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Analysis of VECTO data for Heavy-Duty Vehicles (HDV) CO_2 emission targets

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Analysis of VECTO data for Heavy-Duty Vehicles (HDV) CO2 emission targets

This report summarises the analysis done on the data provided to the European Commission's Joint Research Centre by the Heavy-Duty Trucks manufacturers about the 2016 Heavy-Duty Vehicles fleet composition and CO_2 emissions performance. The results comprise of key metrics and a representative fleet-wide CO_2 emissions baseline distribution for the year 2016 which were key inputs to the impact assessment study that supported the European Commission's proposal for new Heavy-Duty Vehicle CO_2 standards in Europe. All datasets were checked for quality and errors and were validated against similar data calculated by external parties. CO_2 emissions values were normalised to a common reference basis and CO_2 distributions were produced for the four vehicle categories of interest. The normalisation process led to lower fleet-wide CO_2 emissions, an important observation for defining realistic CO_2 limits for the post-2020 period.

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Executive summary

The European member states are committed to in reducing greenhouse gas (GHG) emissions. CO_2 emissions from transport constitute a significant part of the total GHG emissions in Europe. Pursuant to this policy the European Commission has been asked to prepare a proposal for the introduction of CO_2 emissions standards for Heavy-duty vehicles (HDV). In the meantime, in 2017 CO_2 certification for HDVs was established and set to start by the 1st January 2019 (Commission Regulation (EU) 2017/2400, 2017). Due to the fact that HDVs are highly customisable to adapt to their users' needs, it was difficult to design a laboratory certification test like in the case of light-duty vehicles, and for this reason a simulation approach was chosen for the regulation. For this reason, the European Commission has developed the Vehicle Energy Consumption Tool (VECTO), which determines fuel consumption and CO_2 emissions from HDVs. Vehicle Original Equipment Manufacturers (OEM) have to use VECTO to determine the fuel consumption and CO_2 emissions of the vehicles undergoing the certification process and subsequently report officially the CO_2 emissions values.

The certification and monitoring of Heavy-Duty Vehicle CO_2 emissions will start in Europe in 2019 and will be based on the Commission's developed VECTO simulator and the accompanying certification methodology. According to the Commission's strategy for a sustainable transport sector, a proposal for HDV CO_2 standards had to be investigated too and eventually formulated. The European Commission's Directorate-General for Climate Action (DG CLIMA) has requested the Joint Research Centre (JRC) to perform a study to assess any issues on the reporting procedure and calculate a likely estimate of the 2016 fleet-wide CO_2 emissions distribution according to the established procedure. Calculating a representative fleet-wide CO_2 emissions baseline distribution for the year 2016 was a key input for the impact assessment study that supported the Commission's proposal for setting up CO_2 standards for Heavy-Duty vehicles in Europe. Supporting the task, HDV manufacturers (OEMs) have provided to the JRC large datasets regarding their 2016 vehicle fleet and their corresponding VECTO calculated CO_2 emissions. Vehicle OEMs have simulated their 2016 model-year vehicles and provided VECTO output data along with information regarding their sales numbers to JRC.

The JRC has undertaken the task to analyse, validate the data, and subsequently develop a methodology that would enable the normalisation of the results to a common reference. The target vehicle groups were rigid trucks of HDV class 4 and 9 and tractor-trailer trucks of HDV class 5 and 10. The present report summarises the activities of the JRC in this respect. The JRC performed a series of activities to extract key input values for the impact assessment study, normalise the data provided to a common reference and extract a trustworthy estimate of the 2016 emissions distributions. We (i) evaluated the provided data for inconsistencies, (ii) performed an analysis of the HDV fleet characteristics, (iii) evaluated the supplied CO_2 calculations and identified the discrepancies between different datasets, (iv) developed a methodology for normalizing the datasets in order to calculate a robust and representative 2016 CO_2 baseline. The study was extremely challenging as it required the reception, conditioning, analysis and manipulation of very large datasets within a very short timeframe. In addition since a large part of the vehicle specific information remained undisclosed, the normalisation and extraction of a realistic and uniform, fleet-wide CO_2 baseline required substantial technical and scientific analysis by the JRC to characterise vehicles performance.

JRC performed a fleet-characteristics analysis of the sold vehicles focusing on various components such as gearbox type and tyre energy efficiency class. **Figure 1** presents an overview of the fleet composition by grouping the following vehicle characteristics: HDV class, engine rated power, declared vehicle drag area and cabin type.

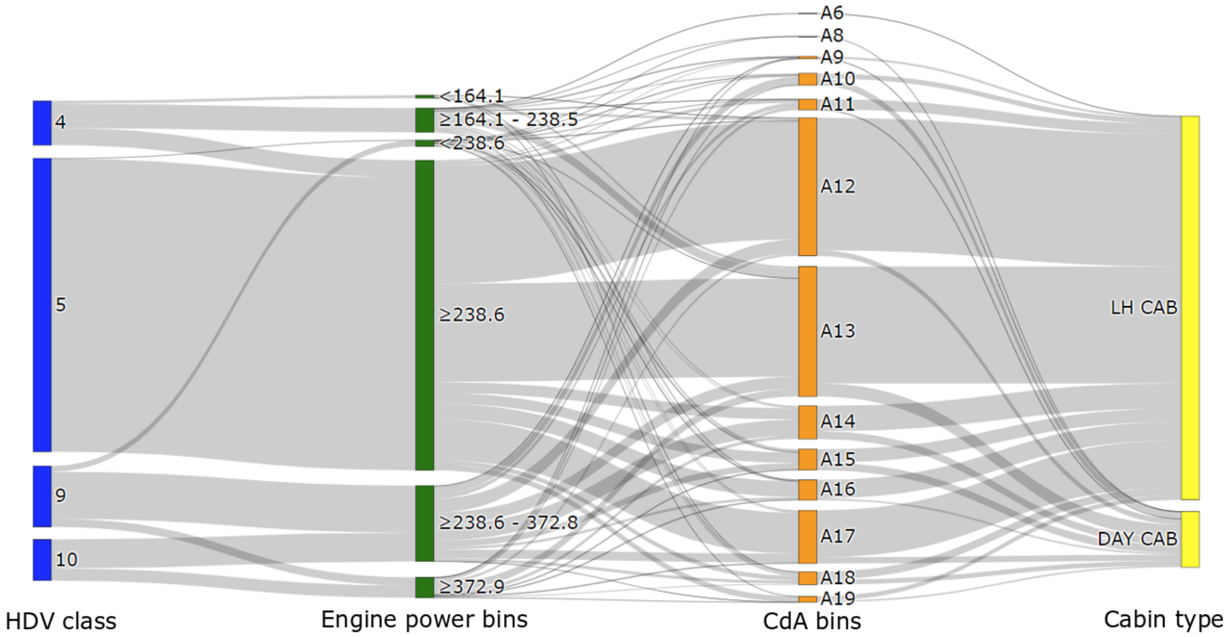

Figure 1. Repartition of HDV CO_2 class, engine power, declared CdA bin and cabin type

The certification regulation (Commission Regulation (EU) 2017/2400, 2017) requires that several components have to be tested in the laboratory to measure their performance, e.g. measure gearbox losses. The OEMs, due to time restrictions, lack of resources, and/or other difficulties, were not always able to follow the testing procedures as foreseen for each component. They have sometimes chosen alternative methods for generating the necessary input data that were used for running the simulations. The data were classified into five categories regarding their compliance with the certification provisions, and are referred to as *data quality*. Based on this input, the next step of the JRC analysis was to classify CO_2 emissions by component and *data quality* in order to assess the impact of different methods used by each OEM. Subsequently, JRC performed a normalisation of the energy consumption associated with the following components: air drag, axle losses and gearbox losses. Average efficiency of engines was analysed and linked to the respective operating conditions. The normalisation process resulted indifferent fuel consumption for some vehicles, and the average engine operating conditions were adjusted accordingly. This resulted in normalised fuel consumption and CO_2 emission dataset that eliminated, to the extent possible, the uncertainties introduced by the assumptions and the quality of the data provided by each OEM. **Figure 2** presents a comparison of the CO_2 emissions distributions between the original OEM data and the JRC normalised values (reference load conditions, regional driving cycle).

Summarizing, the study resulted in the input that was communicated to DG CLIMA for supporting the impact assessment study and the eventual definition of new CO_2 standards for HDV. Multiple inconsistencies were addressed, errors in the datasets were corrected, and the datasets were normalised to a common reference. A key conclusion was that any future reporting procedure must be standardised to prevent data inconsistencies. The normalisation process led to lower fleet-wide CO_2 emissions, an important observation for defining realistic CO_2 limits for the post-2020 period. The observed tendency to overestimate vehicle CO_2 emissions can be attributed to the fact that even vehicle OEMs had limited data originating from officially certified components, as the certification legislation had not been adopted at the time of data provision, hence more conservative values for the energy efficiency of various components were used.

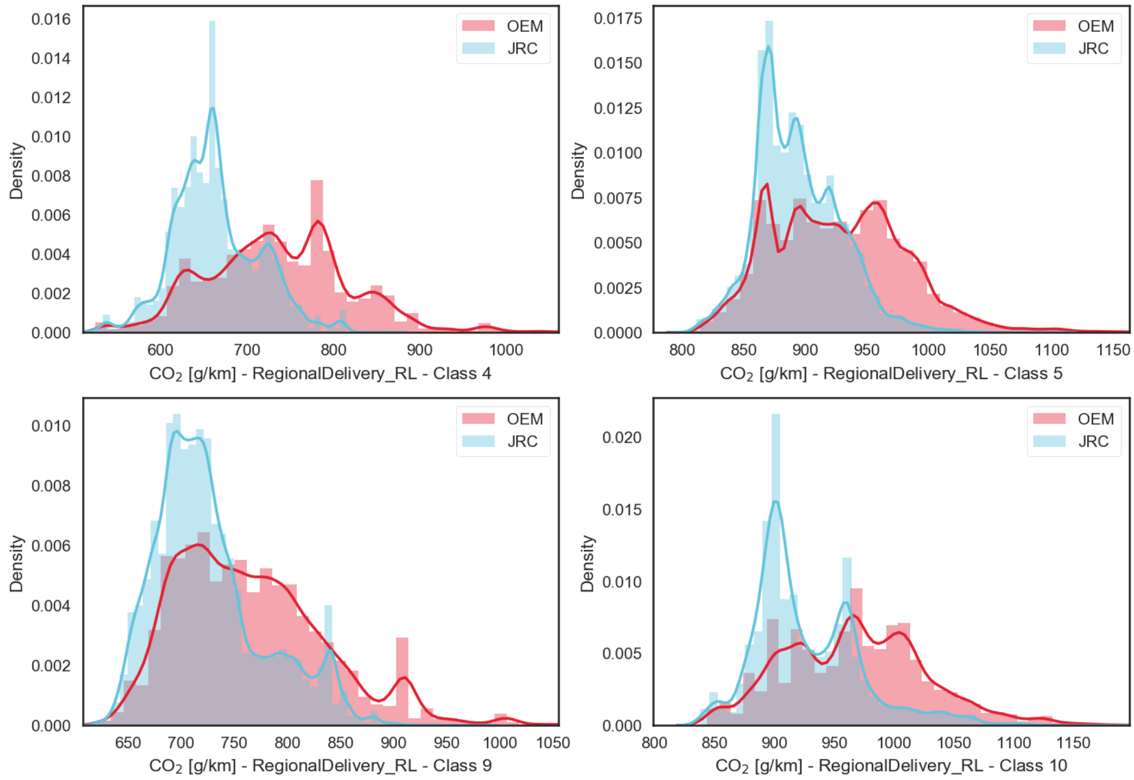

Figure 2. CO_2 emissions [g/km] comparison between OEM declared values and JRC normalisation. Regional delivery, reference load

In terms of CO_2, the results obtained varied for the different vehicle categories. For classes 4 and 9, the normalised median values were calculated at 389 g/tkm and 192 g/tkm, over the weighted regional delivery mission profile, and at 261 and 136 g/tkm over the weighted long haul mission profile. The same figures for Classes 5 and 10 were, 125 g/tkm, 129 g/tkm (weighted regional delivery), 113 g/tkm, 116 g/tkm (weighted long haul) respectively. The variability of these results fluctuated a lot with Class and mission profile ranging from 30 g/tkm to 5 g/tkm. An interesting observation was that the CO_2 distributions were in several cases multimodal, suggesting the existence of possible sub-categories or clusters within the existing classes.

In terms of individual components, the analysis confirmed that the main components of the powertrains exhibit high efficiencies (mean cycle efficiencies) across the different mission profiles with the median values for engines being at 41.5%, for gearboxes approximately at 97% and for axles approximately at 96%. In particular for the latter two additional improvements in the years to come would be very challenging as there appears to be a physical saturation point at about 98-99%. Engine technology could improve as the max mean efficiency that was observed was about 44.5%, i.e. roughly 7% higher than the median value. Technology diffusion could lead to a fleet-wide improvement in the years to come. Tyre rolling resistance is where significant CO_2 could be achieved relatively easily as currently the majority of the vehicles appear to be equipped with Energy-Class C tyres, while Class B and Class A tyres are also present but at much lower shares. The distribution of aerodynamic classes was relatively wide as the manufacturers claimed that not enough time was made available to test their existing vehicles, so generic values were used in several cases. The most common Air Drag categories are A12 and A13 corresponding to air drag values between 5.5 and 6.3 m^2.

Finally, the conditioned datasets and the findings of the current study can be used for supporting future initiatives by DG CLIMA in case needed.

1 Introduction

Heavy-duty vehicles (HDVs) are a major contributor of greenhouse gas (GHG) emissions in the road transport sector, as they are responsible for 30% of the road CO_2 emissions despite accounting for only 4% of the vehicle fleet (Muncrief & Sharpe, 2015). Contrary to light-duty vehicles, until 2017 there has been no official methodology in the European Union for certifying CO_2 emissions from HDVs. The task of defining a measurement or certification scheme for overall vehicle emissions for HDVs has been difficult as the vehicles are customised to a great extent to meet their users' needs (Savvidis, 2014). Hence, the European Commission has chosen a simulation approach that would enable the calculation of CO_2 emissions and fuel consumption (FC). For this reason, EC has developed the Vehicle Energy Consumption calculation TOol (VECTO). Starting from January 2019, the Original Equipment Manufacturers (OEM) will have to determine FCFC and CO_2 emissions through VECTO and subsequently report the calculated values for monitoring purposes as part of the vehicle type approval process.

Prior to the official reporting of the FCFC and CO_2 values from the OEMs, the European Commission has performed an exercise to evaluate and assess the likely fleet-wide emissions baseline for the HDV fleet. Such a baseline would allow the calculation of possible future CO_2 limits for each vehicle category under investigation. For this task, the OEMs have provided datasets of the vehicles sold in year 2016. The datasets include a series of VECTO input parameters for each vehicle along with their respective results. JRC has undertaken the task to evaluate the data, assess the baseline fleet CO_2 emissions and where necessary and possible perform normalisation of the data to eliminate uncertainties introduced by the approaches followed by each OEM. The aim is to obtain a fully comparable dataset that could later be used for setting a reference point for future emission limits determination.

The current report summarises the work done by the JRC, and it is structured as below:

- **Data handling methodology** provides an insight on the data received by the JRC and describes the analysis process.
- **Fleet data outlook** provides an overview of the vehicle market and presents detailed component information.
- **Normalised fleet fuel consumption** presents a normalisation methodology for the presented CO_2 emission values based on air drag and transmission losses.
- **Conclusions**

2 Data handling methodology

2.1 Tools used

The current exercise required handling a big amount of data, which had to be expanded (to reflect the sales-weighted picture of the fleet as it will be explained later), analysed and communicated. Concretely, over 4GB of data were received comprising simulations and sales figures. In total it is estimated that this represents about 240k unique vehicles that could be clustered in about 90k individual VECTO cases. Vehicles falling in the same VECTO case are in most of the cases identical, or in any case, the differences don't produce a change in VECTO resulting FC.

This task required the deployment of several tools to optimise working time allocation and ensure the robustness, reproducibility and quality of the applied processes. The tools used for performing the analysis were:

- Microsoft Excel: Data filtering and visualisation, pivot tables.
- Python: pandas, pytables, numpy, matplotlib, seaborn. Data analysis and visualisation.
- Git: Github for versioning programming code.
- Bash: Handling (move, classify, order) a large number of data files.

2.2 Collection and structuring

The JRC had to develop a standardised approach for checking, structuring and storing the data. The OEMs provided data comprising of VECTO simulations of their vehicles sold in Europe in 2016 classified by vehicle input file. The data contained a series of VECTO input parameters and the output results. For a concrete list of parameters see **Table 14** in Annex 1. A preliminary collection and validation of the data were performed by a third-party company (SIOUX Lime), in agreement with the European Automobile Constructors Association (ACEA), to comply with anti-trust rules and create a basis for cross comparison with the JRC analysis. Lime subsequently forwarded the data to the JRC. The following paragraphs offer an overview of the data and describe the data handling process by the JRC.

Figure 3. Data collection and handling flow at the JRC

2.2.1 VECTO data

VECTO offers two modes for running simulations: Engineering and Declaration mode. In the Engineering mode, the users are free to adjust all the available vehicle parameters to experiment with different simulation configurations. The Declaration mode applies specific boundaries and generic values as foreseen by the EU certification regulation. The Declaration mode also applies a series of predefined driving profiles that include parameters such as the driving cycle and payload. Results provided by OEMs were produced in Declaration mode. The VECTO versions used for the simulations were as in **Table 1**.

Table 1. VECTO versions used by OEMs

Source	VECTO	VECTO.exe
OEM A	3.2.0.940	3.2.0.0
OEM B	3.2.0.925	
OEM C	3.2.0.940	R2.1.0.0
OEM D	3.2.0.940	3.2.0.0
OEM E		3.2.0.0
OEM F	3.2.0.940	3.2.0.0

2.2.2 Data structure

The OEMs forwarded the simulations in XLSX (MS Excel file) or CSV files to SIOUX Lime to perform - as an independent party - quality checks and initial statistical analysis. JRC obtained the data from SIOUX Lime by means of an FTP server using Filezilla. The data was sent in multiple versions; each time an OEM provided new data or corrections to existing data, the most recent versions were downloaded, and the process described in **Figure 3** was applied (see **Table 15** in the Annex for more details). The data provided contained some basic input information along with VECTO output results. Each record of the table referred to a run over one of the officially foreseen driving profiles and in this sense several data records corresponded to the same vehicle. The structure and type of data received by the JRC were not sufficient to allow for VECTO simulation. For example, the data excluded sensitive information such as engine fuel maps and transmission torque loss maps whereas in other cases like the air drag area the data was provided in bins, masking the absolute value used by the OEMs in the simulations. The output data contained pre-agreed VECTO simulation results for each case. Most OEMs run one simulation per vehicle sold, whereas others ran one simulation per truck model and provided an additional separate table with sales number per truck model. This resulted in the necessity to expand the data (data expansion) as will be presented in section 2.2.4. Some OEMs provided full data (one entry per vehicle sold), some others contracted data (vehicles and sales numbers), and some others provided a mix of the two depending on vehicle type.

2.2.3 Data check

To make sure that all information was appropriately received and that no important issues appeared in the datasets, after receiving the data, the JRC performed a series of consistency checks, in summary:

- Naming conventions and data types between all OEMs
- Consistency of data across the dataset (missing, redundant info, corrupted entries etc.)
- Data structuring (see 2.2.4)
- Data consistency (e.g. given input consistent with given output)
- Simulation results quality (e.g. results within expected boundaries, closed energy balances, correct units in the output etc.)
- A comparison between JRC and SIOUX Lime results was made to ensure the equivalence of the input data used in the analyses and the final calculations (see Annex 2)

In certain cases where inconsistencies or other issues appeared, the problem was communicated to SIOUX Lime and/or to the respective OEM with a request for feedback. In some occasions, this process resulted in the delivery of an updated dataset or of parts of it. **Table 15** (Annex 3) contains a summary of the datasets communicated to the JRC within this process. For issues of lesser importance or for issues that appeared after January 2018, when a further update of the sample was not possible due to time restrictions, the JRC proceeded as described in **Table 16** (Annex 3).

2.2.4 Data expansion

In several cases, OEMs did not provide detailed information on the data, or they had used different approaches to vehicle grouping. For this reason, the JRC expanded the data when necessary to obtain an equivalent fleet that would allow further analysis:

- **OEM A** provided one simulation per sold truck for a subgroup of their fleet. For the remaining part, they provided VECTO simulations together with a separate file with the sales number.
- **OEM B** provided one simulation per sold truck in the original database. However, for the Automatic Transmission (AT) Serial vehicles they provided an Excel file with one simulation per truck model and an extra column with the number of sold trucks per model. We expanded the original OEM database with AT Serial models by simply expanding the number of rows of the original OEM database according to the corresponding number of vehicles from the AT Serial database.
- **OEM C** provided one simulation per truck model and an auxiliary CSV file with the sales number for every truck model.. The matching between the truck model simulated and the number of sales is based on an ID. AT Serial vehicles were added afterwards in a separate CSV file in the same way. For the expansion, we simply populated the database rows by the corresponding number of vehicles as indicated in the relative CSV file.
- **OEM D**, **OEM E** and **OEM F** provided one simulation per sold truck.

2.3 Quality of VECTO input data

According to the certification legislation, the data to generate the input files required for the simulation of vehicle components have to be obtained, in most of the cases, following specific standardised test procedures. In particular, such procedures have been defined for the input data of engine, gearbox, axle, vehicle air-drag calculation and tyre rolling resistance. Due to lack of time, testing resources or, in some cases, a complete test protocol, the input data used by the vehicle OEMs in the VECTO simulations did not always comply with the certification standards reported in the HDV CO_2 annex (Commission Regulation (EU) 2017/2400, 2017). In several cases, a different approach was chosen by each OEM and resulting data was used in the simulations. Prior to the exercise, an indicative ranking approach was agreed in order to distinguish data of different origin. The data quality ranking is presented in **Table 2**.

Table 2. Data quality rank description

Data quality rank	Description
1	Measured according HDV CO_2 annex and certified
2	Measured in the presence of Technical Services according HDV CO_2 annex
3	Measured according HDV CO_2 annex but not certified
4	Engineering data (not measured according HDV CO_2 annex)
5	Standard values according to HDV CO_2 annex

2.4 Mission profiles and Fuel Consumption/CO_2 emissions metrics

VECTO declaration mode calculates FCFC and CO_2 emission results of regulated trucks according to the following cycles:

1. Regional Delivery
2. Long Haul
3. Municipal Utility
4. Regional Delivery EMS
5. Long Haul EMS

The Regional Delivery cycle is representative of extra-urban driving conditions. The cycle is highly dynamic due to the many accelerations and decelerations and has an average speed of about 60 km/h. The Long Haul cycle is representative of highway driving at cruising speed, therefore is less transient and with an average cycle speed of 80 km/h being relatively close to the maximum permissible speed in EU. The Municipal Utility cycle is representative of vehicle use in city conditions such as refuse trucks; for this reason, the operating conditions are highly transient, and the average speed is low (about 9 km/h) as a result of multiple stop events taking place. The last two cycles labelled as European Modular System (EMS) have the same driving profile as their respective non-EMS cycles, but they have a different loading configuration with the truck pulling additional trailers and being subjected to higher payloads. All the cycles above are simulated under two different loading conditions: low loading and reference loading.

Each cycle-loading condition results in different figures for FC/CO_2 emissions, for this reason, it is not possible to come up with a unique value of fuel efficiency for a specific truck. When presenting the fuel efficiency of a truck, it is necessary to provide multiple mission profile FC/CO_2 emissions figures. The European Commissions' Directorate General for Climate Action (DG CLIMA) and ACEA agreed that the in-use FCFC could be presented as a weighted-average-value of the aforementioned cycle-loading combinations. Hence, in addition to standardised cycle FCFC and CO_2 emissions, this report presents also weighted values that are calculated for "Long Haul" and "Regional Delivery" equivalent conditions according to specific weighing factors (**Table 3**). These cycles are referred to as *RegionalDelivery_w* (Regional Delivery weighted) and *LongHaul_w* (Long Haul weighted).

Each weighted cycle is calculated using the FC/CO_2 emissions from the standard certification cycles simulated by VECTO: *LongHaul_LL* (Long Haul Low Loading), *LongHaul_RL* (Long Haul Reference Loading), *RegionalDelivery_LL* (Regional Delivery Low Loading) and *RegionalDelivery_RL* (Regional Delivery Reference Loading); each one of these four figures is multiplied by the relative weight factor. Then their sum yields the weighted cycle FC/CO_2 emissions. When calculating the *RegionalDelivery_w* cycle, the weight factors to be taken are in the column *RD_factor*. When calculating the *LongHaul_w* cycle, the weight factors to be taken are in the column *LH_factor*.

In order not to burden the report with excessive information, the following four cycle-loading combinations are reported henceforward:

- RegionalDelivery_RL
- LongHaul_RL
- RegionalDelivery_w
- LongHaul_w

Table 3. Weight factors for the calculation of *RegionalDelivery_w* and *LongHaul_w* fuel efficiency

HDV class	Cycle	Loading	RD_factor	LH_factor
4	RegionalDelivery.vdri	900	0.45	0.05
		4400	0.45	0.05
	LongHaul.vdri	1900	0.05	0.45
		14000	0.05	0.45
5	RegionalDelivery.vdri	2600	0.27	0.03
		12900	0.63	0.07
	LongHaul.vdri	2600	0.03	0.27
		19300	0.07	0.63
9	RegionalDelivery.vdri	1400	0.27	0.03
		7100	0.63	0.07
	LongHaul.vdri	2600	0.03	0.27
		19300	0.07	0.63
10	RegionalDelivery.vdri	2600	0.27	0.03
		12900	0.63	0.07
	LongHaul.vdri	2600	0.03	0.27
		19300	0.07	0.63

For each of the four conditions a series of different metrics are reported as follows:

- FC-Final [l/100km]
- FC-Final [l/100tkm]
- CO_2 [g/km]
- CO_2 [g/tkm]
- Specific FC at wheels [g/kWh]
- Specific CO_2 at wheels [g/kWh]

The last two metrics are obtained as the total grams of fuel/CO_2 divided by energy at wheels expressed in kWh, which is calculated as the sum of energy spent for air drag, rolling resistance, braking, change in potential energy and vehicle inertia (zero if vehicle speed is the same at the beginning and the end of the cycle).

When presenting the results, just the CO_2 in [g/km] will be presented in the body of the report. The information regarding other metrics is presented in the annexes.

3 Fleet data outlook

3.1 Main vehicle characteristics

To obtain an overview of the current vehicle market, we separate the vehicles into categories and perform an analysis of the main vehicle characteristics. The separation into categories is based on the respective HDV Class. The characteristics of the examined HDV classes are presented in **Table 4** below.

