up the majority of the fleet and that subgroups 4-RD, 5-RD and 9-RD have a smaller market share. These findings suggested a small impact of the use of standard values on the fleet reference CO_2 emissions.

The impact of components with standard values on the reference CO_2 emissions was quantified by replacing components with standard values with representative components and recalculating the vehicle's CO_2 emissions and the fleet's reference CO_2 emissions. The validation of the simplified models demonstrated the accuracy of the applied methodology. The choice in representative component led to three different scenarios that were calculated: a conservative, an intermediate and a worst-case scenario. The conservative scenario estimates that the reference CO_2 emissions are 0.4% too high due to the application of standard values. In the intermediate scenario, the inflation increases to 0.6-0.7%, depending on the modelling method and in the worst-case scenario it increases to 1%.

The potential increase of the reference CO_2 emissions appears to be small for each scenario, compared to the legally required reduction of the average CO_2 emissions of 15% and 30% by 2025 and 2030. It has also to be kept in mind that the use of standard values for VECTO simulation is allowed and foreseen by the legislation. Only in case of an undue increase of reference CO2 emissions, i.e. by using standard values for vehicle simulations during the reference period, which by its extent and pattern is atypical, a correction of reference CO_2 emissions according to Article 10 would be justified.

However, considering the relative use of standard values in the different vehicle subgroups such atypical pattern is not suggested, rather the contrary. In fact, standard values are mainly used for vehicles, which have a relatively small impact on the average CO_2 emissions of a manufacturer's fleet due to the low generic lifetime mileage of their sub-groups. In addition, sub-groups with a higher share of vehicles using standard values contain relatively few vehicles in total. This choice of applying standard values is consistent with an economically rational choice of the manufacturer if targets would already apply in the 2019 reporting period: standard values, saving testing costs, are only used if they have no strong increasing effect on the average CO_2

emissions. If manufacturers intended to inflate the reference CO_2 emissions one would rather expect the opposite.

The calculated change in reference CO_2 emissions for the fleet ranges between 0.4 % and 1 %, a percentage that falls well inside the uncertainty margins of the experimental tests used for quantifying component efficiencies or the complete-vehicle fuel consumption and CO_2 emissions simulation. Therefore, no ex-post correction of the reference values is justifiable.

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List of abbreviations and definitions

AMT	Automated Manual Transmission
AT	Automatic Powershifting Transmission
CdxA	Air drag area
CI	Compression Ignition
CNG	Compressed Natural Gas
corr	Corrected
n	Efficiency
E	Energy
EEA	European Environment Agency
FC	Fuel Consumption
F_z	Vertical force
g	Earth’s gravity
gbx	Gearbox
HDV	Heavy-Duty Vehicles
LH	Long Haul
LHV	Lower Heating value
LNG	Liquefied Natural Gas
M	Mass
mp	Mission Profile
MT	Manual Transmission
n	Rotational speed
NG	Natural Gas
ori	Original
PCC	Predictive Cruise Control
PI	Positive Ignition
PL	Payload
PTO	Power Take-Off
r	Reference
RD	Regional Delivery
RRC	Rolling Resistance Coefficient
sg	Subgroup
t	Duration
T	Torque
TPMLM	Technically Permissible Maximum Laden Mass
UD	Urban Delivery
V	Number of vehicles
VECTO	Vehicle Energy consumption Calculation Tool
W	Weighting factor