Table 4. HDV classes characteristics

HDV Class	Vehicle type	Minimum gross vehicle weight (t)	Axle configuration
4	Rigid truck	16	4x2
5	Tractor	16	4x2
9	Rigid truck	-	6x2
10	Tractor	-	6x2

Subsequently, after separating the vehicles into categories, we performed a statistical market analysis, which focused on the vehicles main characteristics. These characteristics include technical aspects that could have an impact on the vehicles CO_2 emissions (e.g. drag area, gearbox type). The list below presents the vehicle characteristics that were used for the market analysis.

- Rigid - Tractor trucks market share
- Curb vehicle mass
- Vehicle drag area
- Engine displacement
- Engine rated power
- Rolling resistance
- Gearbox type
- Retarder type
- Auxiliaries

Initially, the market analysis investigated the fleet composition in terms of vehicle type by calculating the shares of rigid and tractor trucks. HDV Class 4 and 9 vehicles were grouped as rigid trucks, HDV Class 5 and 10 as tractor trucks. **Figure 4** shows that tractor trucks dominate the market with a share of 76.1%, while the rigid trucks comprise the remaining 23.9%.

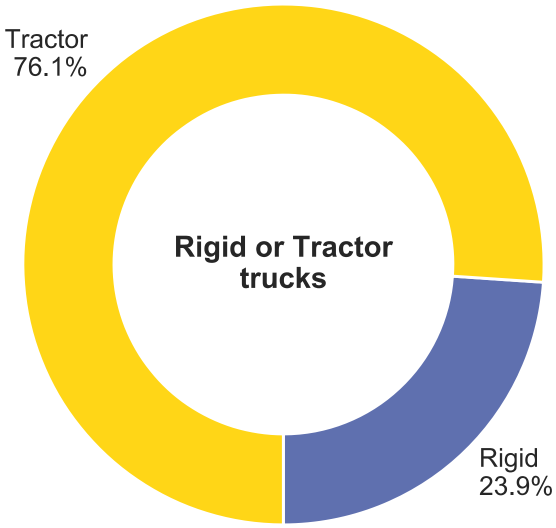

Figure 4. Market share of rigid and tractor trucks

The vehicle curb mass corresponds to the mass of the vehicle not taking into consideration any additional superstructures that are required for hauling the cargo. In VECTO simulations, the additional superstructures refer to the body type of the rigid trucks and the semi-trailer of the tractors. In the case of additional superstructures, when VECTO runs in Declaration mode, it automatically adds their mass according to the standard body types. Regarding rigid trucks, HDV class 4 vehicles have an average curb mass of about 6470 kg, while class 9has a substantially higher average mass of about 8680 kg. The standard deviation is 973 kg and 586.7 kg for class 4 and 9 respectively. The difference between tractor trucks is lower with class 5 having an average mass of 7800 kg and class 10 at about 8630 kg. Additionally, tractors show a lower standard deviation compared to rigid trucks at 433.3 kg for class 5 and 470.7 kg for the class 10. **Figure 5** presents the distribution of curb vehicle mass for each HDV Class, with each plot representing the distribution of the respective HDV class as a proportion of the whole fleet.

During motion, vehicles have to overcome the aerodynamic force (air drag) that constitutes resistance to movement, which is function of vehicle speed. The vehicle drag area (CdA) is the vehicle characteristic that defines the intensity of this resistance and is obtained as the product of the vehicle's frontal area (A) and the aerodynamic coefficient (Cd). The aerodynamic coefficient is dimensionless and is used to describe the aerodynamic properties of the vehicle's shape (it doesn't depend on vehicle dimension). The OEMs have provided vehicles CdA classified into bins as in **Table 5**.

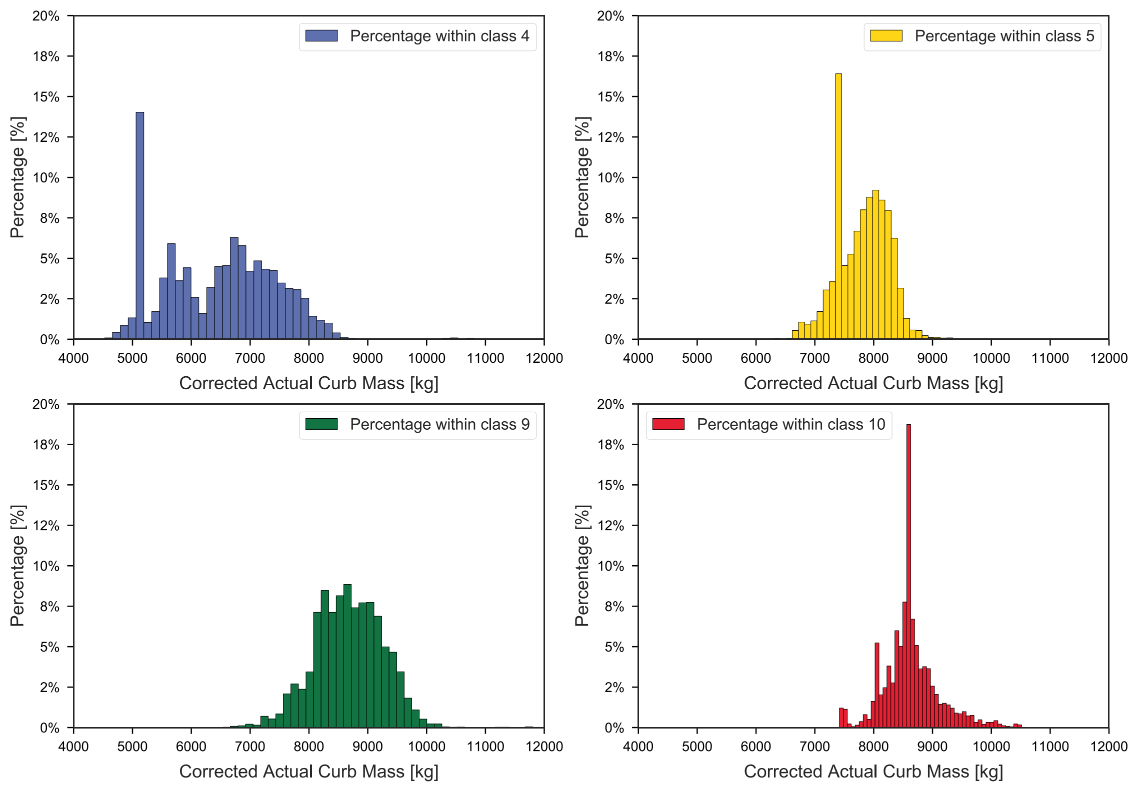

Figure 5. Distribution of curb vehicle mass by HDV Class

Table 5. CdA bins

Bin name	**CdA range [m^2]**	**Bin name**	**CdA range [m^2]**
A1	<3	A11	[5.2 - 5.5)
A2	[3 - 3.2)	A12	[5.5 - 5.9)
A3	[3.2 - 3.4)	A13	[5.9 - 6.3)
A4	[3.4 - 3.6)	A14	[6.3 - 6.7)
A5	[3.6 - 3.8)	A15	[6.7 - 7.1)
A6	[3.8 - 4)	A16	[7.1 - 7.6)
A7	[4 - 4.3)	A17	[7.6 - 8.1)
A8	[4.3 - 4.6)	A18	[8.1 - 8.6)
A9	[4.6 - 4.9)	A19	[8.6 - 9.2)
A10	[4.9 - 5.2)	A20	⩾9.2

The energy used to overcome air drag highly affects FCFC and is proportional to CdA. Therefore vehicles of the lowest CdA bins are associated with higher fuel efficiency. In rigid trucks of HDV class 4, the 37% of the vehicles have a CdA of A13 followed by a CdA of A18 and A12 with 10.1% and 9.8% shares respectively. The highest share of the HDV class 9 vehicles has a CdA of A14 with 22.8%. However, the CdA seems improved compared to the HDV class 4 as the next classes with the highest share are A12 with 16.5% and A10 with 14.9%. The HDV class 5 tractor trailers have a share of 39.8% for the A12 bin and 31.2% for The A13. The HDV class 10 also have a high share of 36.5% of vehicles with a CdA of A13 followed by A17 with 17% and A12 with 16.9%. **Figure 6** presents the share of each drag area bin by vehicle class.

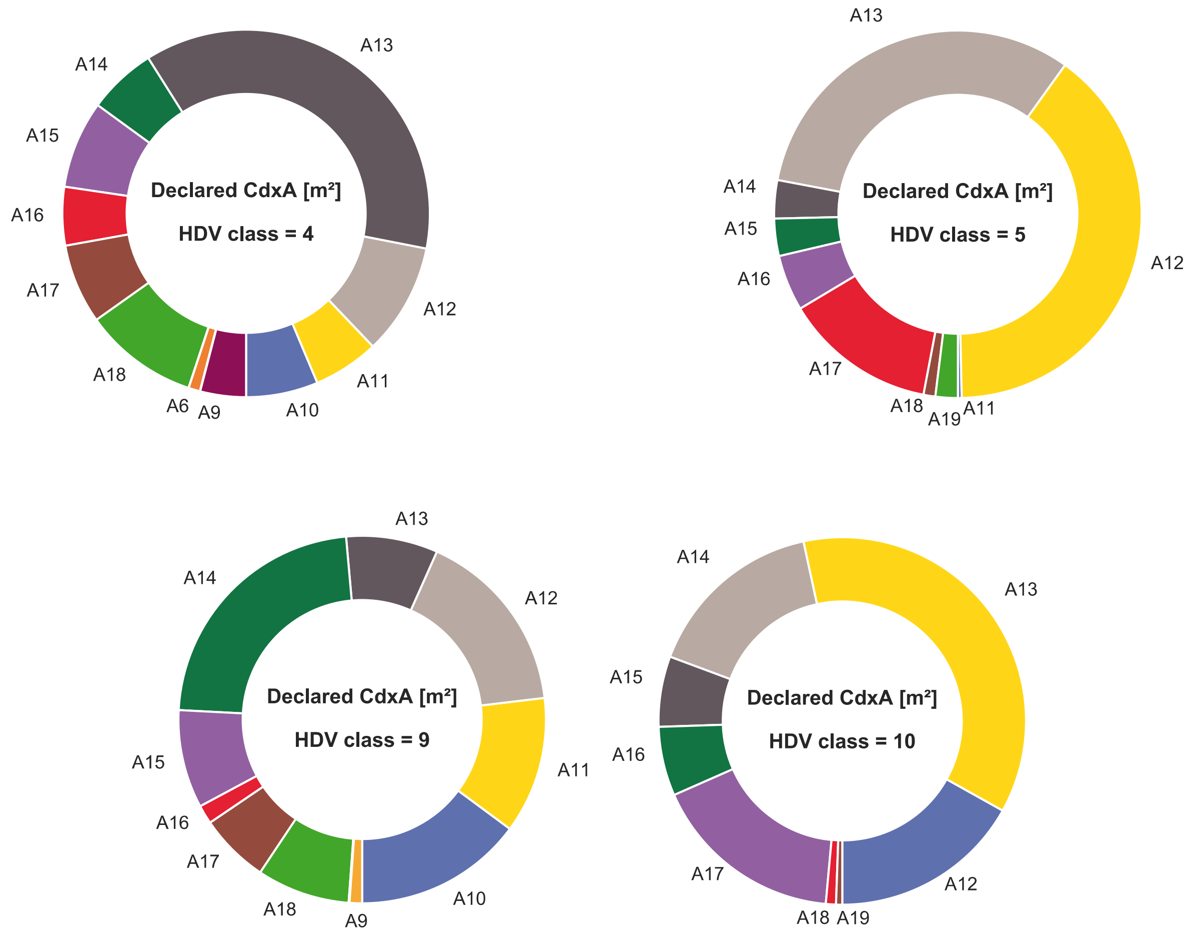

Figure 6. Share of CdA bins by vehicle class

The market analysis regarding engines focused on two parameters: displacement and rated power. The most used engine size is close to 7 litres for class 4, and close to 13 litres for Classes 5, 9 and 10. Tractors present a lower discrepancy in minimum and maximum displacement compared to rigid trucks. **Figure 7** presents the engine displacement distribution by HDV class, with each plot representing the distribution of the respective HDV class as a proportion of the whole fleet.

Subsequently, the market analysis investigated the engine rated power by producing the distribution curves for each HDV class. In the rigid trucks, HDV class 4 has a median rated power of 213.24 kW with a standard deviation of 57.43 kW, while class 9 vehicles have a significantly higher median rated power at 323.53 kW with a standard deviation of 51.94 kW. Regarding tractor trucks, the medians of the engine rated power are relatively close at 340 kW for the HDV class 5 and 345 kW for the HDV class 10. The respective standard deviations are 26.42 and 32.7 kW. **Figure 8** presents the distribution of engine rated power by HDV class. The distribution of the rated power for each of the HDV classes is expressed as a proportion of the whole fleet.

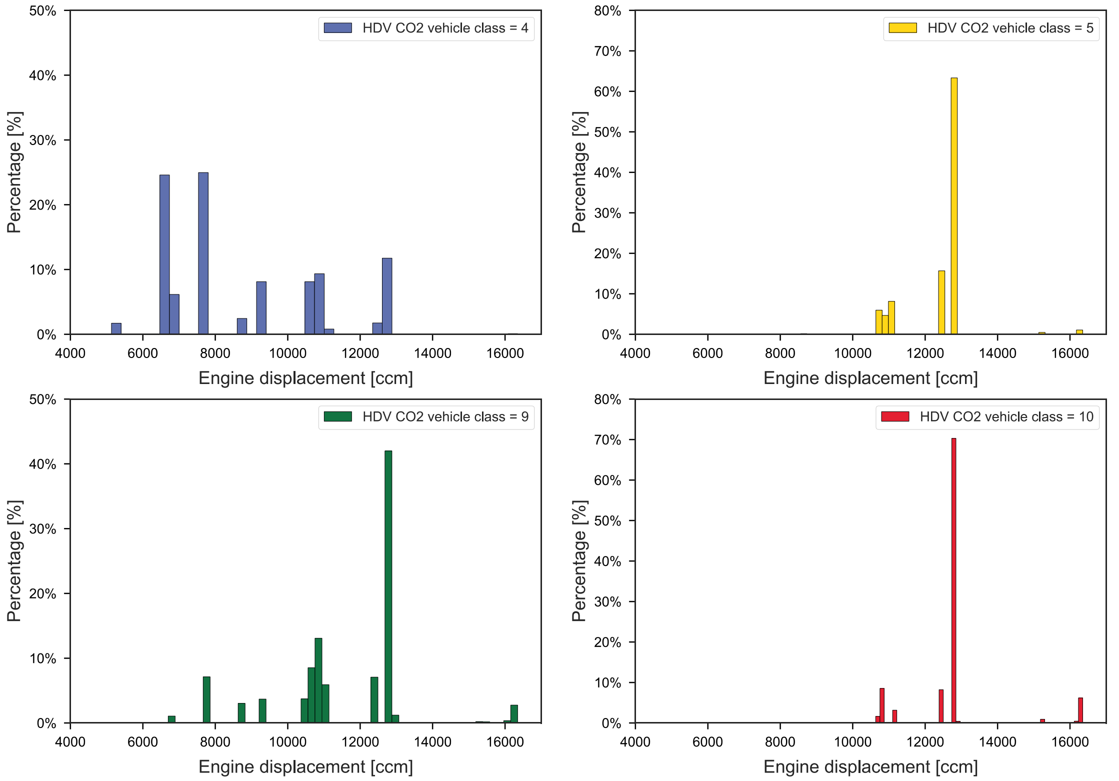

Figure 7. Engine displacement distribution by HDV class

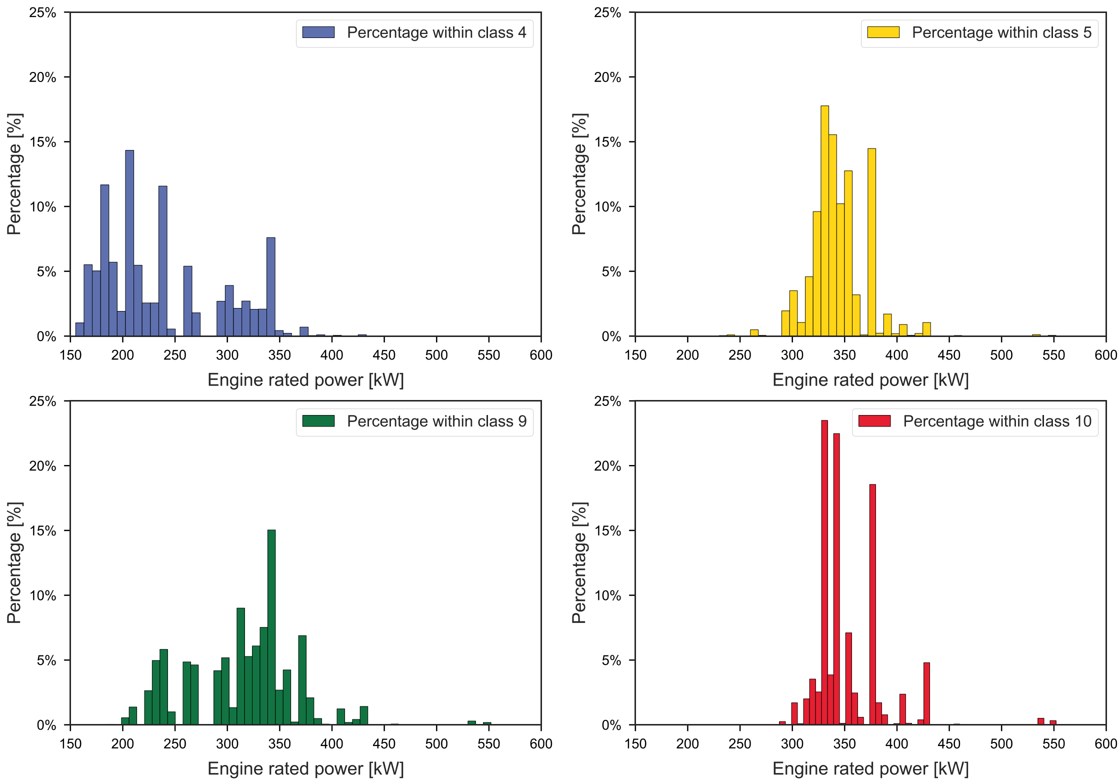

Figure 8. Distribution of engine rated power by HDV class

The common way to describe tyre efficiency is through the Rolling Resistance Coefficient (RRC), which describes the resistance offered to vehicle motion. The Regulation (EC) No 1222/2009 (2009) defines rolling resistance bins, which are labelled as "tyre energy efficiency class". HDVs have C3 type tyres with A class (RRC ≤ 4,0 kg/t) being the most efficient and F class (RRC ≥ 8,1 kg/t) being the least efficient category. A study has identified a decreasing trend in the RRC of the sold C3 tyres and estimated an average RRC value of 6.13 kg/t in 2015, which corresponds to D class tyre (Maagøe, 2016).

VECTO requires two parameters, RRC_{iso} and Fz_{iso}, which define tyre properties (they are solely tyre-specific) and are used to calculate the resisting force acting on the vehicle. Such parameters were not provided by OEMs along with the data of the fleet. For this reason, to perform an analysis of the fleet tyre efficiency, the *total vehicle Rolling Resistance Coefficient* had to be used instead, which is an output of VECTO. It is representative of the vehicle-loading-tyres combination efficiency with regards to rolling resistance, while equation 1 also explains how vehicle characteristics affect the rolling resistance.

$$RRC = \sum_{i=1}^{n} s_{(i)} \cdot RRC_{ISO(i)} \cdot \left(\frac{s_{(i)} \cdot m \cdot g}{w_{(i)} \cdot Fz_{ISO(i)}} \right)^{\beta - 1}$$

Eq. 1

where

RRC : total vehicle Rolling Resistance Coefficient [-]

$s_{(i)}$: weight share for axle i [-]

$RRC_{ISO(i)}$: Rolling Resistance Coefficient of tyres in axle (i) according to ISO 28580 [-]
m: vehicle total mass for the specific cycle-loading condition [kg]

g: gravitational constant [m/s^2]

$w_{(i)}$: tyre configuration of axle (i) [-] (2 if single tyres, 4 if twin tyres)

$Fz_{ISO(i)}$: Tyre test load of tyres in axle (i) according to ISO 28580 [-]

β: constant parameter equal to 0.9 [-].

Figure 9 gives an approximate idea of the fleet tyre efficiency, where the vehicle RRC w/o trailer (VECTO output which doesn't consider the standard bodies influence) for Long Haul cycle, ref. load, was taken and translated into the respective tyre energy efficiency class.

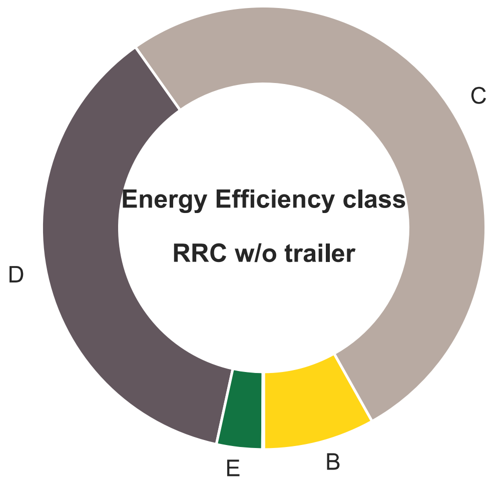

Figure 9. Market share of tyre energy efficiency class by axle

The investigation on the gearbox types identified three gearbox types: Automated Manual Transmission (AMT), Manual Transmission (MT) and Automatic Serial Transmission (ATSerial). The share of each gearbox type varies depending on the vehicle type with AMT having a significantly higher share for both rigid and tractor vehicle types. More specifically, the analysis shows that in rigid trucks AMT has the highest share with 86.2% followed by the MT with 10.8%. A low share of about 3% is also attributed to ATSerial. The analysis shows a different picture in the case of the tractor-trailers where AMT dominates with a share of 98.6% and the remaining 1.4% being attributed to MT. **Figure 10** presents the gearbox type share by vehicle type.

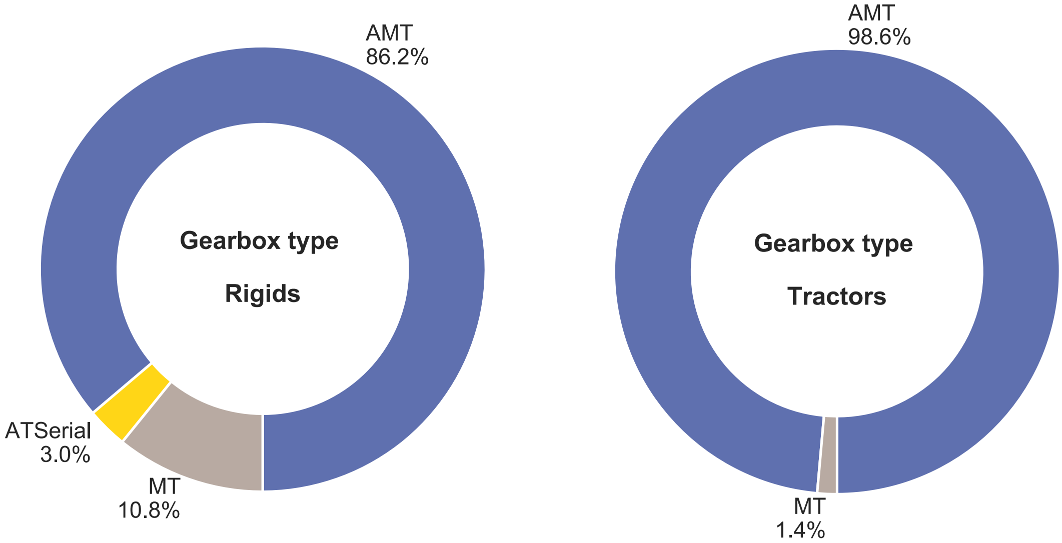

Figure 10. Market share of gearbox types by vehicle type

Retarder is a vehicle component that assists the vehicle in braking by transferring the power from the wheels to an energy dissipation device. As an example of retarder technology we present the hydraulic retarder, which is constituted by a rotor that spins within a liquid medium and dissipates heat to the vehicle's cooling system. The shares of retarder types are presented in **Figure 11**. There was no retarder in the rigid trucks, and all the vehicles that deployed a retarder were HDV class 5 and 10. Breaking down the retarder types, about 43.5% of the vehicles had a secondary retarder, which means that the component is placed between the gearbox and the clutch, as opposed to the primary retarder that is placed between the axle and the gearbox (which was not present in any of the vehicles). About 15% of the vehicles had the retarder included in the transmission loss maps, which signifies a retarder component that is contained within the gearbox compound.

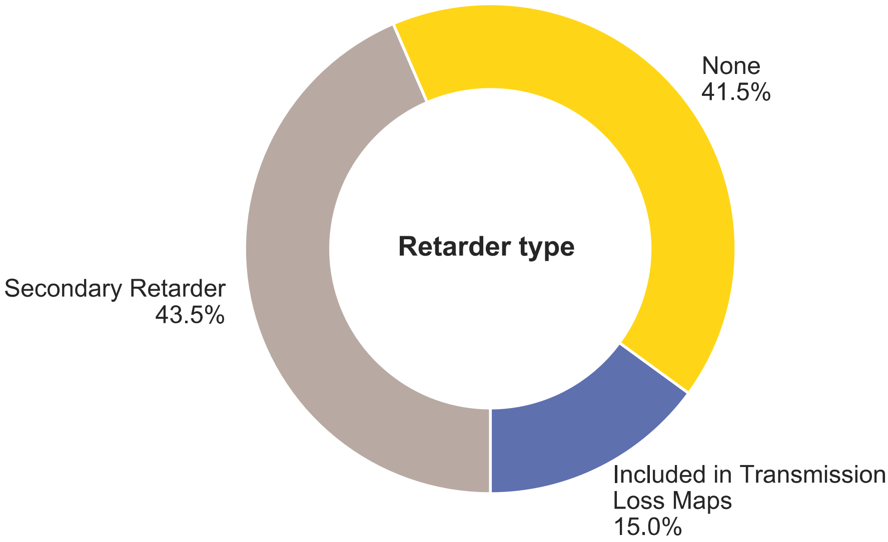

Figure 11. Market share by retarder type

HDVs are equipped with components that are not part of the driveline and are associated with non-negligible power demand. Such components are generally referred to as auxiliaries and are classified in VECTO according to their purpose during vehicle operation. **Table 6** presents a description of the auxiliaries that VECTO takes into consideration.

Table 6. VECTO auxiliaries description

ID	Type	Description
FAN	Fan	Engine cooling technology
STP	Steering pump	Power-assisted steering technology
AC	HVAC	Cabin air conditioning and ventilation
ES	Electric System	Lighting technology system
PS	Pneumatic System	Compressor type for utilizing air brakes

The engine heats up during vehicle operation, and heating built-up can be especially high in increased engine loads. To counteract this, there are several systems that are deployed to cool down the engine, with the most prominent being the fan that is coupled to the engine usually through a clutch whenever cooling requirements are high. However, the use of the fan poses an additional load to the engine that has an impact on FCFC. In order to reduce the load imposed by the fan, but maintain the same cooling capabilities the OEMs have deployed different fan mounting technologies. **Figure 12** shows how the different engine fan technologies (presented with their VECTO names) are distributed over the fleet: 64% of the vehicles deploy a *belt-driven or transmission-driven – electronically controlled visco clutch*, while *Crankshaft mounted - Electronically controlled visco clutch* is deployed in 35.7% of the vehicles and is considered to be the most efficient fan technology (JRC, 2018).

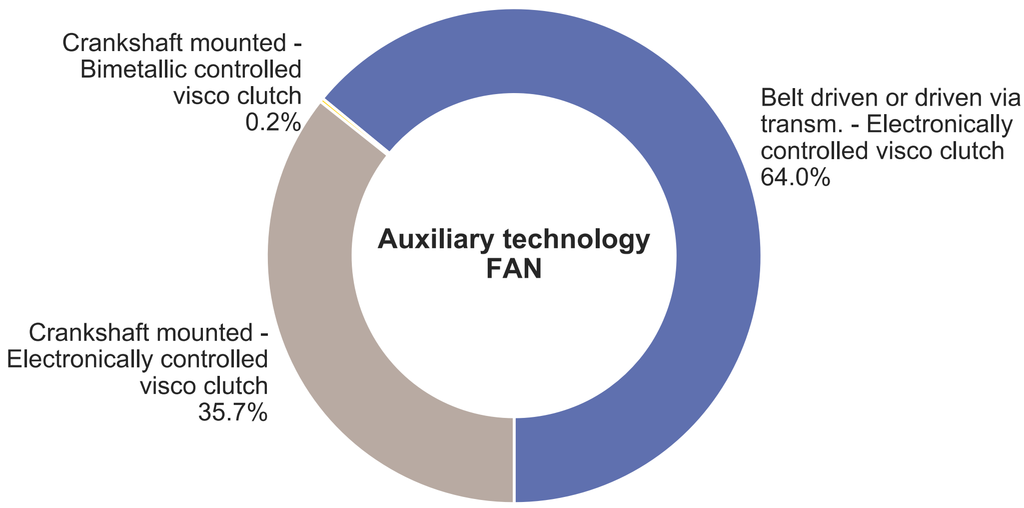

Figure 12. Market share by fan technology

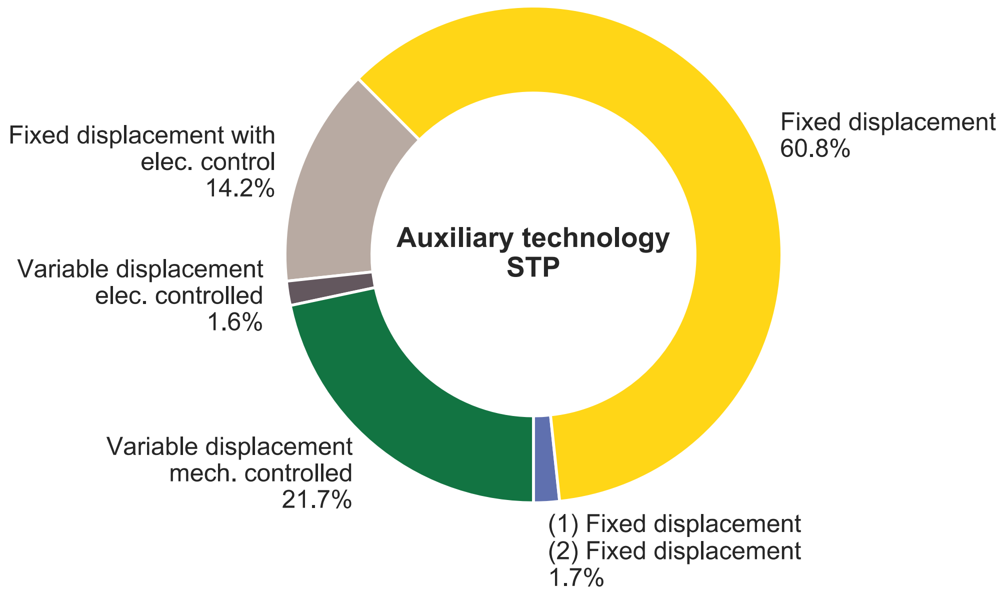

Figure 13. Market share by steering pump technology

The vehicle steering system is assisted by a pump, which provides the additional power that is needed to steer the vehicle. The steering pump is mounted on the engine and poses an additional load, but OEMs offer several technologies that increase the pump efficiency in order to counterbalance this load. **Figure 13** shows that 62.5% of the vehicles deploy a fixed displacement pump followed by a variable mechanically controlled pump with a 21.7% share. The A/C technology list in VECTO for the time being defines only whether an A/C system is present in the vehicle or not. **Figure 14** shows that 99.7% of the vehicles have an A/C system.

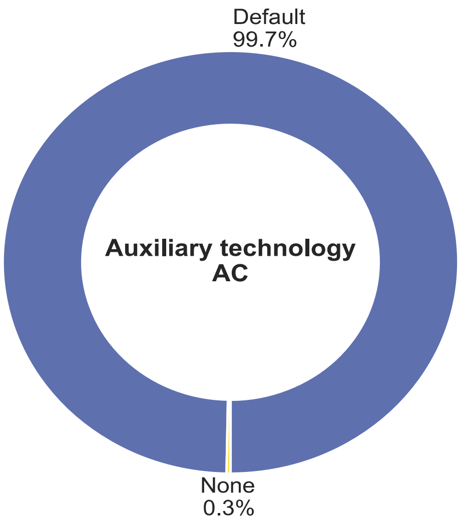

Figure 14. Market share by A/C

The electric system list focuses on the vehicle lighting, and it actually offers two options: standard lighting technology and LED lighting technology. The latter is the most efficient option. According to **Figure 15**, 68.3% of the vehicles deploy standard lighting technology and the remaining 31.7%LED lighting technology (the technologies are presented with their VECTO names in the figure).

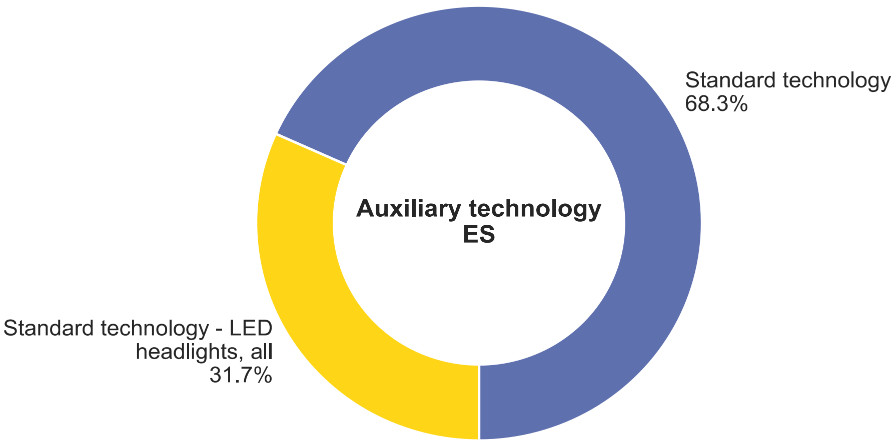

Figure 15. Market share by electric system technology

The vehicle has components that operate with air pressure such as the compressed air brake system. A pneumatic system provides the required air pressure by utilizing an air compressor, which is directly driven by the engine. There are several systems that increase the pneumatic system efficiency such as mechanical clutches, Advanced Mechatronics Systems (AMS) and the Energy Saving Systems (ESS). The pneumatic systems in VECTO are defined based on the air supply capability, the compression stages and any additional efficiency-improving technologies. The air supply capability depends mainly on the vehicle, as heavier vehicles would have higher air pressure requirements in order to operate their air brake system. **Figure 16** presents the market shares of pneumatic system technologies with the names that are in use for VECTO. The most efficient systems are considered to be *Medium Supply 1-stage + mech. clutch + AMS* and *Large Supply + mech. Clutch*, which have shares of 1.3% and 15.1% respectively.

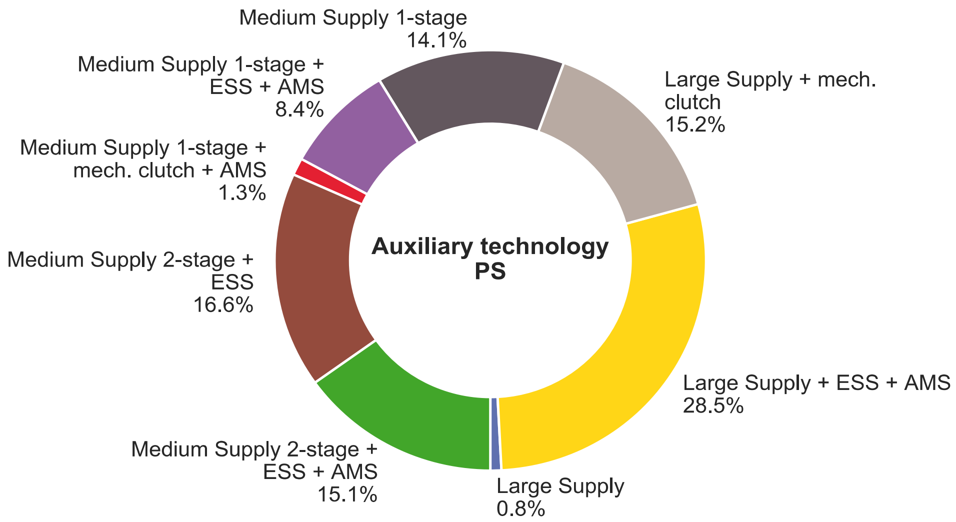

Figure 16. Market share by pneumatic system technology

3.2 Grouped data

We used the clustering approach proposed by DG CLIMA in the framework of their impact assessment study for further grouping the vehicles and deriving statistics per subgroup.

Table 7 presents the resulting subgroups per each HDV class clustered according to the engine rated power bins and cabin type. The table presents for each cluster the total number of vehicles, median of engine displacement, average drag area (estimated) and rolling resistance coefficient (with and without trailer). Class 5 vehicles equipped with Long Haul cabin and at least 238.6 kW of rated power is by far the most numerous subgroup. Hence, it is of big importance to catch the real fuel efficiency of these vehicles in order to reflect the entire fleet accurately. OEMs didn't provide punctual values of vehicles CdA but rather indicated a range in which the CdA (measured or default value) falls. Based on this indication and the VECTO output of energy spent for air drag, JRC produced estimates of vehicles CdAFor many of the engine rated power subgroups, the average estimated CdA is bigger for DAY cabins, which is counter-intuitive (LH cabins generally have bigger cross-sectional area). This anomaly could be explained by the larger use of default values (which are generally higher compared to measured ones) for rigid trucks due to the lack of measured data. This fact is to be cross-validated with data measured according to the official procedure. The last column of the table presents average total vehicle RRC, which is also taken from VECTO data. If a big portion of the fleet adopts new tyres technology, this would turn into a consistent reduction of total RRC compared to the values shown in the table, ranging between 5.9 and 6.5 [kg/t] (best efficiency class tyres have much lower RRC, even below 4 kg/t, under specific loading conditions).

Table 7. Market overview according to the clustering proposed by DG CLIMA

HDV CO_2 vehicle class	Engine rated power [kW]	Cabin type	Vehicle count	Engine displacement median [cm³]	Average estimated CdA [m²]	Average RRC total [kg/t]
4	<164.1	DAY CAB	1469	6700	6.11	6.1
		LH CAB	146	6700	5.75	6
	≥164.1 - 238.5	DAY CAB	10142	7698	6.59	6.23
		LH CAB	3459	7698	5.91	6.23
	≥238.6	DAY CAB	3308	10677	6.25	6.22
		LH CAB	6234	11120	6.37	6.02
5	<238.6	DAY CAB	76	9300	7.06	5.92
		LH CAB	51	7698	7.08	6.01
	≥238.6	DAY CAB	1965	11120	8.04	6.32
		LH CAB	162270	12800	6.3	6.04
9	<238.6	DAY CAB	2794	7698	7.21	6.46
		LH CAB	475	8710	6.42	6.24
	≥238.6 - 372.8	DAY CAB	11156	10837	6.28	6.31
		LH CAB	15146	12740	6.09	6.08
	≥372.9	DAY CAB	157	12809	6.58	6.21
		LH CAB	4391	12800	6	6.23
10	≥238.6 - 372.8	DAY CAB	110	12740	7.99	6.23
		LH CAB	16066	12740	6.59	6.1
	≥372.9	LH CAB	6844	12800	6.36	6.23
Overall			246259	12740	6.33	6.09

3.3 Component information

This section presents basic statistics about the components found in the fleet, along with the analysis of their performances. The efficiency of components has been calculated and evaluated taking into consideration the quality of the input data that produced the VECTO results received from the OEMs. The figures obtained for efficiency and their dependency on data quality are then used in chapter 4 to derive representative component performance values for the fleet.

3.3.1 Unique components

Table 8 shows how many unique components are contained in each subgroup of the clustering proposed by DG CLIMA. For the whole fleet, there are 99 different engine models, 98 different gearbox models and 83 different axle models. Some of the subgroups show a much smaller number of different components (engines, axles, gearboxes) compared to others, which is explained by a smaller size of the subgroup itself and/or different market characteristics (less vehicle variability/customisation).

Table 8. Component counts, using the clustering proposed by DG CLIMA

HDV CO_2 vehicle class	Engine rated power (kW)	Cabin type	Different engine models count				Different gearbox models count				Different axle models count			
4	<164.1	DAY CAB	3	3	94	99	8	8	81	98	8	8	67	83
		LH CAB	2				5				5			
	≥164.1 - 238.5	DAY CAB	27	27			40	41			43	45		
		LH CAB	25				36				36			
	≥238.6	DAY CAB	48	64			55	66			46	53		
		LH CAB	61				58				48			
5	<238.6	DAY CAB	9	10	77		9	10	59		9	11	53	
		LH CAB	8				7				7			
	≥238.6	DAY CAB	51	67			40	58			37	52		
		LH CAB	67				56				50			
9	<238.6	DAY CAB	17	17	86		26	27	75		26	27	62	
		LH CAB	14				19				15			
	≥238.6 - 372.8	DAY CAB	46	47			63	64			51	54		
		LH CAB	46				55				48			
	≥372.9	DAY CAB	11	22			17	30			15	28		
		LH CAB	22				29				26			
10	≥238.6 - 372.8	DAY CAB	14	33	54		11	31	39		12	28	35	
		LH CAB	32				31				28			
	≥372.9	LH CAB	21	21			25	25			27	27		

3.3.2 Data quality shares per component and HDV class

In this paragraph we present how the quality of data on components (engine, gearbox and axle) distributes per HDV class, using the data quality parameter presented in **Table 2**. The quality of input data used by OEMs to run VECTO simulations is here presented for engines (**Figure 17**), gearboxes (**Figure 18**) and axles (**Figure 19**).

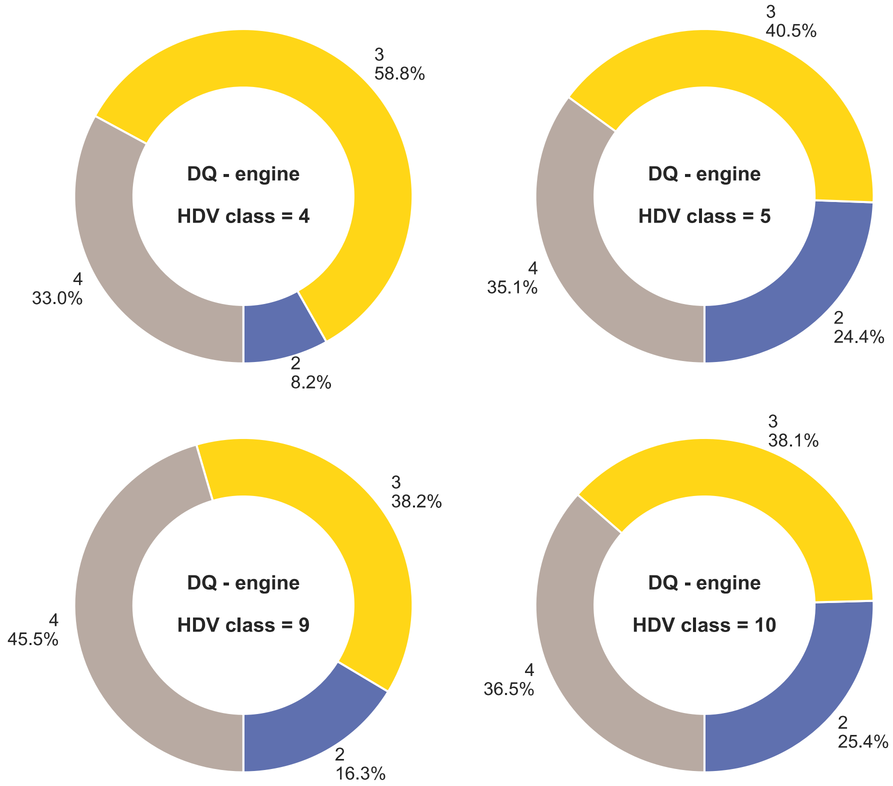

Figure 17. Quality of engine data (per HDV class)

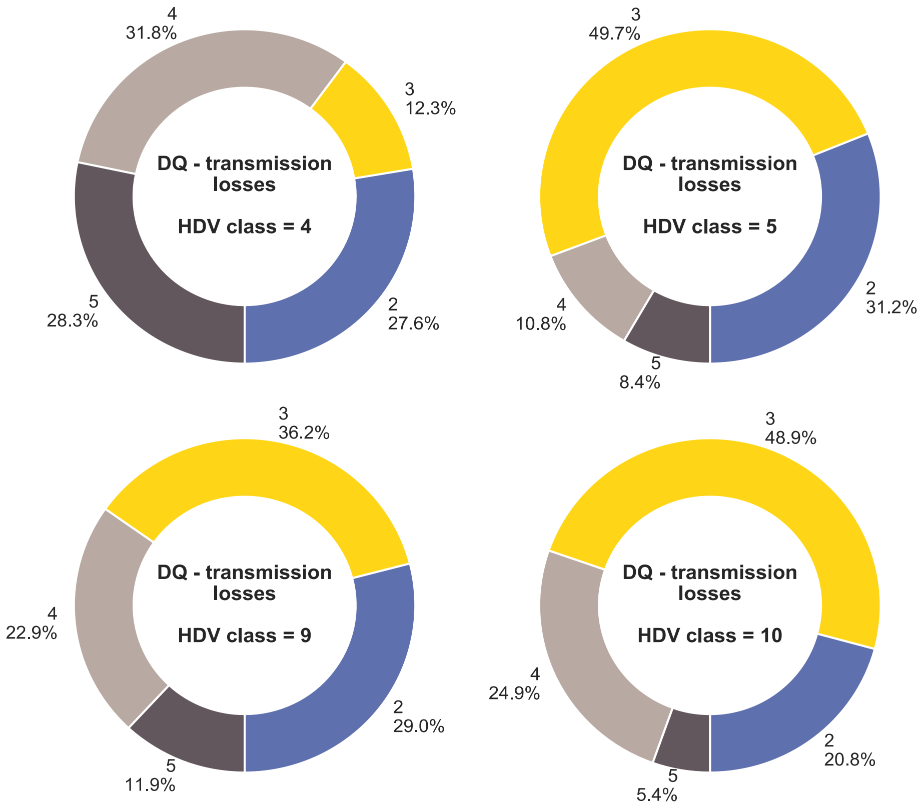

Figure 18. Quality of transmission losses data (per HDV class)

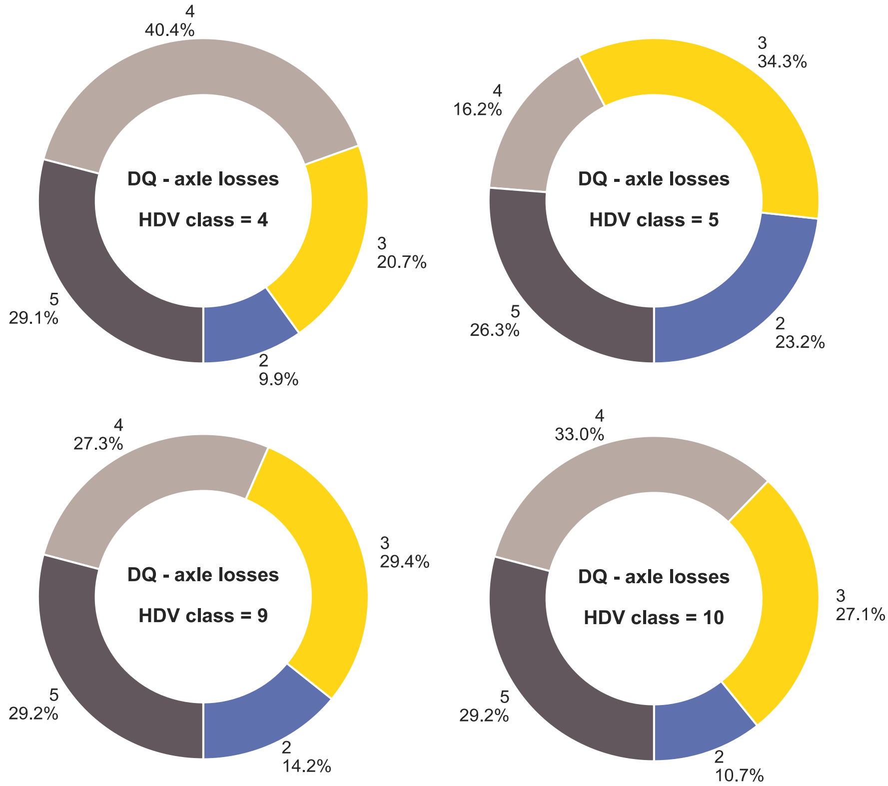

Figure 19. Quality of axle losses data (per HDV class)

Figure 17 shows that default values (data quality 5) were not used to produce engine data and that the share of vehicles that used engine data produced according to the HDV CO_2 annex provisions (data quality 2 and 3) is bigger than 50% in each of the classes. **Figure 18** and **Figure 19** show that for gearboxes and axles data default values were used (especially for axles). It is worth noticing that gearbox data for class 5 vehicles is associated mostly to data quality 2 and 3 (80.9%) whereas for class 4 vehicles the share is much smaller (30.5%). For axles, the input data was produced mainly according to data quality 4 and 5, with the only exception of class 5 vehicles (data quality 2 and 3 share is 57.5%).

3.3.3 Detailed component performance

The current section investigates the performance of various vehicle components by determining their efficiency from the VECTO output data. In order to calculate a vehicle component performance, in the first place it was necessary to identify which data values could be used for such calculations and subsequently produce a formula that would describe the component efficiency. **Figure 20** shows the power flow in the driveline of the generic heavy-duty vehicle equipped with a secondary retarder. Such scheme has been taken as a reference for the calculation of efficiencies. This scheme is not valid for vehicles equipped with primary retarders (not present in the considered HDV fleet) and is incomplete for vehicles equipped with fully automatic transmission (*ATSerial* transmission). In the latter case it is necessary to account also for torque converter losses (*E_tc_loss [kWh]*), that take place in between the engine and the gearbox.