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Annexes

Annex 1. Sum exec data

The following data is listed in the sum exec data file

Table 24. Parameters in the sum exec data file

Job [-]	Retarder manufacturer [-]	E_clutch_loss [kWh]
Input File [-]	Retarder model [-]	E_tc_loss [kWh]
Cycle [-]	Retarder type [-]	E_shift_loss [kWh]
Status	Angledrive manufacturer [-]	E_gbx_loss [kWh]
Vehicle manufacturer [-]	Angledrive model [-]	E_ret_loss [kWh]
VIN number	Angledrive ratio [-]	E_angle_loss [kWh]
Vehicle model [-]	Axle manufacturer [-]	E_axl_loss [kWh]
HDV CO2 vehicle class [-]	Axle model [-]	E_brake [kWh]
Corrected Actual Curb Mass [kg]	Axle gear ratio [-]	E_vehi_inertia [kWh]
Loading [kg]	Auxiliary technology STP [-]	E_air [kWh]
Total vehicle mass [kg]	Auxiliary technology FAN [-]	E_roll [kWh]
Engine manufacturer [-]	Auxiliary technology AC [-]	E_grad [kWh]
Engine model [-]	Auxiliary technology PS [-]	a [m/s^2]
Engine fuel type [-]	Auxiliary technology ES [-]	a_pos [m/s^2]
Engine rated power [kW]	ADAS technology combination [-]	a_neg [m/s^2]
Engine idling speed [rpm]	PTOShaftsGearWheels	AccelerationTimeShare [%]
Engine rated speed [rpm]	Cargo Volume [m^3]	DecelerationTimeShare [%]
Engine displacement [ccm]	time [s]	CruiseTimeShare [%]
Engine WHTCUrban	distance [km]	max. speed [km/h]
Engine WHTCRural	speed [km/h]	max. acc [m/s^2]
Engine WHTCMotorway	altitudeDelta [m]	max. dec [m/s^2]
Engine BFColdHot	FC-Map [g/h]	n_eng_avg [rpm]
Engine CFRegPer	FC-Map [g/km]	n_eng_max [rpm]
Engine actual CF	FC-NCVc [g/h]	gear shifts [-]
Vehicle fuel type [-]	FC-NCVc [g/km]	StopTimeShare [%]

AirDrag model [-]	FC-WHTCc [g/h]	Engine max. Load time share [%]
Declared CdxA [m²]	FC-WHTCc [g/km]	CoastingTimeShare [%]
CdxA [m²]	FC-AAUX [g/h]	BrakingTImeShare [%]
Sleeper cab [-]	FC-AAUX [g/km]	Engine certification number
Declared RRC axle 1 [-]	FC-ADAS [g/h]	Average engine efficiency [%]
Declared FzISO axle 1 [N]	FC-ADAS [g/km]	Torque converter certification option
Declared RRC axle 2 [-]	FC-Final [g/h]	TorqueConverter certification number
Declared FzISO axle 2 [N]	FC-Final [g/km]	Average torque converter efficiency w/o lockup [%]
Declared RRC axle 3 [-]	FC-Final [l/100km]	Average torque converter efficiency with lockup [%]
Declared FzISO axle 3 [N]	FC-Final [l/100t.km]	Gearbox certification option
Declared RRC axle 4 [-]	FC-Final [l/100m³km]	Gearbox certification number
Declared FzISO axle 4 [N]	CO2 [g/km]	Average gearbox efficiency [%]
total RRC [-]	CO2 [g/t.km]	Retarder certification option
weighted RRC w/o trailer [-]	CO2 [g/m³km]	Retarder certification number
r_dyn [m]	P_wheel_in_pos [kW]	Angledrive certification option
Number axles vehicle driven [-]	P_fcmap_pos [kW]	Angledrive certification number
Number axles vehicle non-driven [-]	E_fcmap_pos [kWh]	Average angledrive efficiency [%]
Number axles trailer [-]	E_fcmap_neg [kWh]	Axlegear certification method
Gearbox manufacturer [-]	E_powertrain_inertia [kWh]	Axlegear certification number
Gearbox model [-]	E_aux_FAN [kWh]	Average axlegear efficiency [%]
Gearbox type [-]	E_aux_STP [kWh]	AirDrag certification number
Gear ratio first gear [-]	E_aux_AC [kWh]	AirDrag certification option
Gear ratio last gear [-]	E_aux_PS [kWh]	Gear 0 TimeShare [%]
Torque converter manufacturer [-]	E_aux_ES [kWh]	Gear 1 TimeShare [%]
Torque converter model [-]	E_aux_sum [kWh]	Gear X TimeShare [%]

Source: VECTO, 2022.