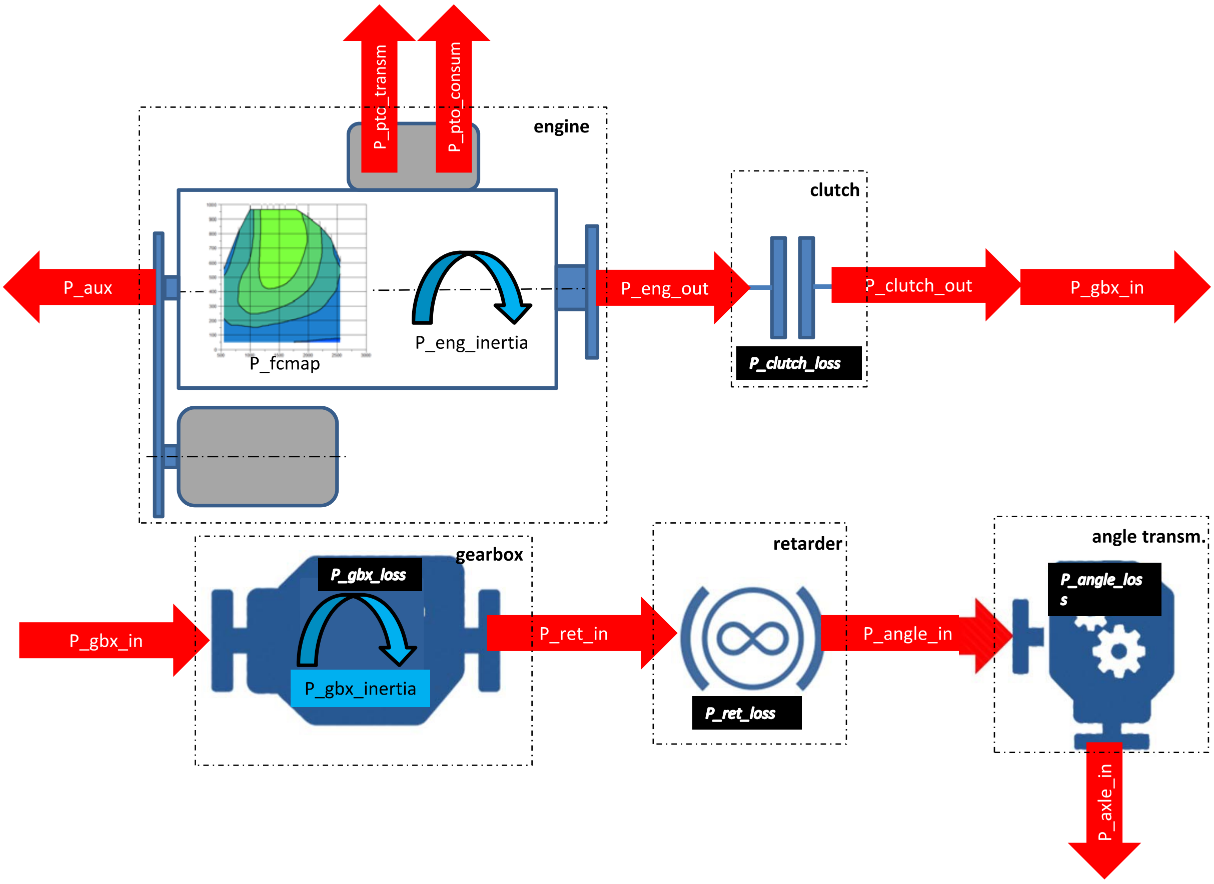

Figure 20. Driveline architecture and power flow of the generic vehicle with secondary retarder (JRC & TUG, 2018)

The following paragraphs focus on the describing the process for calculating the efficiency/performance for the following components:

- Engine
- Gearbox
- Axle
- Tyres

3.3.3.1 Engine efficiency

Average Brake Mean Effective Pressure ($\overline{BMEP}$) and Average Fuel Mean Effective Pressure ($\overline{FuMEP}$) are taken as indicators for describing the engine performances. They are representative of the average operating condition and average fuel usage over a cycle, respectively, and are calculated as follows:

$$\overline{BMEP}\ [bar] = \frac{2 \cdot \overline{Eng.\ Power\ Output}\ [W]}{Eng.Displacement\ [m^3] \cdot \overline{Eng.speed}\ [rps]} \cdot 10^{-5}$$

Eq. 2

$$\overline{FuMEP}\ [bar] = \frac{2 \cdot \overline{Fuel\ power}\ [W]}{Eng.Displacement\ [m^3] \cdot \overline{Eng.speed}\ [rps]} \cdot 10^{-5}$$

Eq. 3

where

$$\overline{Fuel\ Power}\ [W] = \frac{Fuel\ consumed_{cycle}\ [g] \cdot LHV\ [J/g]}{Cycle\ Duration\ [s]}$$

Eq. 4

consequently, average engine efficiency is:

$$\overline{\eta_{eng}}\ [\%] = \frac{\overline{BMEP}}{\overline{FuMEP}} \cdot 100$$

Eq. 5

The correlation between $\overline{BMEP}$ and $\overline{FuMEP}$ was found to be linear and is presented in **Figure 21**, along with $\overline{\eta_{eng}}$. The information necessary to calculate $\overline{BMEP}$ and $\overline{FuMEP}$ are derivable from VECTO outputs contained in VECTO simulation summary files (vsum files):

- $\overline{Eng.\ Power\ Output}\ [W]$: $1000 \cdot P\_fcmap\_pos\ [kW]$
- $Eng. Displacement\ [m^3]$: $Engine\ displacement\ [ccm] \cdot 10^{-6}$
- $\overline{Eng. speed}\ [rps]$: $n\_eng\_avg\ [rpm]\ /\ 60$
- $Fuel\ consumed_{cycle}\ [g]$: $\mathrm{FC - Final\ [g/km] \cdot distance\ [km]}$
- $Cycle\ Duration\ [s]$: $\mathrm{time\ [s]}$

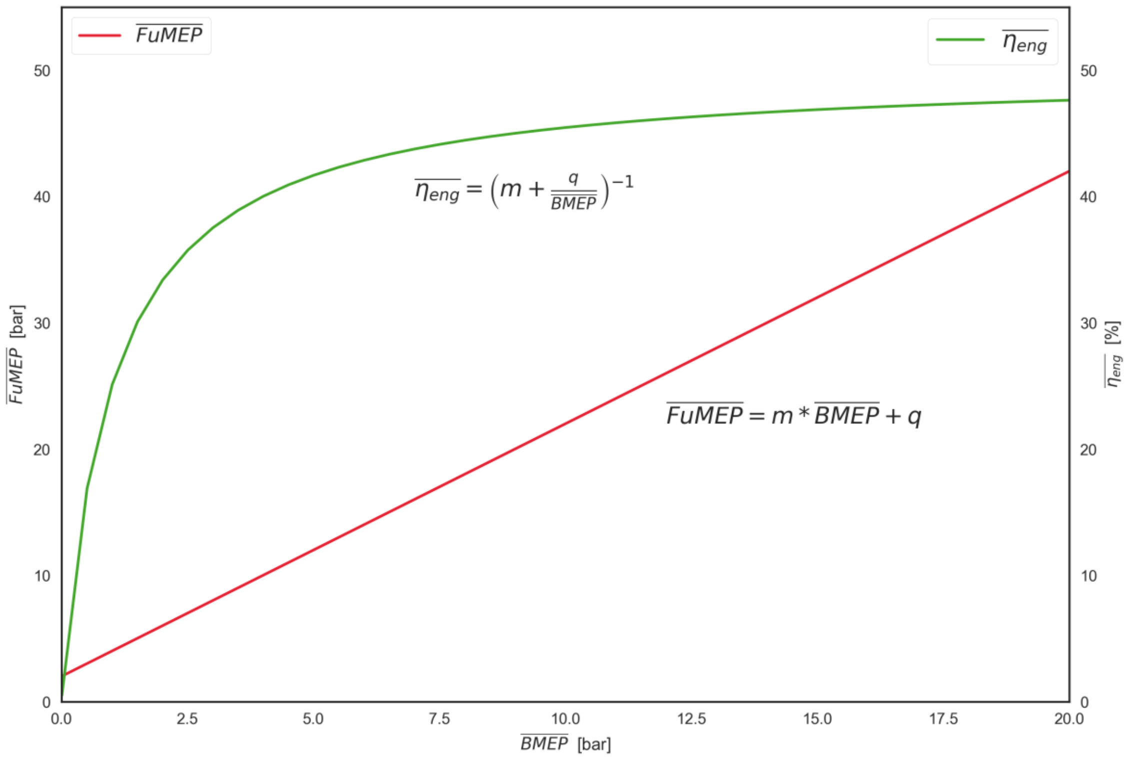

Figure 21. $\overline{FuMEP}$ and $\overline{\eta_{eng}}$ dependency on $\overline{BMEP}$

Finally, the fuel Lower Heating Value (LHV) can be found in the FuelTypes.csv file contained in the Declaration folder of VECTO. All the trucks of the fleet considered are powered by diesel fuel, which has a value of 42700 [kJ/kg] (which is equivalent to the unit measure [J/g]).

3.3.3.2 Gearbox efficiency

The parameter used to define gearbox efficiency is the total energy loss at the gearbox calculated by VECTO throughout the whole mission profile (it is subsequently cycle- and loading- dependent), referred to as E_gbx_loss in VECTO simulations results and expressed in kWh. The following generic definition of efficiency has been used as a starting point:

$$\eta[-] = \frac{Component\ energy\ output}{Component\ \ energy\ input} = 1 - \frac{Component\ energy\ loss}{Component\ energy\ input}$$

Eq. 6

Thus, gearbox efficiency has been defined in the following way:

$$\eta_{gbx}[-] = 1 - \frac{E\_gbx\_loss}{E\_gbx\_in}$$

Eq. 7

where E_gbx_loss is the energy loss at the gearbox in [kWh] as indicated in the simulation output of VECTO and E_gbx_in is the total energy provided at the gearbox input in [kWh] during the cycle calculated as follows:

$$E\_gbx\_in\ [kWh] = E\_fcmap\_pos - (E_{powertrain_{inertia}} + E_{PTO_{CONSUM}} + E_{PTO_{TRANSM}} + E\_aux\_sum + E\_clutch\_loss + E\_gbx\_loss)$$

Eq. 8

The contributions to energy consumption used in the previous formula are available in the output of VECTO simulations and are all expressed in [kWh].

3.3.3.3 Axle efficiency

As for gearboxes, axle efficiency is defined as function of its own losses, which for the specific case are *E_axle_loss [kWh]* from VECTO simulation output:

$$\eta_{axle}[-] = 1 - \frac{E\_axle\_loss}{E\_axle\_in}$$

Eq. 9

where:

$$E\_axle\_in\ [kWh] = E\_gbx\_in - (E\_gbx\_loss + E\_ret\_loss + E\_angle\_loss).$$

Eq. 10

The additional contributions to energy consumption encountered between gearbox and axle are also present in the output of VECTO simulations and are expressed in [kWh].

3.3.4 Efficiencies per component type

This section presents the distributions of components efficiency calculated with the approach described in the previous sections. The per class and per cycle-loading averages of efficiency of components are presented in annex 4 in the form of tables.

3.3.4.1 Engine efficiency distribution

The calculated engine efficiency was found to have the highest value for Data Quality (DQ) 3 with an average value over all classes of 42.5% in the Long Haul cycle and 41.2% in the Regional Delivery. The lowest values were calculated for DQ 4 at 42.5% and 41% respectively for the Long Haul and the Regional Delivery cycles. **Figure 22** presents the distribution of engine efficiency values for all vehicle classes coloured by data quality.

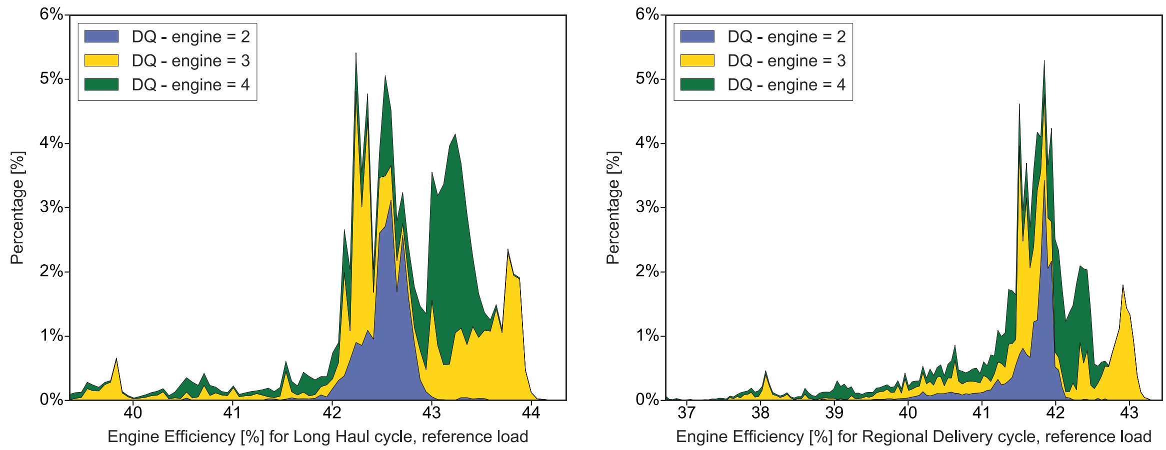

Figure 22. Engine efficiency per data quality – engine, Long Haul and Regional Delivery, Reference load

3.3.4.2 Gearbox efficiency distribution

The highest efficiency for the gearbox was also calculated for DQ 3 with an average value over all classes of 98.2% for the Long Haul and 97.7% for the Regional Delivery. Respectively, the lowest values were found for DQ 5 and were at 95% and 93.8%. **Figure 23** presents the distribution of the gearbox efficiency values for all vehicle classes coloured by data quality.

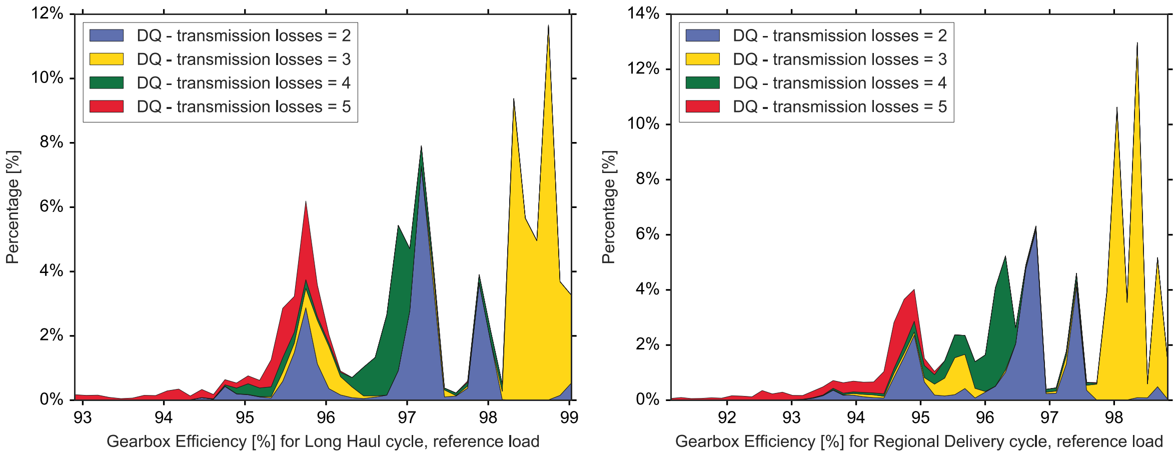

Figure 23. Gearbox efficiency per data quality – transmission losses, Long Haul and Regional Delivery, Reference load

3.3.4.3 Axle efficiency distribution

The axle efficiency was found to have the highest value for DQ 3 for all HDV classes with an average value of 97.3% for the Long Haul and 96.6% for the regional delivery. DQ 5 delivered the lowest efficiency in all cases with values of 85% and 81.5% for the long haul and the regional delivery respectively. **Figure 24** presents the distribution of the axle efficiency values for all vehicle classes coloured by data quality.

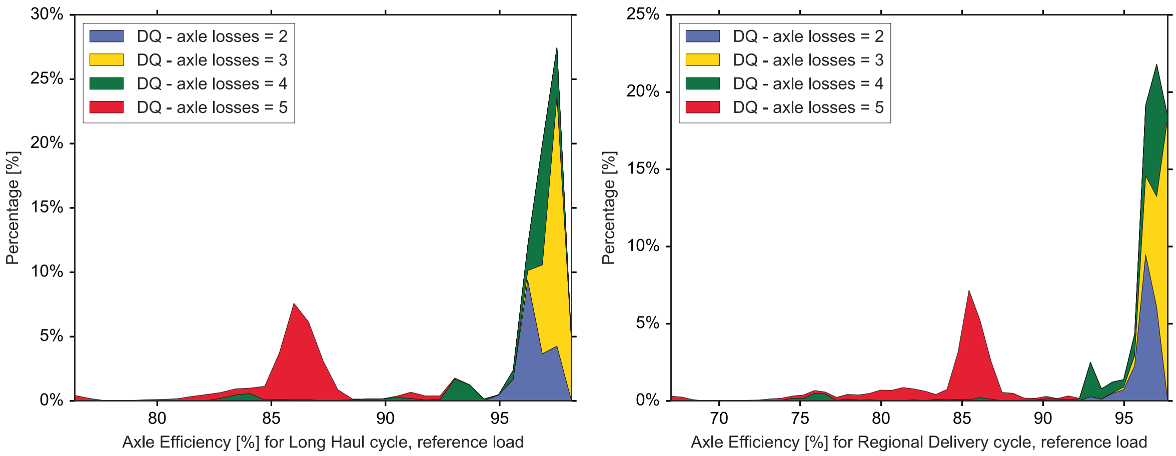

Figure 24. Axle efficiency per data quality – axle losses, Long Haul and Regional Delivery, Reference load

From the figures presented above, it is possible to conclude that DQ4 and DQ5 input data (engineering estimates or default values) return lower efficiencies for axles and gearboxes. The impact of DQ on final FC/CO_2 is further discussed in section 3.5.

3.4 Estimating market penetration of different technologies

As a part of the study, we attempted an estimate of the market penetration of different fuel-saving technologies. The approach followed was to:

1. Identify the distribution of efficiency or energy consumption of different components
2. Assume a certain threshold of efficiency above which a component was considered to be "energy efficient" (alternatively an energy consumption threshold below which the component was characterised as efficient)
3. Calculate the percentage of the fleet featuring the particular component.

Fuel-saving technologies are present and desirable in many of the areas analysed in this chapter, either at component-level or at vehicle-level. Fuel savings are achieved through the adoption of innovative technologies and/or innovative vehicle design. This section presents which areas are considered to have fuel saving potential and for which is desirable to increase the market penetration.

Table 9 presents which technologies present the best efficiency in their respective class at a component-level. For these technologies, the energy-saving potential is already captured by VECTO.

Table 9. Technologies with fuel-saving potential and respective estimated share in the 2016 HDV fleet from JRC internal data (JRC, 2018)

Classification	**Technology / Criteria**	**Estimated fleet share**
Best power steering	Electric hydraulic power steering	< 10 %
Best lighting	LED lights	30 - 50 %
Best air compressor	-Medium Supply 1-stage + mech. clutch + AMS -Large Supply + mech. clutch	10 - 30 %
Best cooling FAN	Crankshaft mounted - Electronically controlled visco clutch	30 - 50 %
Engine improvement	Engine downspeeding	10 - 30 %
Reduced rolling resistance	Class A tyres	< 10 %
Efficient gearboxes	Efficiency above threshold -> $\eta_{GBX} > 96.25\%$ (reduction of 50% in gearbox losses)	< 10 %
Efficient axles	Efficiency above threshold -> $\eta_{AXL} > 98.13\%$ (reduction of 50% in axle losses)	< 10 %

Fuel savings at vehicle-level are to be achieved with innovative design concepts: improved aerodynamics, powertrain hybridisation, optimisation of performances with synergies exploitation among components (Zacharof & Fontaras, 2016; Zacharof et al., 2017; Muncrief & Rodríguez, 2017). The certification scheme can accurately capture the reduction in vehicle energy consumption coming from the adoption of innovative aerodynamics solutions (rounder designs, spoilers, flaps, covers, etc.) since they will consist in a reduction of CdA to be provided as input to VECTO.O. On the other hand, the use of standard bodies, trailers and semi-trailers with pre-defined aerodynamics performance generally leads to less evident improvements in vehicle air drag. For the other innovative design concepts, the information available was not sufficient to perform an analysis on their penetration in the current HDV fleet.

3.5 CO_2 emissions and fuel consumption

In section 3.3.4 the relation between quality of component data and component efficiency was presented. The general outcome of the analysis is that data quality of type 4 and 5 (data not measured according to the HDV CO_2 annex) are associated with lower component efficiencies. This was evident for gearboxes and axles mainly, while engines showed a weaker relation in this regard. This section presents the impact of data quality on final fuel efficiency of trucks, for axles, gearboxes, engines, CdA and rolling resistance.

Figure 25 presents the distribution of CO_2 emissions in g/km coloured by axle loss data quality for the four cycles described in section 2.4. The total coloured area of each chart represents 100% of the observations for the specific cycle considered. The colouring allows understanding how axle loss data quality relates to final CO_2 emissions. As the red coloured area is concentrated at the right end of the distributions, it is possible to conclude that axle losses have a big impact on total energy consumption for vehicles where data quality is low. **Figure 26** presents how the quality of gearbox data affects final CO_2 emissions of vehicles. In this case, the impact of data quality is lower.

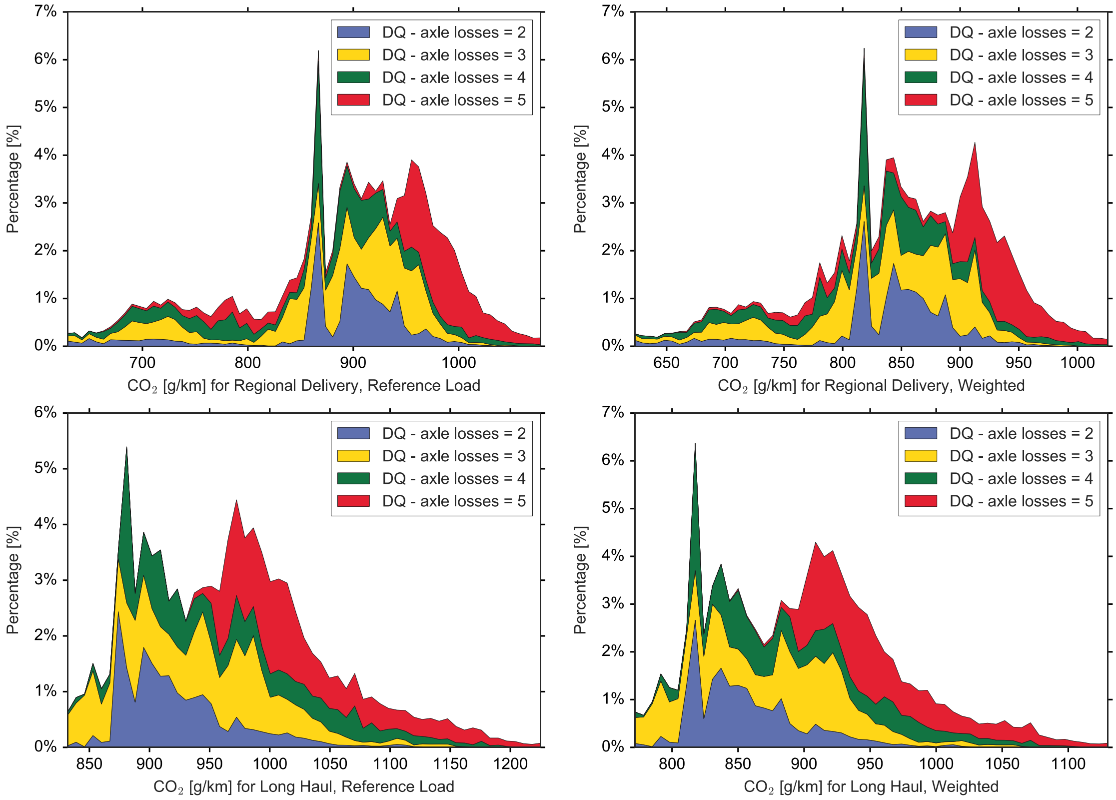

Figure 25. CO_2 emissions in [g/km] per cycle, coloured by data quality – axle losses

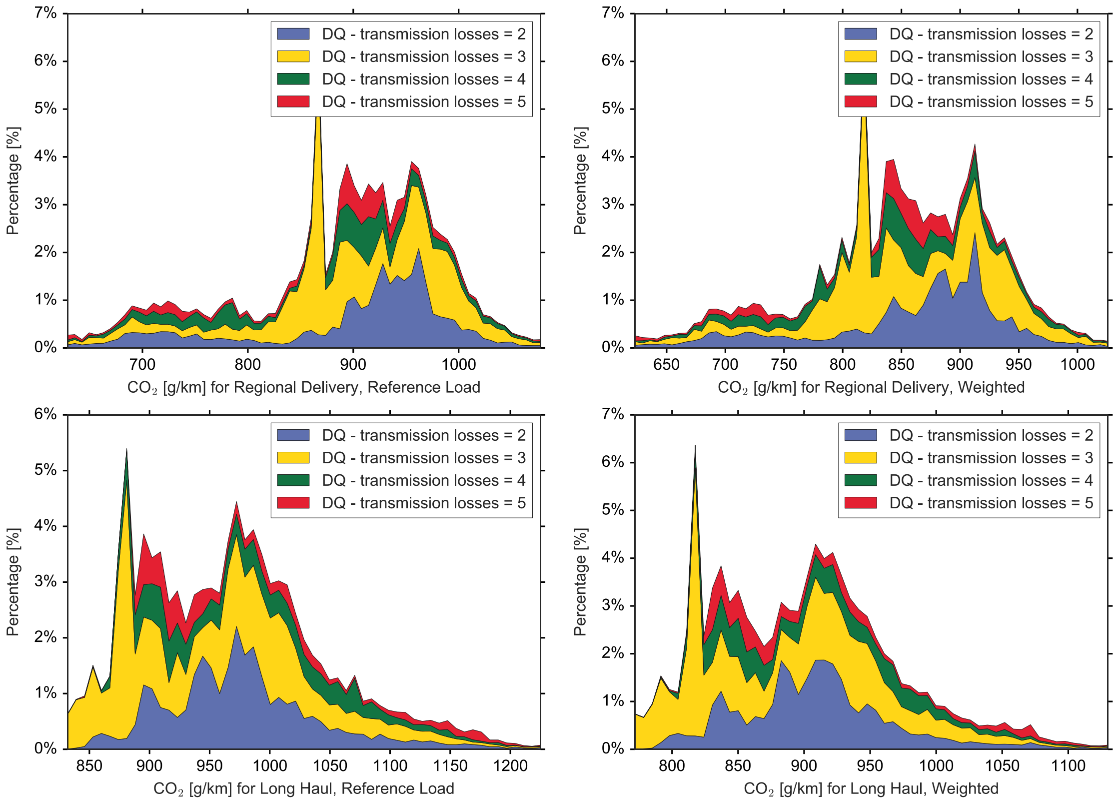

Figure 26. CO_2 emissions in [g/km] per cycle, coloured by data quality – transmission losses

The first explanation is the overall smaller impact of gearbox losses on total vehicle energy consumption (especially for Long Haul cycle). The second one is the smaller variance of gearbox efficiency with regard to data quality, i.e., standard values are relatively close to those measured and certified (as it can be seen in **Figure 23**, the minimum gearbox efficiency is few per cent points below the maximum one, differently from axle efficiency).

Following a similar approach as for transmissions and axles, **Figure 27** depicts the distribution of the engine data quality. As for **Figure 22** (engine efficiency coloured by engine data quality), no clear dependency on engine data quality is visible.

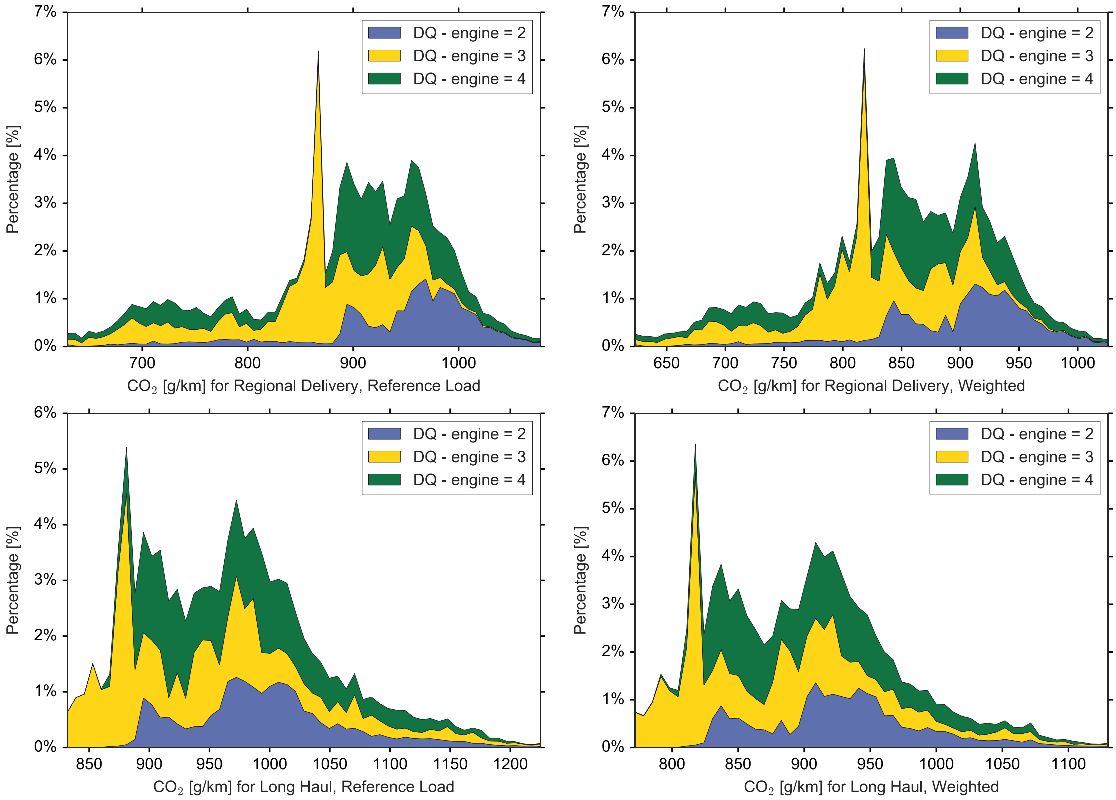

Figure 27. CO_2 emissions in [g/km] per cycle, coloured by data quality – engine

Figure 28 and **Figure 29** are accordingly coloured by data quality for air drag and rolling resistance, respectively. Air drag shows a minor dependency on data quality, which is more evident for Long Haul cycles rather than Regional Delivery cycles due to the different average speed and impact of air drag losses on final FC. In conclusion, there is no evident relation that can be perceived between data quality of tyre rolling resistance and CO_2 emissions.

The figures reported in this section give insight on how data quality obtained with other methods than the provisions of the HDV CO_2 annex can result in lower vehicle efficiency outputs with subsequent increased final FC and CO_2 emissions. In order to estimate the fuel efficiency of the fleet correctly it becomes necessary to adjust vehicles that are associated with data quality 4 and 5, most importantly with regards to axle losses, and secondly also for gearbox and air drag losses.

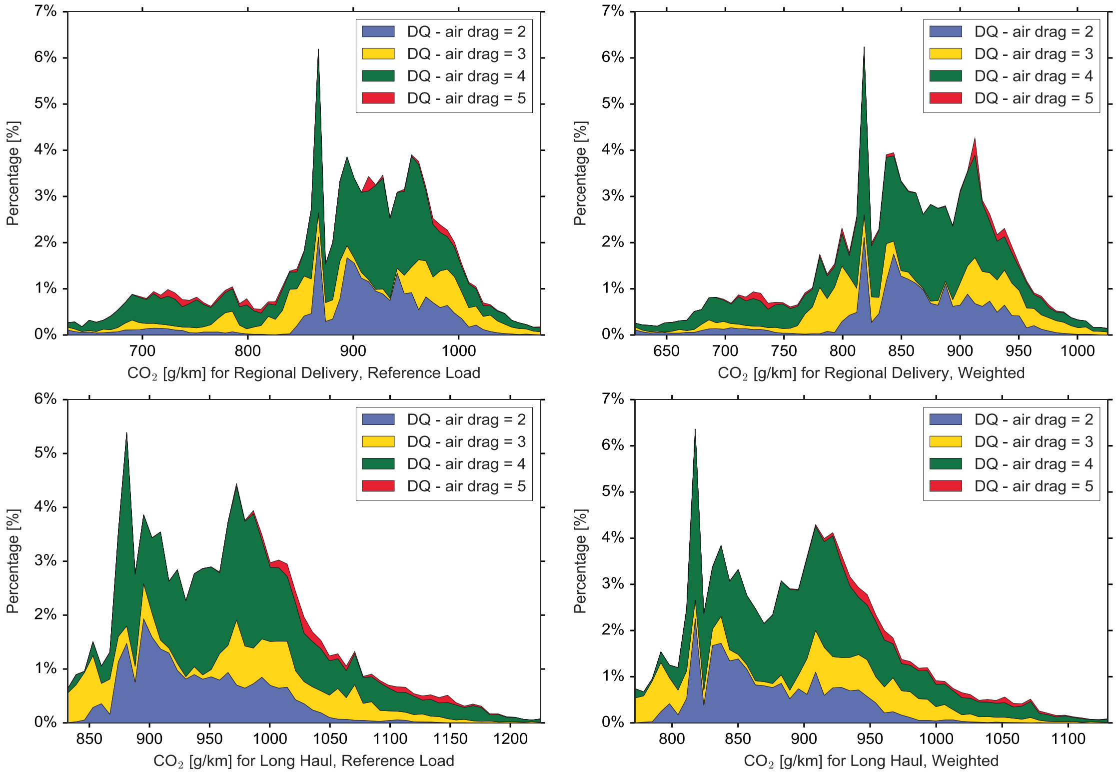

Figure 28. CO_2 emissions in [g/km] per cycle, coloured by data quality – air drag

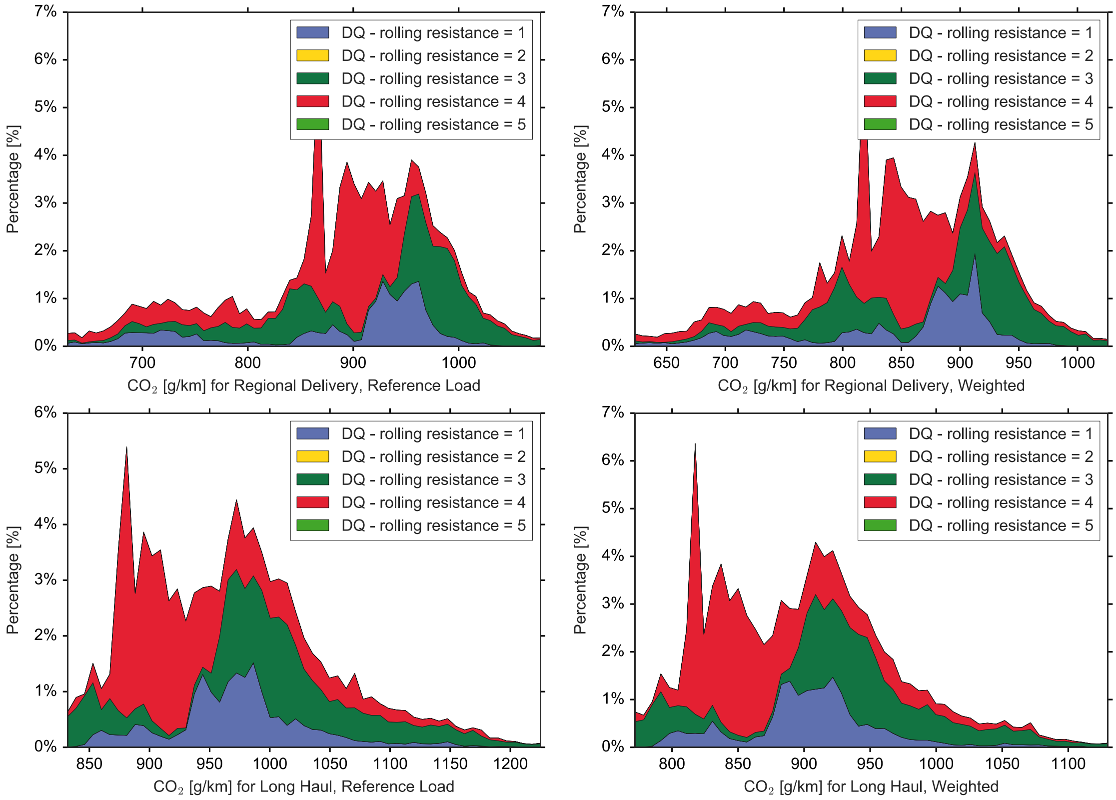

Figure 29. CO_2 emissions in [g/km] per cycle, coloured by data quality – rolling resistance

4 Normalised fleet fuel consumption

Based on the components efficiency calculation and the data quality analysis presented in the previous chapter, JRC has derived a normalised version of the fleet data in terms of energy consumption and fuel efficiency. The normalisation process was applied to take into account the impact on fuel efficiency of input data that was not produced according to the HDV CO_2 annex provisions. The approach followed for the normalisation and the comparison with the baseline are presented in this chapter.

4.1 Normalisation method and assumptions

Thanks to the analysis performed on air drag data quality and efficiency of components, it was possible to derive an approach for the normalisation of vehicle fuel efficiency values that were considered to be unrealistic.

The sources of energy losses that have been evaluated and normalised (where appropriate) are:

- Air Drag losses
- Axle losses
- Gearbox losses

For every vehicle of the fleet where the normalisation is applied, a change in the operating condition of the engine is also taken into consideration and its average efficiency is changed accordingly.

For such vehicles, positive energy produced at the engine (*E_fcmap_pos*) has been recalculated, taking as a starting point the energy at wheels (unchanged or the resulting value using normalised air drag losses)) and backward calculating the losses in the driveline according to components efficiencies (gearbox and axle, unchanged or normalised efficiencies) and the other unchanged losses (clutch, retarder, angle drive, torque converter, auxiliaries, PTO technologies). The assumptions taken for the normalisation of air drag losses, axle efficiencies and gearbox efficiencies are explained in the following sections.

In **Figure 30** the sources of energy losses and the total component energy input and output are depicted in the form of blocks. The red block is the starting point of the chain of normalisation steps. In case the vehicle considered for the normalisation showed unrealistic CdA and air drag losses, a new CdA was assigned to the vehicle, and consequently the new energy consumed for air drag losses was calculated. The dashed blue blocks are sources of energy consumption that -- at the end of the normalisation process -- might differ from the initial value contained in the input data from the OEM. The difference could be due to a change in air drag losses, change in axle efficiency, change in gearbox efficiency, or a combination of the previous situations. The dashed green blocks are component efficiency values (gearbox and axle) that could also differ from what derived from the input data. Components associated with data quality 4 and 5 that shows efficiency below a certain threshold are assigned with a new more realistic efficiency. The orange blocks are sources of energy losses that do not change due to the normalisation process. They are OEM declared data that are taken into account to recalculate the total vehicle energy consumption in a specific cycle.

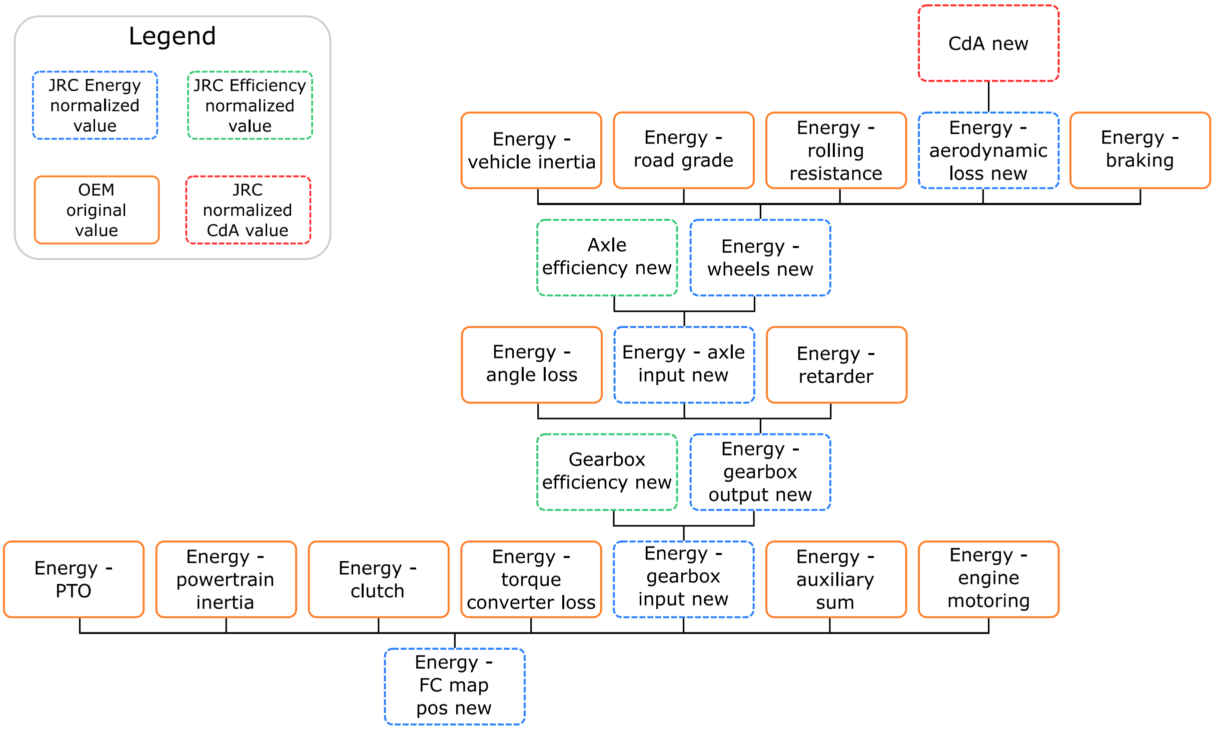

Figure 30. Energy consumption and CO_2 emissions normalisation process

Figure 30 is detailed in the following list:

- $CdA\_new \rightarrow E\_air\_new$
- $Ewheels\_new = E\_air\_new + E\_roll + E\_brake + E\_grad + E\_vehi\_inertia$
- $E\_axl\_input\_new = \frac{E\_wheels\_new}{axl\_eff\_new}$
- $E\_gbx\_output\_new = E\_axl\_input\_new + E\_ret + E\_angle\_loss$
- $E\_gbx\_input\_new = \frac{E\_gbx\_output\_new}{gbx\_eff\_new}$
- $E\_fcmap\_pos\_new = E\_gbx\_input\_new + E\_aux\_sum + E\_tc\_loss + E\_clutch + E\_powertrain\_inertia + E\_fcmap\_neg + E\_PTO$

The normalisation applied according to the methodology presented in this section consisted in a general reduction of energy losses over the cycle, and a consequent reduction of the positive energy produced at the engine throughout the cycle. This generally turns into a lower average load for the engine, justifying the need of adjusting the engine efficiency according to the new operating condition ($\overline{BMEP}_{norm}$). For this reason, FCFC and CO_2 emissions are calculated as last step using the specific $\overline{BMEP}$-$\overline{FuMEP}$ function of the engine considered.

4.1.1 Air drag losses normalisation

This section explains the applied normalisation with regards to energy spent for air drag to exclude the values that seemed unrealistic. Energy consumed for air drag in vehicles of class 5 equipped with LH Cabin type, belonging to A17, A18 and A19 CdA bins has been limited to a fixed value depending on the cycle. This correction is justified by the fact that 94.5% of the observations from these bins are associated with data quality 4 and 5, as can be seen in **Figure 31**, which implies that the true CdA value can deviate significantly from the one declared by OEMs. The very few vehicles associated with data quality 2 and 3 in these CdA bins are considered to be outliers, possibly vocational vehicles with true CdA higher than 7.6 m^2 (lower CdA value of bin A17) meant for a very specific use. Considering the highway driving as the expected predominant use of class 5 vehicles equipped with LH Cabin, it is reasonable oto assume that vehicles of this category are designed in order to limit air drag losses (low CdA), which largely affect FCFC.

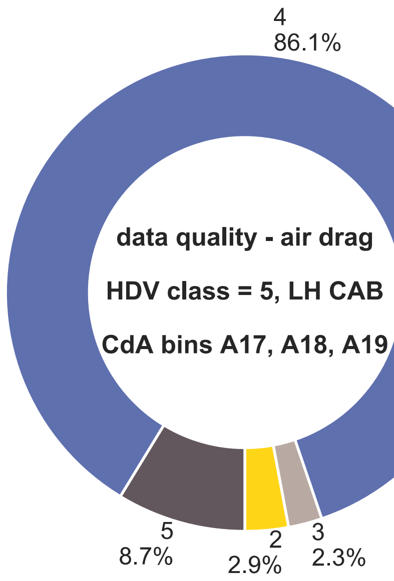

Figure 31. Air drag losses data quality shares in bins A17, A18 and A19

Based on these assumptions, every vehicle fulfilling the conditions mentioned above (class 5, LH CAB, CdA bin from A17 to A19) has been normalised by limiting the energy consumed for air drag losses (E_air [kWh]). Both the value to be used for Long Haul and Regional Delivery mission profiles were calculated as the 1st percentile (to exclude outliers) of E_air distributions of such vehicles, as shown in **Figure 32**.

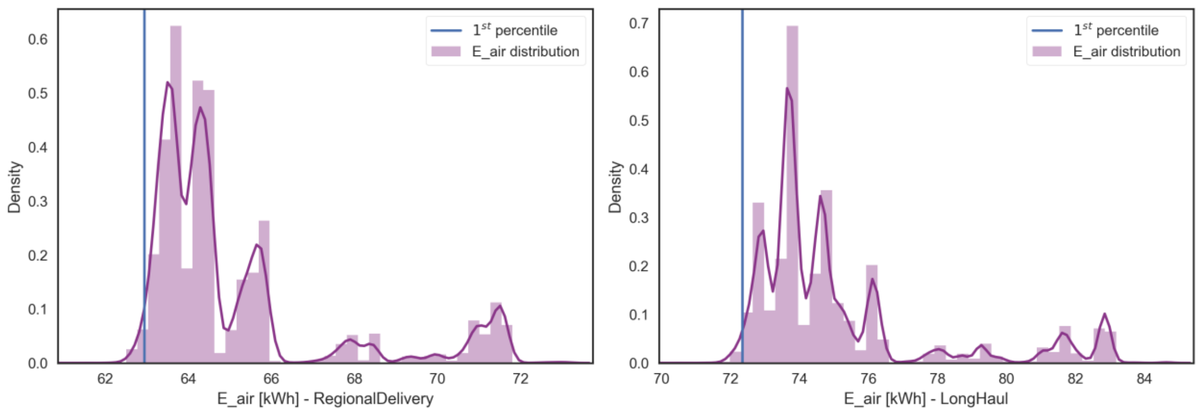

Figure 32. E_air distribution of class 5 vehicles with LH CAB, in CdA bins from A17 to A19, Long Haul cycle and Regional delivery cycle

4.1.2 Axle losses normalisation

Normalised axle losses were derived based on normalised axle efficiency. Axle efficiency was calculated from OEM data for all the vehicles of the fleet and each cycle - loading combination, using Eq. 9. From this set of values, axle efficiencies obtained with axle losses of data quality 2 and 3 were left unchanged, whereas the ones with data quality 4 and 5 were replaced. When a vehicle with data quality 4 or 5 axle losses was considered, the value used for the replacement was taken as the maximum between the median of efficiency (values reported in **Table 10**) from the original data quality and the 25th percentile (values reported in **Table 11**) from data quality 2 and 3 grouped together. As an example, if the condition considered for the normalisation was a class 4 vehicle in the

Regional Delivery low loading mission profile, with quality 4 axle losses data, the values that are to be compared are 92.78% (**Table 10**, second row, first column) and 94.12% (**Table 11**, first row, first column). The maximum of the two values, in this case the one obtained from quality 2-3, is taken to replace the original axle efficiency of the vehicle with data quality 4 axle losses and new losses are calculated.

Table 10. Medians of axle efficiencies [%] per cycle, load, HDV class and data quality

Cycle	**Regional Delivery**								**Long Haul**							
Loading	**Low load**				**Ref. load**				**Low load**				**Ref. load**			
Class	**4**	**5**	**9**	**10**	**4**	**5**	**9**	**10**	**4**	**5**	**9**	**10**	**4**	**5**	**9**	**10**
Qual. 2 - 3	95.9	96.8	96.3	96.9	96.3	97.2	96.7	96.9	96.8	96.8	97.2	96.4	97.0	97.3	97.6	97.0
Qual. 4	92.8	96.2	95.4	96.4	89.2	96.9	95.9	97.0	94.6	96.1	96.5	96.3	95.3	96.9	97.1	97.0
Qual. 5	72.7	82.5	78.3	82.4	74.8	85.6	81.0	85.4	79.4	82.6	83.7	82.4	82.1	86.2	86.7	85.9

Table 11. 25^{th} percentile of axle efficiencies [%] per cycle, load, HDV class and data quality

Cycle	**Regional Delivery**								**Long Haul**							
Loading	**Low load**				**Ref. load**				**Low load**				**Ref. load**			
Class	**4**	**5**	**9**	**10**	**4**	**5**	**9**	**10**	**4**	**5**	**9**	**10**	**4**	**5**	**9**	**10**
Qual. 2 - 3	94.1	95.7	95.3	96.0	95.2	96.4	95.9	96.7	95.4	95.6	96.3	95.9	96.1	96.5	97.0	96.8
Qual. 4	74.3	95.3	93.9	95.9	76.4	96.2	94.6	96.5	81.6	95.1	95.2	95.8	84.0	96.2	96.0	96.5
Qual. 5	64.8	82.0	76.8	81.5	67.4	85.1	79.6	84.7	73.3	82.1	82.5	81.4	76.5	85.7	85.6	85.2

4.1.3 Gearbox losses normalisation

The process followed to normalise gearbox losses is analogous to the one for normalizing axles losses. Also in this case, normalised gearbox losses for vehicles with quality 4 and 5 gearbox losses were derived based on gearbox efficiencies calculated with Eq. 9. Medians and 25^{th} percentiles of gearbox efficiency are presented in **Table 12** and **Table 13**, respectively. The maximum between the median of gearbox efficiency from the original data quality (4 or 5) and the 25^{th}percentile of gearbox efficiency from data quality 2 and 3 grouped is used.

Table 12. Medians of gearbox efficiencies [%] per cycle, load, HDV class and data quality

Cycle	Regional Delivery								Long Haul							
Loading	Low load				Ref. load				Low load				Ref. load			
Class	4	5	9	10	4	5	9	10	4	5	9	10	4	5	9	10
Qual. 2 - 3	96.6	97.9	97.3	98.0	96.6	98.0	97.3	98.0	97.2	98.2	98.0	98.3	97.1	98.3	97.9	98.4
Qual. 4	95.7	96.0	95.8	96.1	95.9	96.2	96.0	96.3	96.8	96.5	96.7	96.6	97.0	96.8	96.9	96.9
Qual. 5	93.3	94.2	92.7	94.5	93.6	94.7	93.3	94.9	94.3	95.0	95.0	95.3	94.8	95.6	95.3	95.8

Table 13. 25th percentile of gearbox efficiencies [%] per cycle, load, HDV class and data quality

Cycle	Regional Delivery								Long Haul							
Loading	Low load				Ref. load				Low load				Ref. load			
Class	4	5	9	10	4	5	9	10	4	5	9	10	4	5	9	10
Qual. 2 - 3	94.4	96.6	96.3	97.4	94.6	96.7	96.4	97.3	95.7	97.0	97.1	97.3	96.1	97.2	97.1	97.6
Qual. 4	95.3	95.9	95.4	95.6	95.6	96.1	95.7	96.2	96.5	96.2	96.4	96.3	96.6	96.6	96.4	96.6
Qual. 5	92.2	94.1	91.4	94.4	92.6	94.5	92.1	94.8	93.5	94.8	93.3	95.2	94.1	95.5	94.1	95.7

4.1.4 Calculation of normalised fuel consumption and CO_2 emissions

This section presents how, as a consequence of the normalisation process, the different power request to the engine is taken into consideration with the goal of evaluating the engine efficiency of the new operating condition. The normalisation process generally results in a different total cycle energy consumption, from which the average BMEP representative of the engine operating condition can be calculated. This new BMEP value is used to calculate the new FuMEP for the specific vehicle and mission profile, using the specific BMEP-FuMEP line for the engine considered (see **Figure 33**). The updated FuMEP is then used to get the metrics for FCFC and CO_2 emissions. The steps necessary to obtain the fuel consumed in the new operating condition are:

$$P\_fcmap\_pos_{norm}[W] = E\_fcmap\_pos_{norm}[kWh] \cdot 1000 \cdot 3600 \,/\, time\,[s]$$

Eq. 11

$$\overline{BMEP}_{norm}\,[bar] = \frac{2 \cdot P\_fcmap\_pos_{norm}\,[W]}{Eng.Displacement[m^3] \cdot \overline{Eng.speed}[rps]} \cdot 10^{-5}$$

Eq. 12

$$\overline{FuMEP}_{norm}\,[bar] = m \cdot \overline{BMEP}_{norm}[bar] + q$$

Eq. 13

$$\overline{Fuel\ Power}\,[W] = \frac{\overline{FuMEP}_{norm}\,[bar] \cdot 10^5 \cdot Eng.Displacement\,[m^3] \cdot \overline{Eng.speed}\,[rps]}{2}$$

Eq. 14

$$Fuel\ consumed_{cycle}\ [g] = \frac{(\overline{Fuel\ Power}\ [W] \cdot\ Cycle\ Duration\ [s])}{LHV[J/g]}$$

Eq. 15

From $Fuel\ consumed_{cycle}\ [g]$ it is then possible to derive all the FCFC and CO_2 emissions metrics of interest, by using fuel density [g_{fuel}/$litre_{fuel}$] and CO_2 per FuelWeight [g_{CO2}/g_{fuel}], both available in the FuelTypes.csv file in the declaration folder of VECTO.

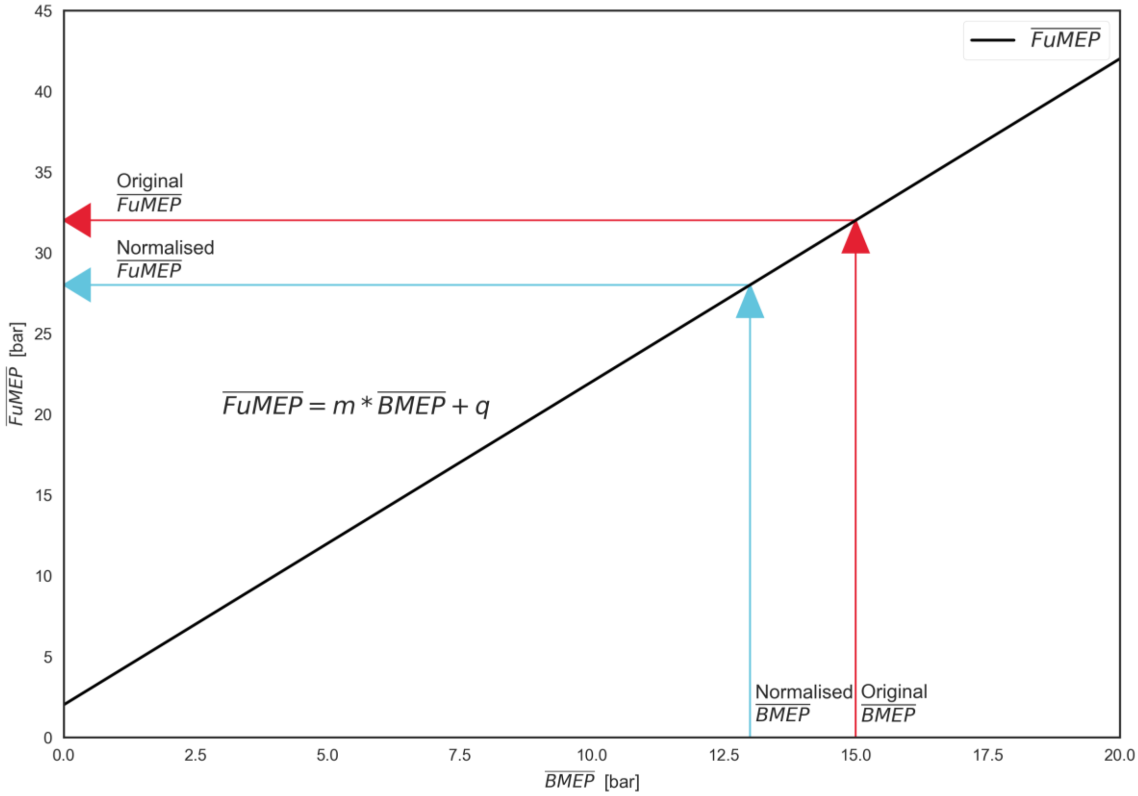

Figure 33. Adjustment of engine operating condition according to $\overline{BMEP}$ normalised

4.2 Results

This section presents the result of the normalised version of fleet FCFC together with the one provided by the OEMs. CO_2 emissions in g/km are here presented for reference load Regional Delivery and Long Haul cycles. The other metrics can be found in Annex 5.