Annex 2. Reference vehicle models

Table 25. Average vehicle properties of vehicles in groups 4 and 5

	4-RD	**4-LH**	**5-RD**	**5-LH**
Curb mass [kg]	6328	7675	7093	7747
Rated power [kW]	224	323	311	354
Idling speed [rpm]	601	543	542	547
Engine rated speed [rpm]	2053	1732	1754	1733
Engine capacity [l]	8.04	11.9	11.5	12.6
Dynamic tyre radius [m]	0.4922	0.4922	0.5223	0.4922
RRC axle 1 [-]	0.0057	0.0052	0.0056	0.0052
RRC axle 2 [-]	0.0064	0.0058	0.0062	0.0057
PTO share [%]	27.82	35.63	50.13	26.80
PTO type	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel
Gearbox type	AMT	AMT	AMT	AMT
Share gearbox type [%]	83.79	98.68	97.05	99.71
Retarder type	None	None	None	None
CdxA [m^2]	5.45	5.16	6.62	5.63
Number of gears	12	12	12	12
Transmission ratio final gear	0.86	0.98	0.97	0.99
Axle ratio	3.97	2.56	2.94	2.53
Engine cooling fan	Crankshaft mounted - Electronically controlled visco clutch	Crankshaft mounted - Electronically controlled visco clutch	Crankshaft mounted - Electronically controlled visco clutch	Belt driven or driven via transm. - Electronically controlled visco clutch
Steering pump	Fixed displacement	Variable displacement mech. controlled	Fixed displacement	Variable displacement mech. controlled

AC system	Default	Default	Default	Default
Electric system	Standard technology	Standard technology	Standard technology	Standard technology
Pneumatic system	Large Supply + ESS + AMS	Large Supply + ESS + AMS	Large Supply + ESS + AMS	Medium Supply 2-stage + ESS + AMS
Axle efficiency [%]	94.83	97.10	96.70	97.37
Gearbox efficiency [%]	96.74	98.42	98.11	98.48
Engine efficiency [%]	39.90	43.14	42.78	43.53
Engine CF	1.02	1.01	1.02	1.01
FC [l/100km]	24.01	29.11	33.63	29.87

Source: VECTO, 2022.

Table 26. Average vehicle properties of vehicles in groups 9 and 10

	9-RD	**9-LH**	**10-RD**	**10-LH**
Curb mass [kg]	8245	9009	8041	8638
Rated power [kW]	289	345	332	367
Idling speed [rpm]	565	545	543	540
Engine rated speed [rpm]	1827	1760	1785	1746
Engine capacity [l]	10.6	12.4	12.4	13.0
Dynamic tyre radius [m]	0.5223	0.4922	0.4922	0.4922
RRC axle 1 [-]	0.0057	0.0054	0.0057	0.0055
RRC axle 2 [-]	0.0064	0.0061	0.0064	0.0057
RRC axle 3 [-]	0.0057	0.00544	0.0062	0.0060
PTO share [%]	44.53	23.49	50.00	28.80
PTO type	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel	only the drive shaft of the PTO - shift claw, synchronizer, sliding gearwheel
Gearbox type	AMT	AMT	AMT	AMT
Share gearbox type [%]	85.18	97.62	100.00	99.29

Retarder type	None	None	None	None
CdxA [m^2]	5.47	5.15	6.50	5.68
Number of gears	12	12	12	12
Transmission ratio final gear	0.93	0.97	0.98	0.98
Axle ratio	3.36	2.72	2.74	2.62
Engine cooling fan	Belt driven or driven via transm. - Electronically controlled visco clutch	Belt driven or driven via transm. - Electronically controlled visco clutch	Crankshaft mounted - Electronically controlled visco clutch	Belt driven or driven via transm. - Electronically controlled visco clutch
Steering pump	Fixed displacement	Variable displacement mech. controlled	Fixed displacement	Variable displacement mech. controlled
AC system	Default	Default	Default	Default
Electric system	Standard technology	Standard technology	Standard technology	Standard technology
Pneumatic system	Large Supply + ESS + AMS	Large Supply + ESS + AMS	Large Supply + mech. clutch + AMS	Large Supply + mech. clutch + AMS
Axle efficiency [%]	95.60	97.17	96.89	97.17
Gearbox efficiency [%]	97.35	98.39	98.19	98.37
Engine efficiency [%]	41.21	43.48	43.52	43.43
Engine CF	1.02	1.01	1.02	1.01
FC [l/100km]	26.54	33.06	32.41	30.92

Source: JRC, 2022.

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