Figure 34 presents a comparison of the JRC normalised CO_2 emissions and the declared OEM emissions for the regional delivery cycle with a reference payload. Accordingly, **Figure 35** presents in a similar way the comparison for the Long Haul cycle. Lastly, **Figure 36** and **Figure 37** present the comparison of CO_2 emissions from the weighted cycles. From the figures, it is evident that the normalisation that has been applied caused a general reduction in the average CO_2 emissions and in the standard deviation of the distribution. However, the most evident difference is between the maximum values of OEM and JRC distribution. The reduction in the emissions could be expected as the applied normalisation on the investigated components resulted in an increase of the component efficiency. Such differences highlight once again the need to follow the defined guidelines from the HDV CO_2 Annex for properly assessing the component and overall vehicle efficiency.

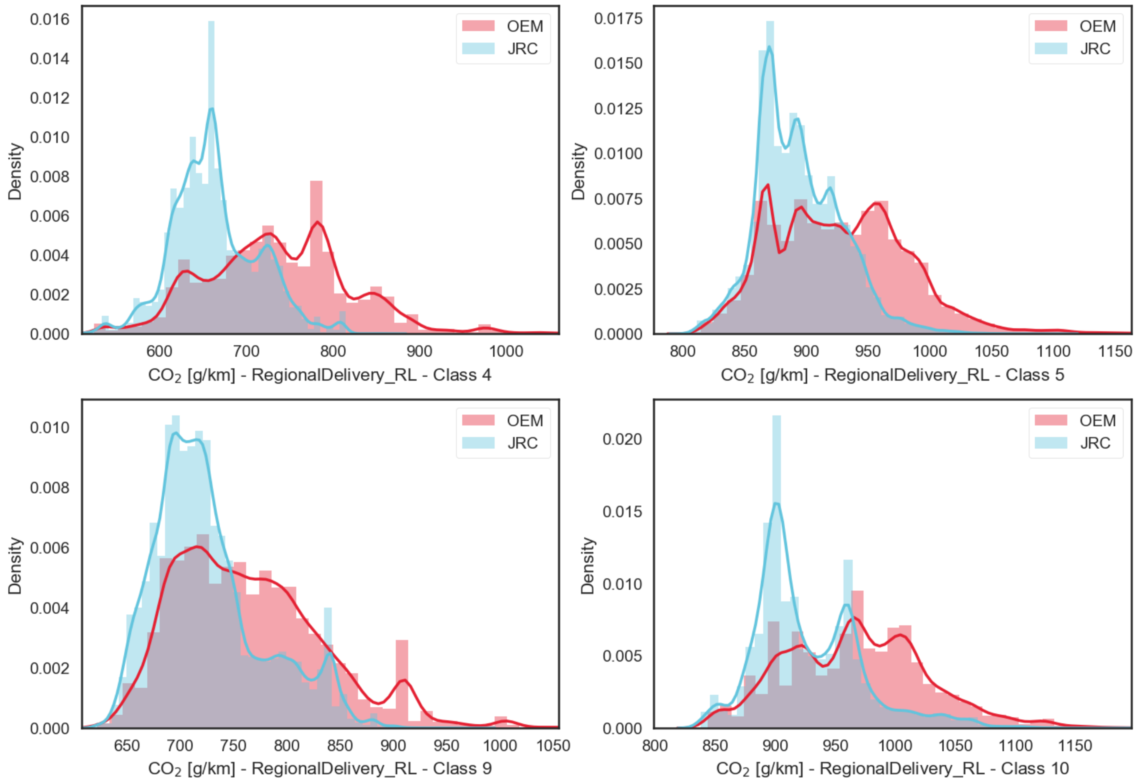

Figure 34. CO_2 emissions [g/km] comparison between OEM declared values and JRC normalisation. Regional delivery, reference load

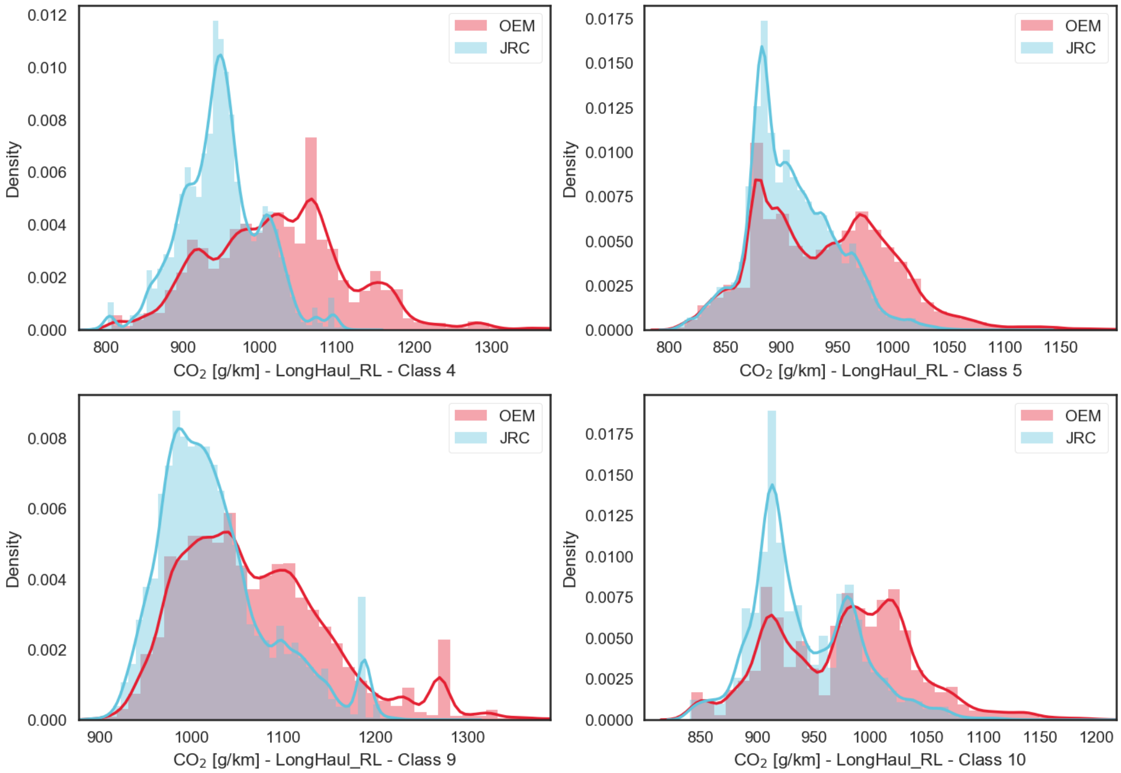

Figure 35. CO_2 emissions [g/km] comparison between OEM declared values and JRC normalisation. Long Haul, reference load

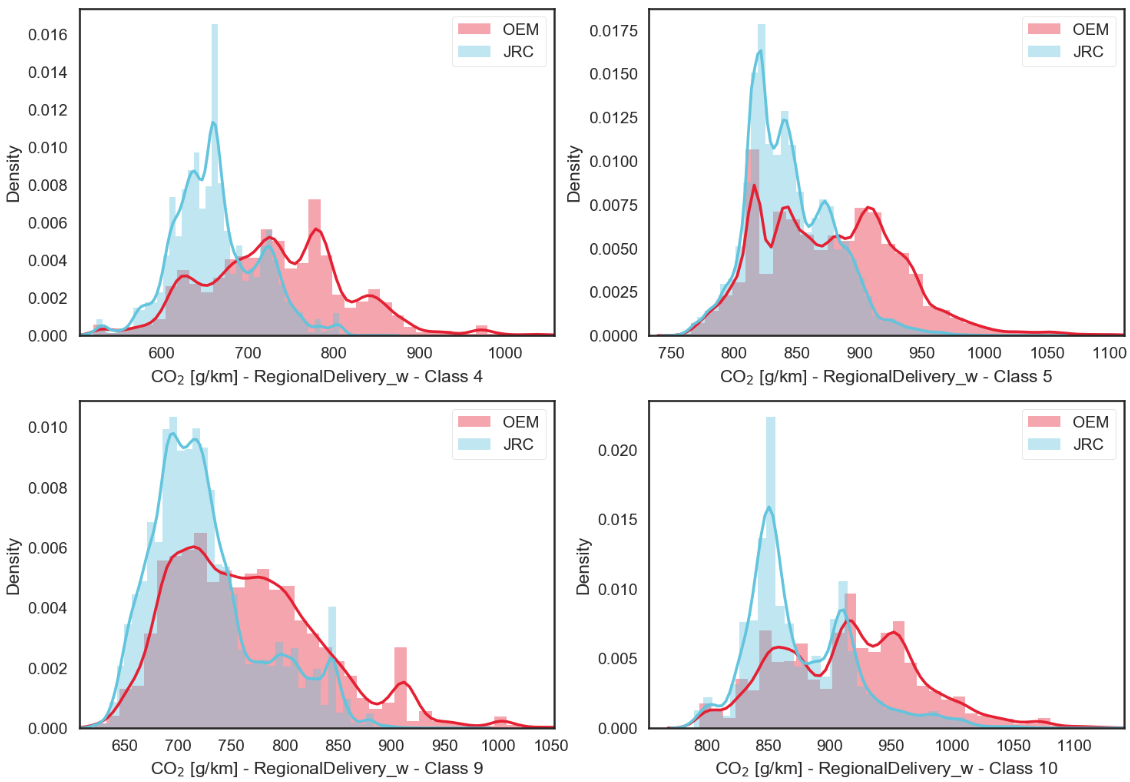

Figure 36. CO_2 emissions [g/km] comparison between OEM declared values and JRC normalisation. Regional Delivery, weighted

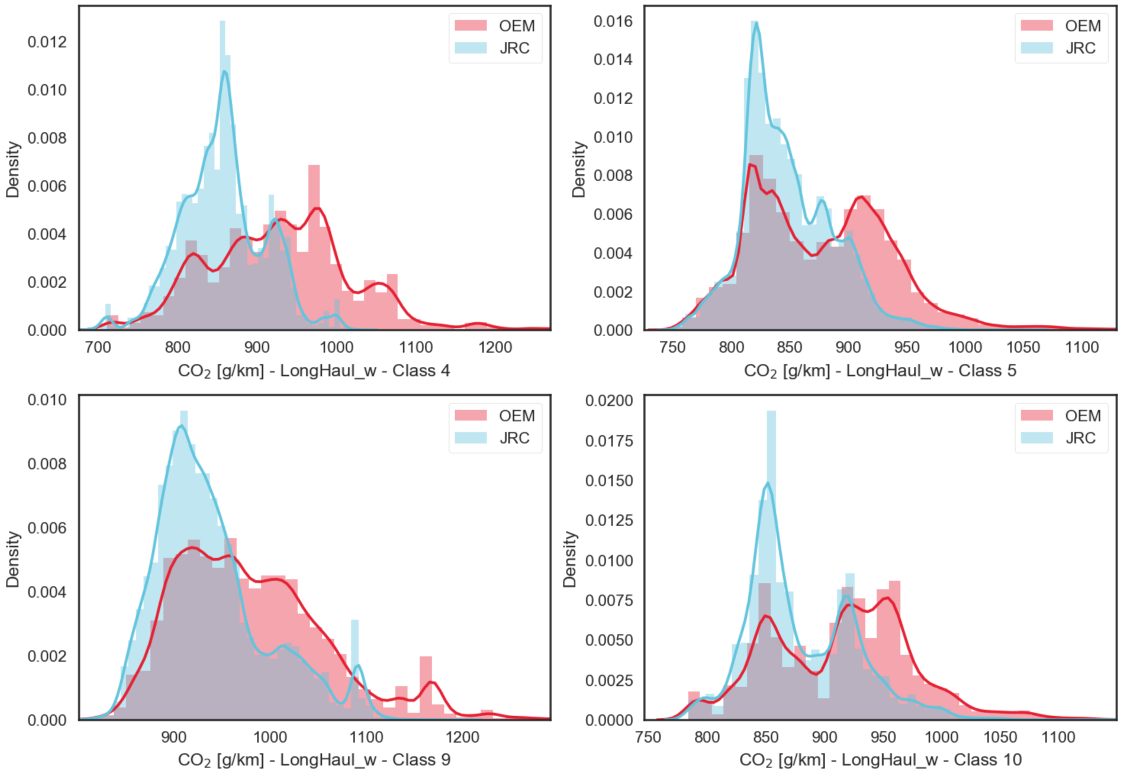

Figure 37. CO_2 emissions [g/km] comparison between OEM declared values and JRC normalisation. Long Haul, weighted

5 Conclusions

The present report summarised the work done by the JRC after a request from DG CLIMA on the analysis of the 2016 Heavy-Duty Vehicle fleet and CO_2 and in this context this study:

- collected and structured in a uniformed way the input data from the OEMs
- identified problems/inconsistencies/ missing data in the datasets
- collected the respective feedback from the OEMs to fix the issues
- produce a first picture of the fuel efficiency of regulated HDV Classes as declared by the OEMs
- identified the aspects that needed for corrections as the approach followed has not always been uniform
- produced a version of the fleet fuel efficiency that is more realistic
- found the component efficiency should be assessed based on the technical annex otherwise there is a divergence

The analysis showed that although the data provided allow a detailed estimation of the average CO_2 emissions for the 2017 vehicles fleet, the results are not always equivalent to those that would be obtained under the established certification procedure. This is mainly a result of the input information that was used for running the simulations which was not always in line with the provisions of the certification regulation. Such situations need to be considered particularly if specific reference CO_2 emissions values are to be established in the future for introducing CO_2 standards in the HDV sector. The normalisation procedure applied by the JRC led to significant changes in the distribution of CO_2 values and could be considered as a likely correction approach in the future, should there be inconsistencies or gaps in the datasets to be reported for such purposes.

In terms of CO_2, the results obtained varied for the different vehicle categories. For classes 4 and 9, the normalised median values were calculated at 389 g/tkm and 192 g/tkm, over the weighted regional delivery mission profile, and at 261 and 136 g/tkm over the weighted Long Haul mission profile. The same figures for classes 5 and 10 were, 125 g/tkm, 129 g/tkm (weighted Regional Delivery), 113 g/tkm, 116 g/tkm (weighted Long Haul) respectively. The variability of these results varied a lot with HDV class and mission profile ranging from 30 g/tkm to 5 g/tkm. An interesting observation was that the CO_2 distributions were in several cases multimodal, suggesting the existence of possible sub-categories or clusters within the existing classes. Their identification could be the scope of future research.

In terms of individual components, the analysis confirmed that the main components of the powertrains exhibit very high efficiencies (mean cycle efficiencies) across the different mission profiles with the median values for engines being at 41.5%, for gearboxes at approximately 97% and for axles at approximately 96%. In particular for the latter two additional improvements in the years to come would be very challenging as there appears to be a physical saturation point at about 98-99%. Engine technology could improve as the max mean efficiency that was observed was about 44.5%, i.e. roughly 7% higher than the median value. Technology diffusion could lead to a fleet-wide improvement in the years to come. Tyre rolling resistance is where significant CO_2 could be achieved relatively easily as presently the majority of the vehicles appear to be equipped with Energy-Class C tyres, while Class B and Class A tyres are also present but at much lower shares. The distribution of aerodynamic classes was relatively wide as the manufacturers claimed that not enough time was made available to test their existing vehicles, so generic values were used in several cases. The most common Air Drag categories are A12 and A13 corresponding to air drag values between 5.5 and 6.3 m^2.

Regarding future steps, the information collected and the analysis performed could be used for creating generic VECTO models, representative of the four vehicles classes, that could in turn be used to support more macroscopic analysis of the HDV fleet energy performance and assess likely evolution scenarios for the future.

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List of abbreviations and definitions

A	Frontal area (m^2)
AMS	Advanced Mechatronics System
AMT	Automated Manual Transmission
AT	Automatic Transmission
ATSerial	Automatic Serial Transmission
BMEP	Brake Mean Effective Pressure
Cd	Aerodynamic drag coefficient (-)
CdA	Vehicle Drag Area (m^2)
CSV	Comma Separated Values file
DAY CAB	Day cabin
DQ	Data quality
EMS	European Modular System
ES	Electric System
ESS	Energy Saving System
EU	European Union
FAN	Vehicle engine fan
FC	Fuel Consumption
FuMEP	Fuel Mean Effective Pressure
HDV	Heavy-Duty Vehicle
HVAC	Heating Ventilation Air Conditioning
JRC	Joint Research Centre
LED	Light Emitting Diode
LH	Long Haul cycle
LH CAB	Long Haul Cabin
LHV	Lower Heating Value
LHw	weighted Long-Haul Delivery
MT	Manual Transmission
OEM	Original Equipment Manufacturer
PS	Pneumatic System
PTO	Power Take-Off
RD	Regional Delivery cycle
RDw	weighted Regional Delivery
RRC	Rolling Resistance Coefficient (-)
STP	Steering Pump
VECTO	Vehicle Energy Consumption calculation TOol
vsum	VECTO summary file extension
XLSX	MS Excel file

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Annexes

Annex 1. Data received from the OEMs

Table 14. Table with input and output parameters communicated by OEMs

1	Job [-]	**29**	r_dyn [m]
2	Input File [-]	**30**	Number axles vehicle driven [-]
3	Cycle [-]	**31**	Number axles vehicle non-driven [-]
4	Status	**32**	Number axles trailer [-]
5	Vehicle manufacturer [-]	**33**	Gearbox manufacturer [-]
6	VIN number	**34**	Gearbox model [-]
7	Vehicle model [-]	**35**	Gearbox type [-]
8	HDV CO2 vehicle class [-]	**36**	Gear ratio first gear [-]
9	Corrected Actual Curb Mass [kg]	**37**	Gear ratio last gear [-]
10	Loading [kg]	**38**	Torque converter manufacturer [-]
11	Total vehicle mass [kg]	**39**	Torque converter model [-]
12	Engine manufacturer [-]	**40**	Retarder manufacturer [-]
13	Engine model [-]	**41**	Retarder model [-]
14	Engine fuel type [-]	**42**	Retarder type [-]
15	Engine rated power [kW]	**43**	Angledrive manufacturer [-]
16	Engine idling speed [rpm]	**44**	Angledrive model [-]
17	Engine rated speed [rpm]	**45**	Angledrive ratio [-]
18	Engine displacement [ccm]	**46**	Axle manufacturer [-]
19	Engine WHTCUrban	**47**	Axle model [-]
20	Engine WHTCRural	**48**	Axle gear ratio [-]
21	Engine WHTCMotorway	**49**	Auxiliary technology STP [-]
22	Engine BFColdHot	**50**	Auxiliary technology FAN [-]
23	Engine CFRegPer	**51**	Auxiliary technology AC [-]
24	Engine actual CF	**52**	Auxiliary technology PS [-]
25	Declared CdxA [m^2]	**53**	Auxiliary technology ES [-]
26	CdxA [m^2]	**54**	Cargo Volume [m^3]
27	total RRC [-]	**55**	time [s]
28	weighted RRC w/o trailer [-]	**56**	distance [km]

57	speed [km/h]	**85**	E_aux_sum [kWh]
58	altitudeDelta [m]	**86**	E_clutch_loss [kWh]
59	FC-Map [g/h]	**87**	E_tc_loss [kWh]
60	FC-Map [g/km]	**88**	E_shift_loss [kWh]
61	FC-AUXc [g/h]	**89**	E_gbx_loss [kWh]
62	FC-AUXc [g/km]	**90**	E_ret_loss [kWh]
63	FC-WHTCc [g/h]	**91**	E_angle_loss [kWh]
64	FC-WHTCc [g/km]	**92**	E_axl_loss [kWh]
65	FC-AAUX [g/h]	**93**	E_brake [kWh]
66	FC-AAUX [g/km]	**94**	E_vehi_inertia [kWh]
67	FC-Final [g/h]	**95**	E_air [kWh]
68	FC-Final [g/km]	**96**	E_roll [kWh]
69	FC-Final [l/100km]	**97**	E_grad [kWh]
70	FC-Final [l/100tkm]	**98**	a [m/s^2]
71	FC-Final [l/100m³km]	**99**	a_pos [m/s^2]
72	CO2 [g/km]	**100**	a_neg [m/s^2]
73	CO2 [g/tkm]	**101**	AccelerationTimeShare [%]
74	CO2 [g/m³km]	**102**	DecelerationTimeShare [%]
75	P_wheel_in_pos [kW]	**103**	CruiseTimeShare [%]
76	P_fcmap_pos [kW]	**104**	max. speed [km/h]
77	E_fcmap_pos [kWh]	**105**	max. acc [m/s²]
78	E_fcmap_neg [kWh]	**106**	max. dec [m/s²]
79	E_powertrain_inertia [kWh]	**107**	n_eng_avg [rpm]
80	E_aux_FAN [kWh]	**108**	n_eng_max [rpm]
81	E_aux_STP [kWh]	**109**	gear shifts [-]
82	E_aux_AC [kWh]	**110**	StopTimeShare [%]
83	E_aux_PS [kWh]	**111**	Engine max. Load time share [%]
84	E_aux_ES [kWh]	**112**	CoastingTimeShare [%]

113	BrakingTImeShare [%]	**127**	Gear 13 TimeShare [%]
114	Gear 0 TimeShare [%]	**128**	Gear 14 TimeShare [%]
115	Gear 1 TimeShare [%]	**129**	Gear 15 TimeShare [%]
116	Gear 2 TimeShare [%]	**130**	Gear 16 TimeShare [%]
117	Gear 3 TimeShare [%]	**131**	E_PTO_TRANSM [kWh]
118	Gear 4 TimeShare [%]	**132**	E_PTO_CONSUM [kWh]
119	Gear 5 TimeShare [%]	**133**	Cabin type [-]
120	Gear 6 TimeShare [%]	**134**	Cabin code [-]
121	Gear 7 TimeShare [%]	**135**	data quality - engine
122	Gear 8 TimeShare [%]	**136**	data quality - air drag
123	Gear 9 TimeShare [%]	**137**	data quality - rolling resistance
124	Gear 10 TimeShare [%]	**138**	data quality - transmission losses
125	Gear 11 TimeShare [%]	**139**	data quality - axle losses
126	Gear 12 TimeShare [%]		

Annex 2. SIOUX Lime analysis

SIOUX Lime preliminary analysis

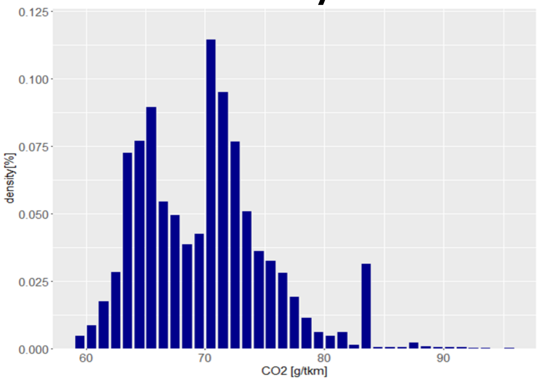
In order to verify the results of the analysis, a comparison was done against values and data calculated by an external independent contractor appointed by ACEA.

The fleet was split into subgroups according to HDV class, cabin type and engine power. For instance, one of such groups comprises of all trucks that are:

- Class: 4
- Cycle: Long Haul
- Loading: 14 t
- Engine rated power ≥ 320 hp
- Cabin type: LH cab

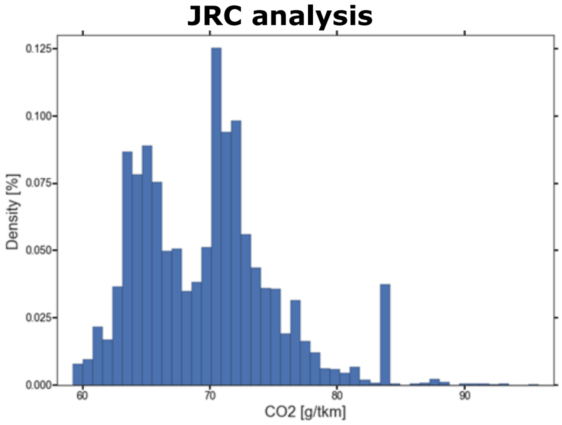
For such group, we have:

LIME analysis



- Number of vehicles: 6222
- Median: 69.91
- Minimum: 59.23
- Maximum: 95.18
- Mean: 69.73
- Standard deviation: 5.33
- Mean absolute deviation: 4.23
- Mean engine rated power [hp]: 415.49

JRC analysis



- Number of vehicles: 6222
- Median: 69.91
- Minimum: 59.23
- Maximum: 95.18
- Mean: 69.73
- Standard deviation: 5.38
- Mean absolute deviation: 4.28
- Mean engine rated power [hp]: 414.41

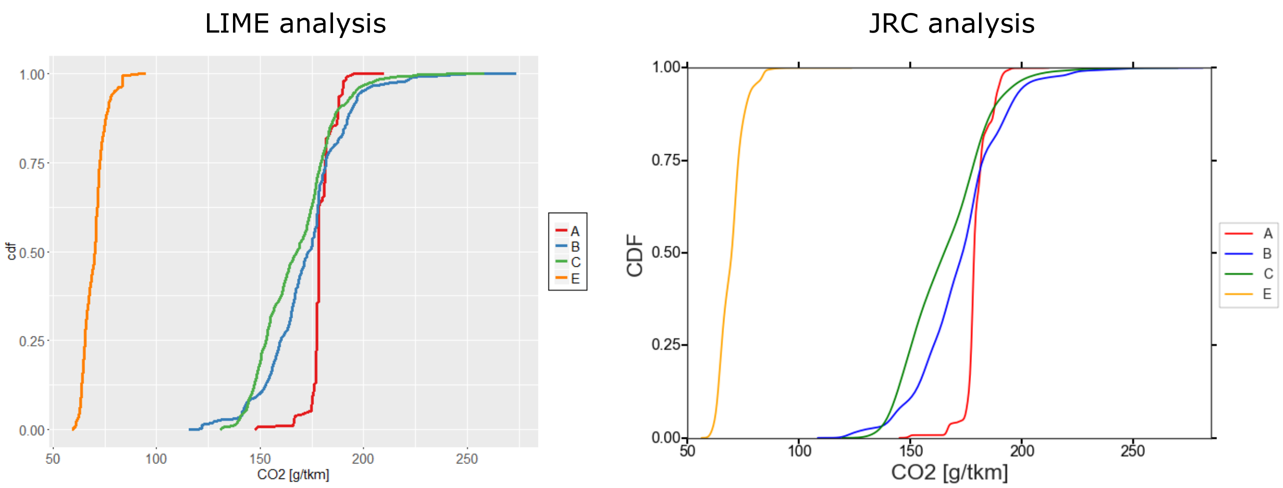
Also, the cumulative distributions for:

RegionalDelivery.vdri - 4400 kg - all_cabin_types - hp < 220

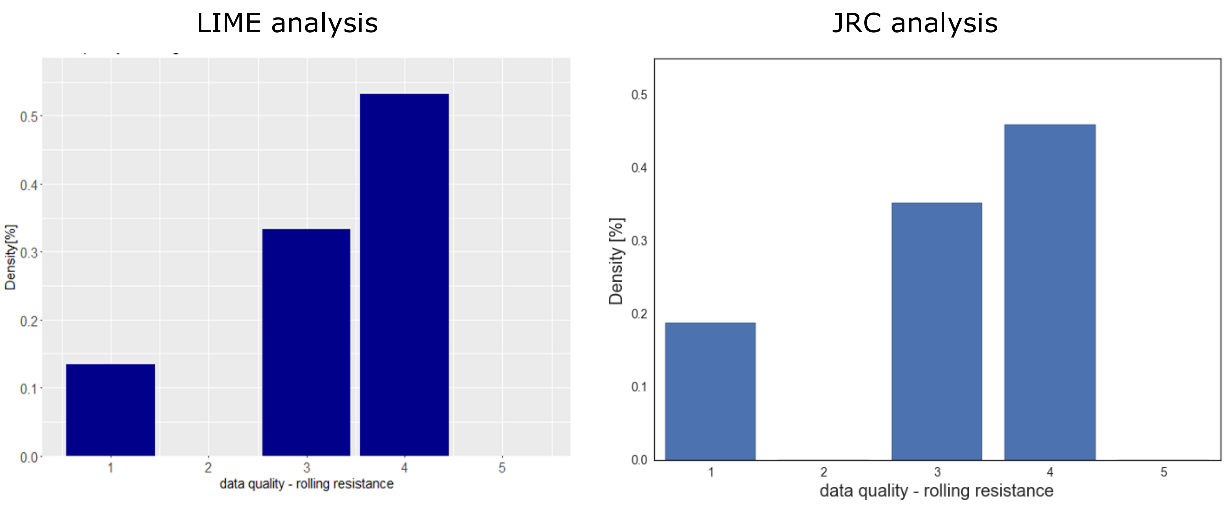
RegionalDelivery.vdri - 4400 kg - all_cabin_types - hp < 320

RegionalDelivery.vdri - 4400 kg - DAY CAB - hp >= 320

LongHaul.vdri - 14000 kg - LH CAB - hp >= 320



Lastly, we also compared data quality, like for rolling resistance:



Annex 3. Data check

Table 15. Data transfer history

Date	**Source**	**Info**
03-10-17	OEM C	Information removed in public version due to possible confidentiality issues
03-10-17	OEM D	
05-10-17	OEM E	
06-10-17	OEM A	
24-10-17	OEM C	
24-10-17	OEM B	
06-11-17	OEM F	
15-11-17	OEM C	
15-11-17	OEM A	
16-11-17	OEM E	
20-11-17	OEM C	
21-11-17	OEM F	
21-11-17	OEM D	
27-11-17	OEM B	
01-12-17	OEM C	
07-12-17	OEM A	
15-01-18	OEM A	
05-02-18	OEM A	
16-02-18	OEM F	

Table 16. Issues encountered with the data

OEM	Issue	Solution
Information removed due to possible confidentiality Issues	A single vehicle had PTO power consumption of 67.61 W, not associable with any PTO technology of VECTO.	Excluded from the analysis
	Named cabin types as "sleeper" and "day", while other OEMs use "DAY CAB" and "LH CAB"	Homogenised data according to "DAY CAB" and "LH CAB"
	Ordered data by Cycle and Load instead of HDV Class and Input file	Ordered by HDV Class and Input file
	Technology naming: Provided for Auxiliary technology ES column the value "Standard technology - LED headlights"	Changed according to VECTO value to "Standard technology - LED headlights, all"
	OEMs vehicles with AT - serial transmission contained no Engine model	Matched with real engine models based on declared engine power
Information removed due to possible confidentiality Issues	Technology naming: Provided for Auxiliary technology ES column the value "Standard technology - LED headlights"	Changed according to VECTO value to "Standard technology - LED headlights, all"
	Provided input data for 7 models, but no results	Excluded from the analysis
	Engine models were named in a generic way as "Engine A" and "Engine B"	Matched with real engine models based on declared engine power
	Axle model column was empty	Named axle model based axle ratio and data quality
	A single quote (') preceded all OEMs files	Removed quote
Information removed due to possible confidentiality Issues	Notified us of a vehicle with a wrong engine model due to a bug	Minimal effect on the results (<4%), retained as it was
Information removed due to possible confidentiality Issues	Trailing spaces in some cases in the engine manufacturer column	Removed trailing spaces
	OEM provided different first and last gear ratios under the same gearbox model	Named gearbox model as "model_A" and "model_B" for the different gear ratios
Information removed due to possible confidentiality Issues	Provided three vehicles which were missing long haul cycle results	Excluded from the analysis
	1594 vehicles had problem with the energy balance due to simulation abortion	Excluded from the analysis
	Different cabin types and cabin codes depending on the cycle-load affecting 153 vehicles	Requested and received corrected values
All	Slightly different column naming conventions, especially for gear shares for gears 13 to 16, cabin type, E_PTO_TRANSM and E_PTO_CONSUM	Homogenised data

Annex 4. Components efficiency

Axles

Table 17. Axle efficiency average [%] per cycle, loading, HDV class and data quality type

			Data quality – axle losses			
Cycle [-]	**Load**	**HDV class**	**2**	**3**	**4**	**5**
LongHaul.vdri	**LL**	**4**	94.99	96.81	89.46	78.80
		5	95.71	96.92	95.01	82.61
		9	96.06	97.20	94.73	83.82
		10	95.83	96.78	95.40	82.22
	RL	**4**	95.63	97.12	90.90	81.44
		5	96.55	97.48	96.06	86.13
		9	96.72	97.61	95.75	86.61
		10	96.63	97.38	96.32	85.79
LongHaulEMS.vdri	**LL**	**5**	96.49	96.61	95.98	85.66
		9	96.68	96.62	96.45	84.98
		10	96.57	96.78	96.23	85.30
	RL	**5**	97.12	97.32	96.82	88.70
		9	97.25	97.32	97.16	88.08
		10	97.17	97.44	96.97	88.40
MunicipalUtility.vdri	**LL**	**4**	95.58	96.77	88.71	77.34
		9	96.57	97.30	95.00	84.26
	RL	**4**	95.84	96.87	89.68	79.13
		9	96.87	97.51	95.55	86.37
RegionalDelivery.vdri	**LL**	**4**	93.30	95.95	85.33	71.99
		5	95.81	96.95	95.05	82.53
		9	94.90	96.38	92.91	78.71
		10	95.95	96.91	95.46	82.22
	RL	**4**	94.04	96.21	86.40	74.05
		5	96.47	97.40	95.91	85.56
		9	95.55	96.78	93.79	81.22
		10	96.55	97.30	96.19	85.26
RegionalDeliveryEMS.vdri	**LL**	**5**	96.54	96.72	96.03	85.73
		9	96.72	96.72	96.49	85.04
		10	96.62	96.87	96.26	85.42
	RL	**5**	97.03	97.27	96.69	88.30
		9	97.16	97.26	97.04	87.63
		10	97.07	97.38	96.85	88.01

Gearboxes

Table 18. Gearbox efficiency average [%] per cycle, loading, HDV class and data quality type

			Data quality – transmission losses			
Cycle [-]	**Load**	**HDV class**	**2**	**3**	**4**	**5**
LongHaul.vdri	**LL**	**4**	96.44	97.79	96.69	93.90
		5	96.71	98.10	96.18	94.82
		9	97.05	98.08	96.61	93.99
		10	97.15	98.27	96.21	95.12
	RL	**4**	96.51	97.97	96.87	94.51
		5	96.95	98.29	96.57	95.42
		9	97.10	98.23	96.82	94.56
		10	97.33	98.41	96.58	95.67
LongHaulEMS.vdri	**LL**	**5**	96.85	98.23	96.60	95.60
		9	97.46	98.08	96.53	95.06
		10	97.48	98.46	96.64	95.81
	RL	**5**	96.90	98.22	96.71	95.83
		9	97.39	98.13	96.73	95.39
		10	97.50	98.40	96.74	96.01
MunicipalUtility.vdri	**LL**	**4**	94.32	96.05	93.75	90.61
		9	94.53	96.40	94.41	88.33
	RL	**4**	94.46	96.20	94.01	90.97
		9	94.71	96.54	94.70	89.30
RegionalDelivery.vdri	**LL**	**4**	95.64	97.03	95.60	92.71
		5	96.24	97.86	95.85	94.10
		9	96.27	97.41	95.74	91.94
		10	96.76	98.04	95.83	94.45
	RL	**4**	95.74	97.19	95.83	93.09
		5	96.36	97.97	96.08	94.53
		9	96.36	97.57	95.96	92.58
		10	96.83	98.08	96.11	94.84
RegionalDeliveryEMS.vdri	**LL**	**5**	96.28	97.95	96.21	94.85
		9	96.98	97.81	96.20	94.34
		10	97.04	98.16	96.27	95.12
	RL	**5**	96.17	97.80	96.14	94.89
		9	96.79	97.72	96.20	94.49
		10	96.91	97.98	96.15	95.09

Engines

Table 19. Engine efficiency average [%] per cycle, loading, HDV class and data quality type

			Data quality – engine losses			
Cycle [-]	**Load**	**HDV class**	**2**	**3**	**4**	**5**
LongHaul.vdri	**LL**	**4**	41.8	41.1	41.6	-
		5	41.9	42.1	42.1	-
		9	42.1	42.3	42.0	-
		10	41.8	42.1	41.8	-
	RL	**4**	42.2	41.1	42.0	-
		5	42.5	43.0	42.8	-
		9	42.5	42.8	42.5	-
		10	42.5	43.0	42.6	-
LongHaulEMS.vdri	**LL**	**5**	42.6	42.3	42.9	-
		9	42.4	42.4	42.5	-
		10	42.5	42.5	42.6	-
	RL	**5**	42.8	42.9	43.1	-
		9	42.6	43.0	42.8	-
		10	42.7	43.0	42.8	-
MunicipalUtility.vdri	**LL**	**4**	34.0	35.3	34.0	-
		9	34.3	34.7	33.8	-
	RL	**4**	34.3	35.5	34.3	-
		9	34.8	35.2	34.4	-
RegionalDelivery.vdri	**LL**	**4**	39.5	39.2	39.4	-
		5	41.2	41.3	41.2	-
		9	40.0	40.1	39.6	-
		10	41.1	41.3	40.8	-
	RL	**4**	40.1	39.5	40.0	-
		5	41.8	42.1	41.9	-
		9	40.7	40.9	40.5	-
		10	41.7	42.2	41.5	-
RegionalDeliveryEMS.vdri	**LL**	**5**	41.9	41.7	42.0	-
		9	41.6	41.7	41.6	-
		10	41.8	41.8	41.6	-
	RL	**5**	42.1	42.2	42.2	-
		9	41.8	42.3	41.9	-
		10	42.0	42.3	41.7	-

Annex 5. Results

Values of CO_2 emissions [g/km] from the distributions presented in chapter 4.2

Table 20. Distribution statistics. CO_2 emissions [g/km], Regional Delivery, reference load

	HDV class	Counts [-]	Mean [g/km]	St. Dev. [g/km]	Min [g/km]	Median [g/km]	Max [g/km]
OEM	**4**	23880	737.1	84.2	510.0	733.7	1204.1
	5	162936	927.4	54.4	803.3	924.9	1345.6
	9	33550	765.5	70.7	622.4	755.2	1204.7
	10	21841	968.1	59.0	844.0	966.6	1341.5
JRC	**4**	23880	663.8	49.1	504.8	658.8	865.0
	5	162936	893.8	34.2	799.0	889.8	1109.9
	9	33550	726.1	51.2	621.3	716.0	977.9
	10	21841	926.4	44.2	838.1	913.5	1209.7

Table 21. Distribution statistics. CO_2 emissions [g/km], Long Haul, reference load

	HDV class	Counts [-]	Mean [g/km]	St. Dev. [g/km]	Min [g/km]	Median [g/km]	Max [g/km]
OEM	**4**	23880	1024.9	91.4	793.3	1024.4	1493.4
	5	162936	938.2	61.1	801.7	935.3	1388.5
	9	33550	1070.0	81.6	892.8	1056.1	1540.2
	10	21841	977.3	62.2	841.9	982.6	1354.0
JRC	**4**	23880	949.2	51.3	781.4	947.8	1139.0
	5	162936	908.9	39.1	802.5	902.8	1131.8
	9	33550	1025.4	59.7	891.0	1013.9	1293.8
	10	21841	941.2	46.3	840.8	928.4	1221.0

Table 22. Distribution statistics. CO_2 emissions [g/km], Regional Delivery, weighted

	HDV class	Counts [-]	Mean [g/km]	St. Dev. [g/km]	Min [g/km]	Median [g/km]	Max [g/km]
OEM	**4**	23880	733.9	84.1	506.6	730.9	1201.7
	5	162936	876.4	54.7	755.1	874.1	1298.1
	9	33550	765.4	70.9	621.4	755.6	1207.7
	10	21841	916.2	58.7	793.5	916.7	1287.4
JRC	**4**	23880	662.0	49.5	503.1	659.0	855.7
	5	162936	844.2	34.1	752.6	839.2	1055.9
	9	33550	725.6	51.6	621.5	715.3	975.3
	10	21841	876.2	44.1	789.6	862.3	1158.3

Table 23. Distribution statistics. CO_2 emissions [g/km], Long Haul, weighted

	HDV class	Counts [-]	Mean [g/km]	St. Dev. [g/km]	Min [g/km]	Median [g/km]	Max [g/km]
OEM	**4**	23880	928.9	89.8	697.1	929.0	1401.0
	5	162936	876.6	59.6	746.5	873.6	1321.9
	9	33550	981.0	79.0	812.4	968.2	1448.0
	10	21841	914.9	61.0	783.8	920.2	1287.1
JRC	**4**	23880	856.7	51.8	688.4	856.2	1031.6
	5	162936	847.6	37.8	748.2	840.8	1060.7
	9	33550	938.8	57.8	814.0	926.9	1199.8
	10	21841	879.4	45.8	783.9	865.6	1157.4

CO_2 emissions [g/tkm]

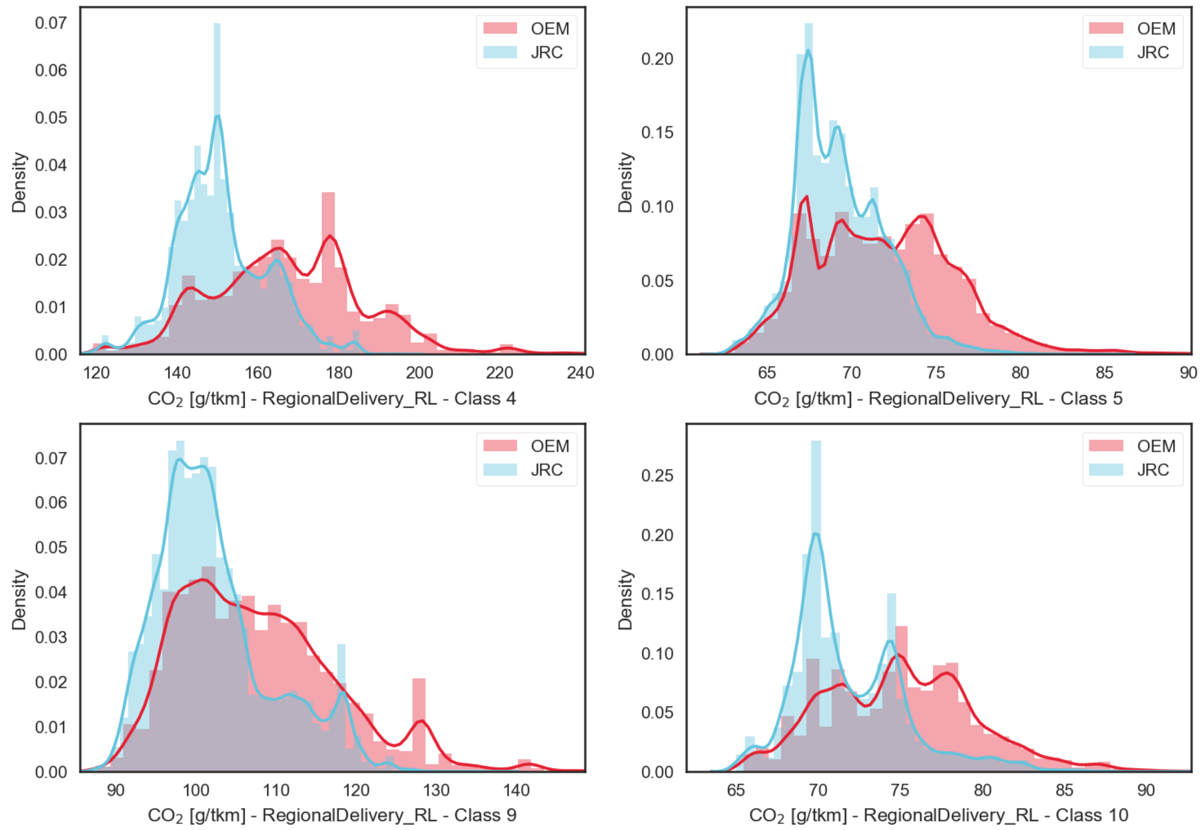


Figure 38. CO_2 emissions [g/tkm] comparison between OEM declared values and JRC normalisation. Regional delivery, reference load

Table 24. Distribution statistics. CO_2 emissions [g/tkm], Regional Delivery, reference load

	HDV class	Counts [-]	Mean [g/tkm]	St. Dev. [g/tkm]	Min [g/tkm]	Median [g/tkm]	Max [g/tkm]
OEM	**4**	23880	167.5	19.1	115.9	166.8	273.6
	5	162936	71.9	4.2	62.3	71.7	104.3
	9	33550	107.8	10.0	87.7	106.4	169.7
	10	21841	75.0	4.6	65.4	74.9	104.0
JRC	**4**	23880	150.9	11.2	114.7	149.7	196.6
	5	162936	69.3	2.7	61.9	69.0	86.0
	9	33550	102.3	7.2	87.5	100.8	137.7
	10	21841	71.8	3.4	65.0	70.8	93.8

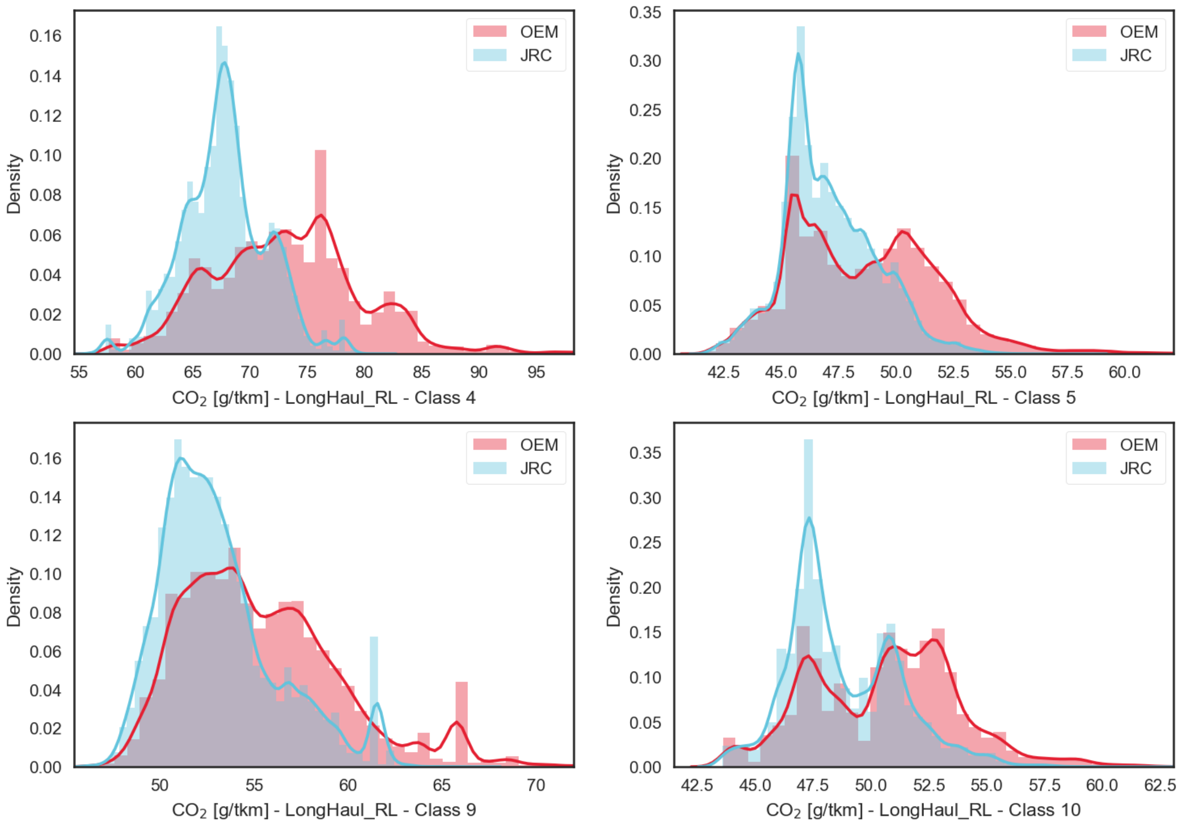


Figure 39. CO_2 emissions [g/tkm] comparison between OEM declared values and JRC normalisation. Long Haul, reference load

Table 25. Distribution statistics. CO_2 emissions [g/tkm], Long Haul, reference load

	HDV class	Counts [-]	Mean [g/tkm]	St. Dev. [g/tkm]	Min [g/tkm]	Median [g/tkm]	Max [g/tkm]
OEM	**4**	23880	73.2	6.5	56.7	73.2	106.7
	5	162936	48.6	3.2	41.5	48.5	71.9
	9	33550	55.4	4.2	46.3	54.7	79.8
	10	21841	50.6	3.2	43.6	50.9	70.2
JRC	**4**	23880	67.8	3.7	55.8	67.7	81.4
	5	162936	47.1	2.0	41.6	46.8	58.6
	9	33550	53.1	3.1	46.2	52.5	67.0
	10	21841	48.8	2.4	43.6	48.1	63.3

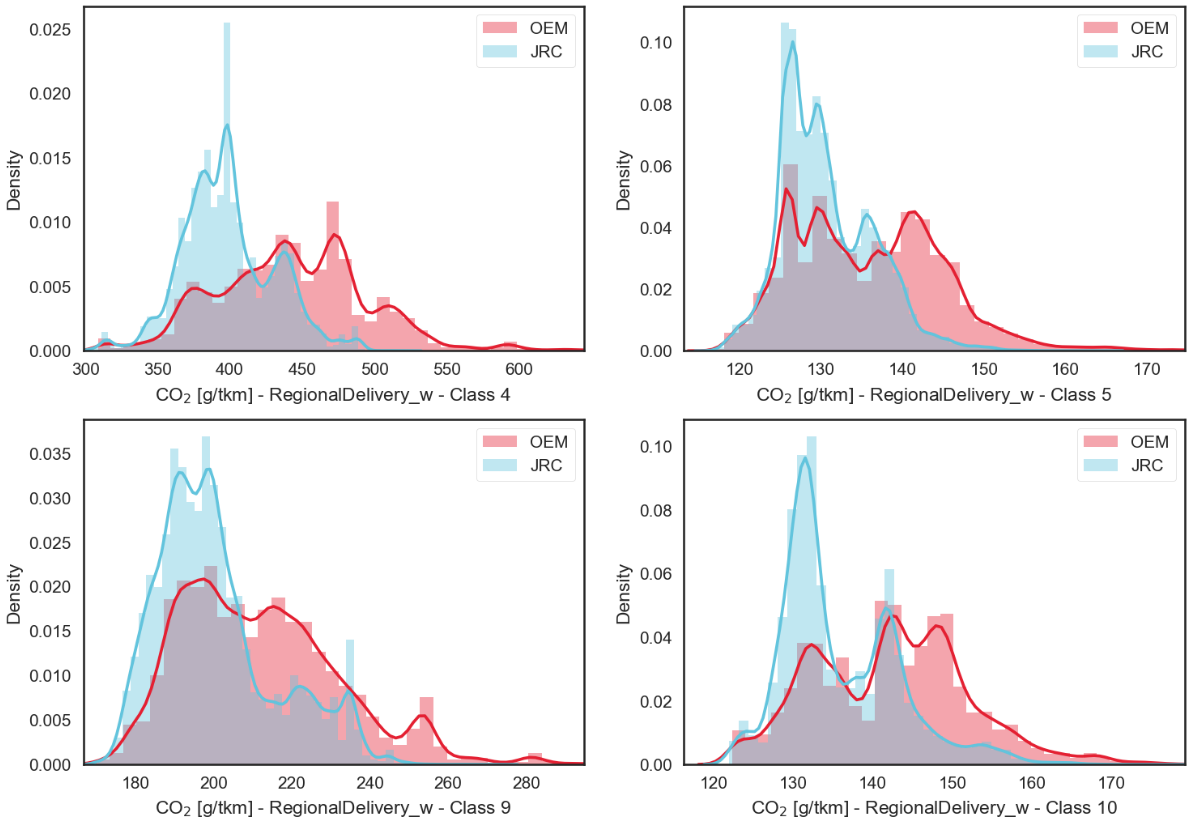


Figure 40. CO_2 emissions [g/tkm] comparison between OEM declared values and JRC normalisation. Regional Delivery, weighted

Table 26. Distribution statistics. CO_2 emissions [g/tkm], Regional Delivery, weighted

	HDV class	Counts [-]	Mean [g/tkm]	St. Dev. [g/tkm]	Min [g/tkm]	Median [g/tkm]	Max [g/tkm]
OEM	**4**	23880	443.2	52.7	299.9	441.6	739.0
	5	162936	135.8	9.1	116.3	135.4	206.6
	9	33550	212.0	20.6	169.8	209.5	342.8
	10	21841	142.3	9.7	122.3	142.5	204.1
JRC	**4**	23880	398.5	31.4	298.0	396.8	520.0
	5	162936	130.6	5.6	116.2	129.5	165.4
	9	33550	200.3	15.1	170.4	197.5	272.7
	10	21841	135.9	7.3	121.9	133.3	183.0

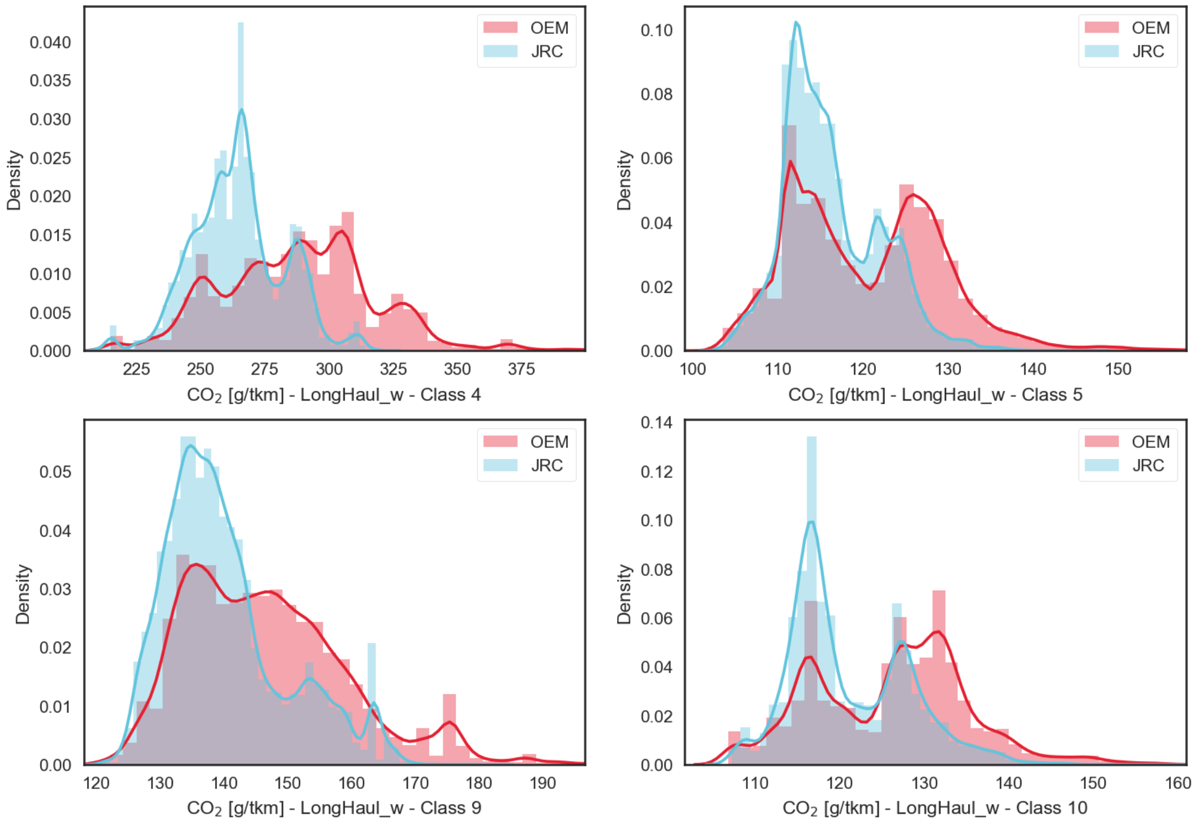


Figure 41. CO_2 emissions [g/tkm] comparison between OEM declared values and JRC normalisation. Long Haul, weighted

Table 27. Distribution statistics. CO_2 emissions [g/tkm], Long Haul, weighted

	HDV class	Counts [-]	Mean [g/tkm]	St. Dev. [g/tkm]	Min [g/tkm]	Median [g/tkm]	Max [g/tkm]
OEM	**4**	23880	288.0	29.8	210.2	288.6	447.3
	5	162936	120.5	9.0	101.8	119.8	188.4
	9	33550	146.6	12.8	120.0	145.0	224.5
	10	21841	126.2	9.2	106.8	127.1	182.3
JRC	**4**	23880	264.5	17.5	208.0	264.4	321.0
	5	162936	116.2	5.6	102.3	115.0	147.3
	9	33550	140.0	9.4	120.9	138.0	182.2
	10	21841	121.0	7.0	107.2	118.6	163.1

Fuel consumption [l/100km]

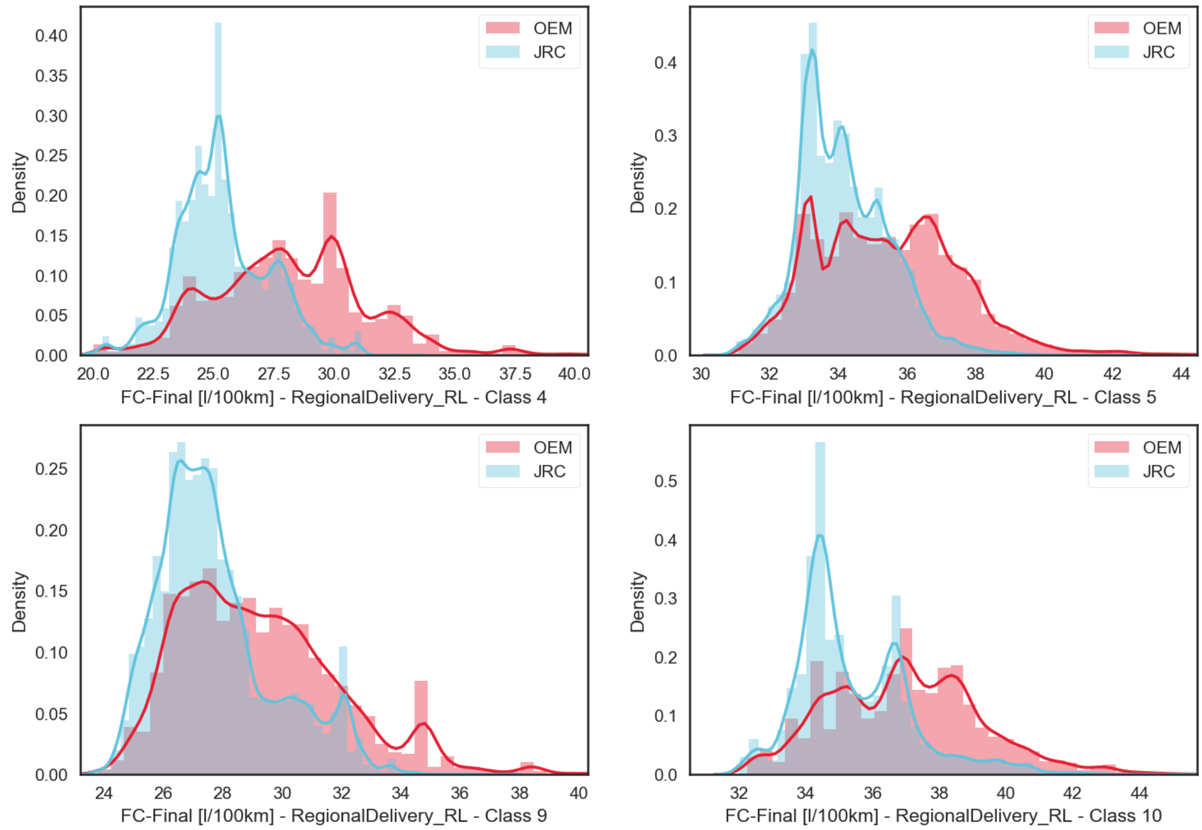


Figure 42. FC [l/100km] comparison between OEM declared values and JRC normalisation. Regional delivery, reference load

Table 28. Distribution statistics. FC [l/100km], Regional Delivery, reference load

	HDV class	Counts [-]	Mean [l/100km]	St. Dev. [l/100km]	Min [l/100km]	Median [l/100km]	Max [l/100km]
OEM	**4**	23880	28.17	3.22	19.49	28.04	46.01
	5	162936	35.44	2.08	30.70	35.35	51.43
	9	33550	29.25	2.70	23.79	28.86	46.04
	10	21841	37.00	2.26	32.25	36.94	51.27
JRC	**4**	23880	25.37	1.88	19.29	25.18	33.06
	5	162936	34.16	1.31	30.54	34.00	42.42
	9	33550	27.75	1.96	23.74	27.36	37.37
	10	21841	35.40	1.69	32.03	34.91	46.23

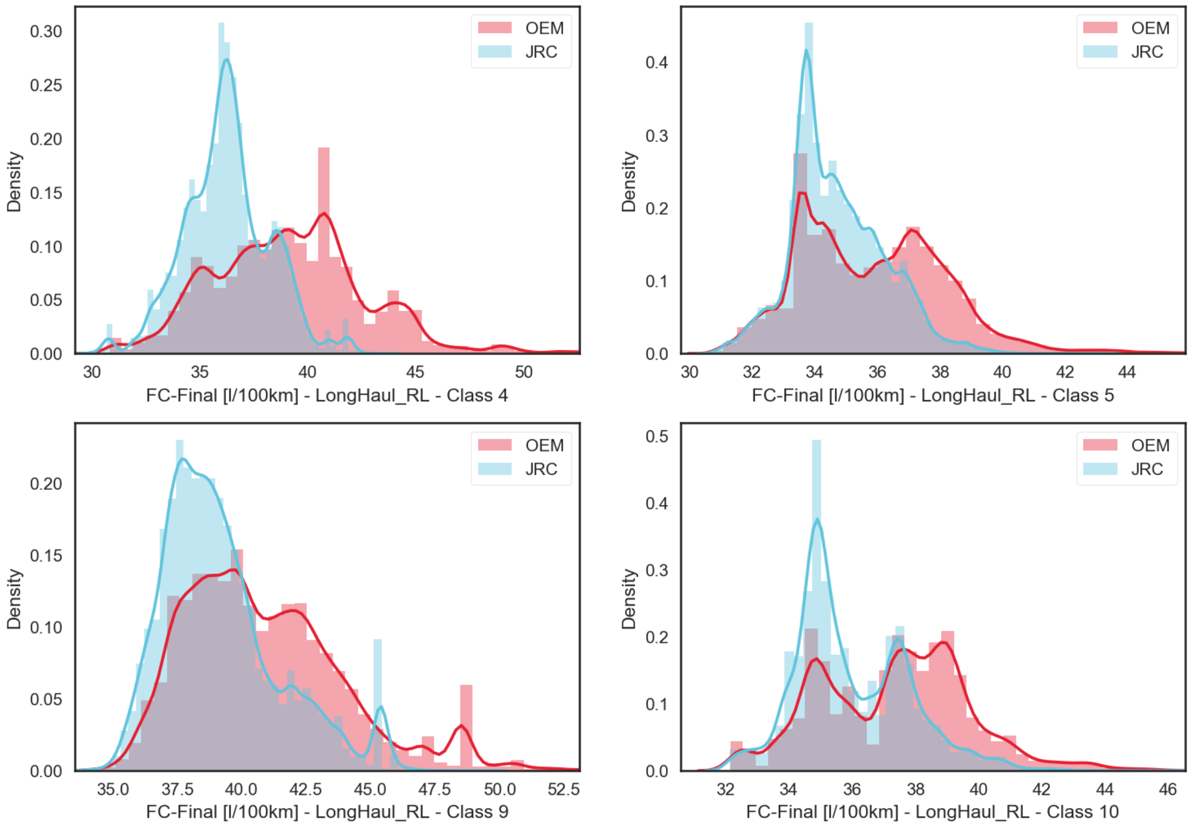


Figure 43. FC [l/100km] comparison between OEM declared values and JRC normalisation. Long Haul, reference load

Table 29. Distribution statistics. FC [l/100km], Long Haul, reference load

	HDV class	Counts [-]	Mean [l/100km]	St. Dev. [l/100km]	Min [l/100km]	Median [l/100km]	Max [l/100km]
OEM	**4**	23880	39.17	3.49	30.32	39.15	57.07
	5	162936	35.86	2.33	30.64	35.74	53.06
	9	33550	40.89	3.12	34.12	40.36	58.86
	10	21841	37.35	2.38	32.17	37.55	51.75
JRC	**4**	23880	36.28	1.96	29.86	36.22	43.53
	5	162936	34.74	1.49	30.67	34.50	43.25
	9	33550	39.19	2.28	34.05	38.75	49.45
	10	21841	35.97	1.77	32.13	35.48	46.66

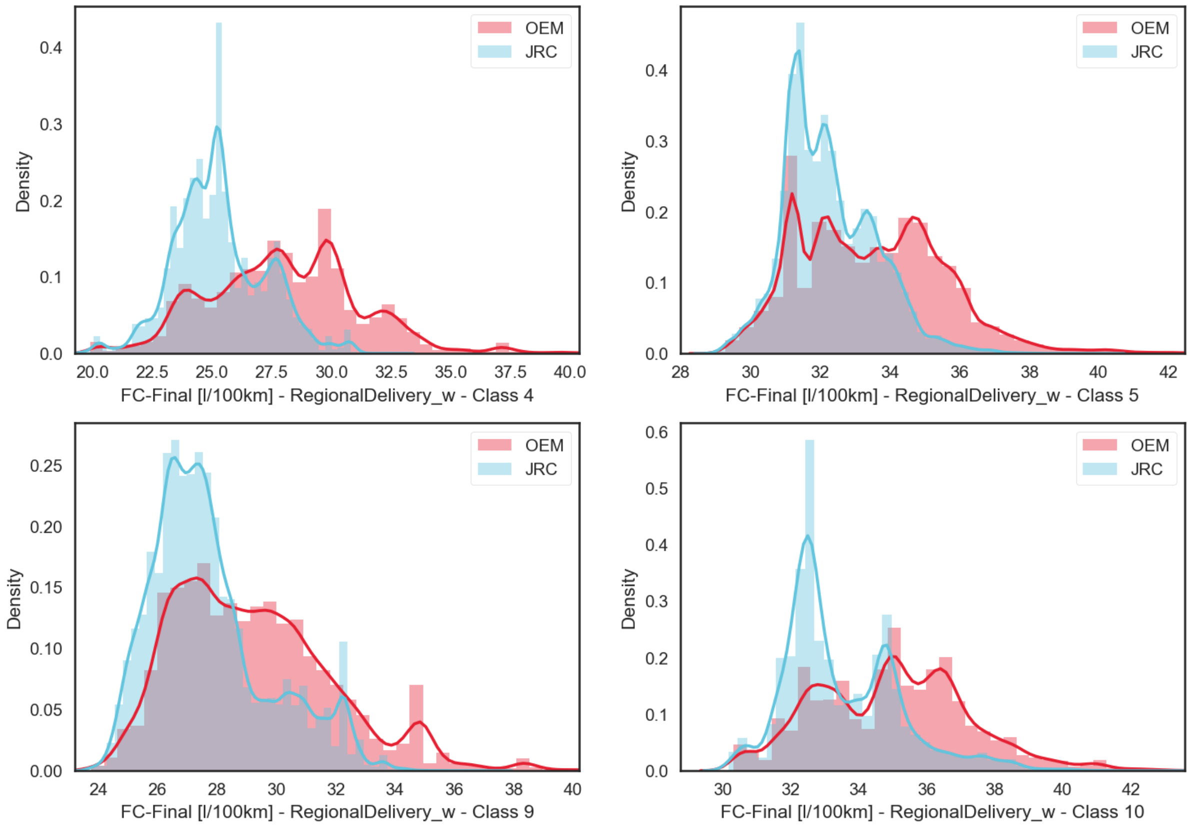


Figure 44. FC [l/100km] comparison between OEM declared values and JRC normalisation. Regional Delivery, weighted

Table 30. Distribution statistics. FC [l/100km], Regional Delivery, weighted

	HDV class	Counts [-]	Mean [l/100km]	St. Dev. [l/100km]	Min [l/100km]	Median [l/100km]	Max [l/100km]
OEM	**4**	23880	28.05	3.22	19.36	27.93	45.92
	5	162936	33.49	2.09	28.86	33.40	49.61
	9	33550	29.25	2.71	23.75	28.88	46.15
	10	21841	35.01	2.24	30.33	35.03	49.20
JRC	**4**	23880	25.30	1.89	19.23	25.18	32.70
	5	162936	32.26	1.30	28.76	32.07	40.35
	9	33550	27.73	1.97	23.75	27.34	37.27
	10	21841	33.49	1.68	30.17	32.95	44.26

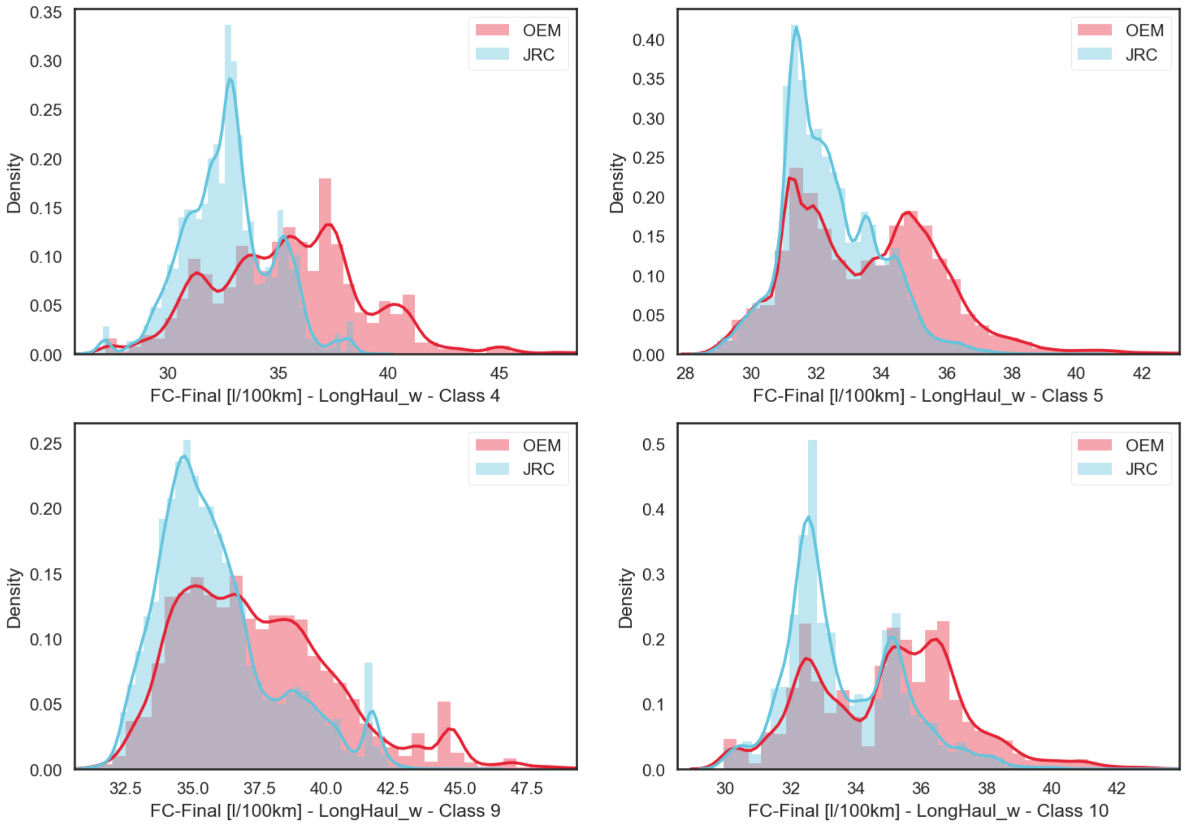


Figure 45. FC [l/100km] comparison between OEM declared values and JRC normalisation. Long Haul, weighted

Table 31. Distribution statistics. FC [l/100km], Long Haul, weighted

	HDV class	Counts [-]	Mean [l/100km]	St. Dev. [l/100km]	Min [l/100km]	Median [l/100km]	Max [l/100km]
OEM	**4**	23880	35.50	3.43	26.64	35.50	53.54
	5	162936	33.50	2.28	28.53	33.38	50.52
	9	33550	37.49	3.02	31.05	37.00	55.34
	10	21841	34.96	2.33	29.95	35.17	49.19
JRC	**4**	23880	32.74	1.98	26.31	32.72	39.42
	5	162936	32.39	1.44	28.59	32.13	40.54
	9	33550	35.88	2.21	31.11	35.42	45.85
	10	21841	33.61	1.75	29.96	33.08	44.23

Fuel consumption [l/100tkm]

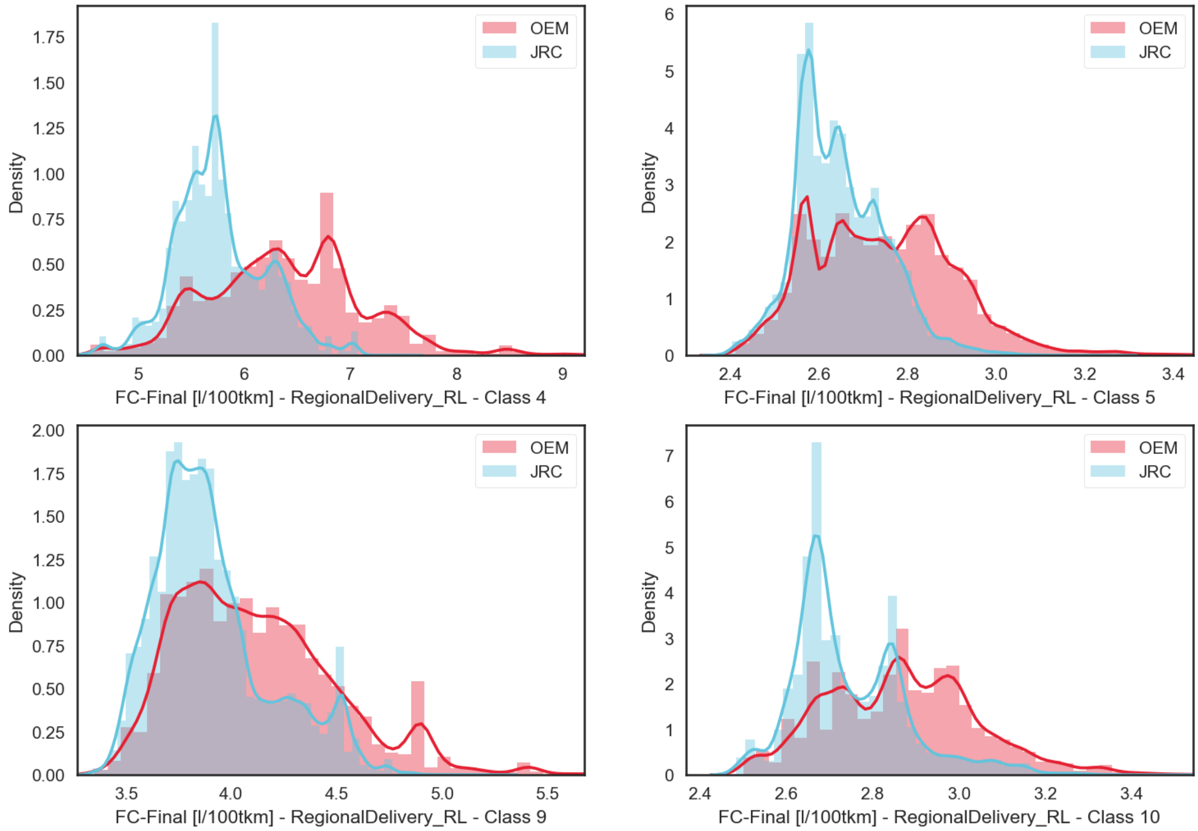


Figure 46. FC [l/100tkm] comparison between OEM declared values and JRC normalisation. Regional delivery, reference load

Table 32. Distribution statistics. FC [l/100tkm], Regional Delivery, reference load

	HDV class	**Counts [-]**	**Mean [l/100tkm]**	**St. Dev. [l/100tkm]**	**Min [l/100tkm]**	**Median [l/100tkm]**	**Max [l/100tkm]**
OEM	**4**	23880	6.40	0.73	4.43	6.37	10.46
	5	162936	2.75	0.16	2.38	2.74	3.99
	9	33550	4.12	0.38	3.35	4.07	6.48
	10	21841	2.87	0.17	2.50	2.86	3.97
JRC	**4**	23880	5.77	0.43	4.38	5.72	7.51
	5	162936	2.65	0.10	2.37	2.64	3.29
	9	33550	3.91	0.28	3.34	3.85	5.26
	10	21841	2.74	0.13	2.48	2.71	3.58

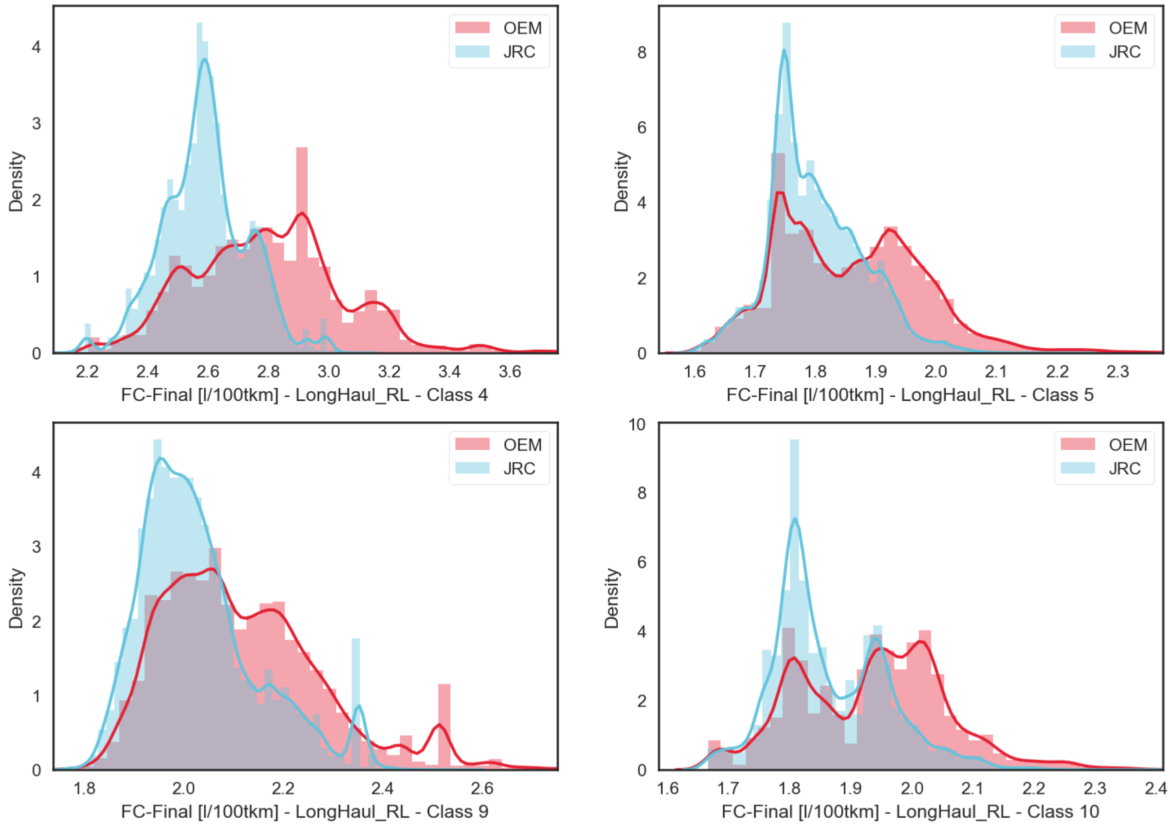


Figure 47. FC [l/100tkm] comparison between OEM declared values and JRC normalisation. Long Haul, reference load

Table 33. Distribution statistics. FC [l/100tkm], Long Haul, reference load

	HDV class	Counts [-]	Mean [l/100tkm]	St. Dev. [l/100tkm]	Min [l/100tkm]	Median [l/100tkm]	Max [l/100tkm]
OEM	**4**	23880	2.80	0.25	2.17	2.80	4.08
	5	162936	1.86	0.12	1.59	1.85	2.75
	9	33550	2.12	0.16	1.77	2.09	3.05
	10	21841	1.94	0.12	1.67	1.95	2.68
JRC	**4**	23880	2.59	0.14	2.13	2.59	3.11
	5	162936	1.80	0.08	1.59	1.79	2.24
	9	33550	2.03	0.12	1.76	2.01	2.56
	10	21841	1.86	0.09	1.66	1.84	2.42

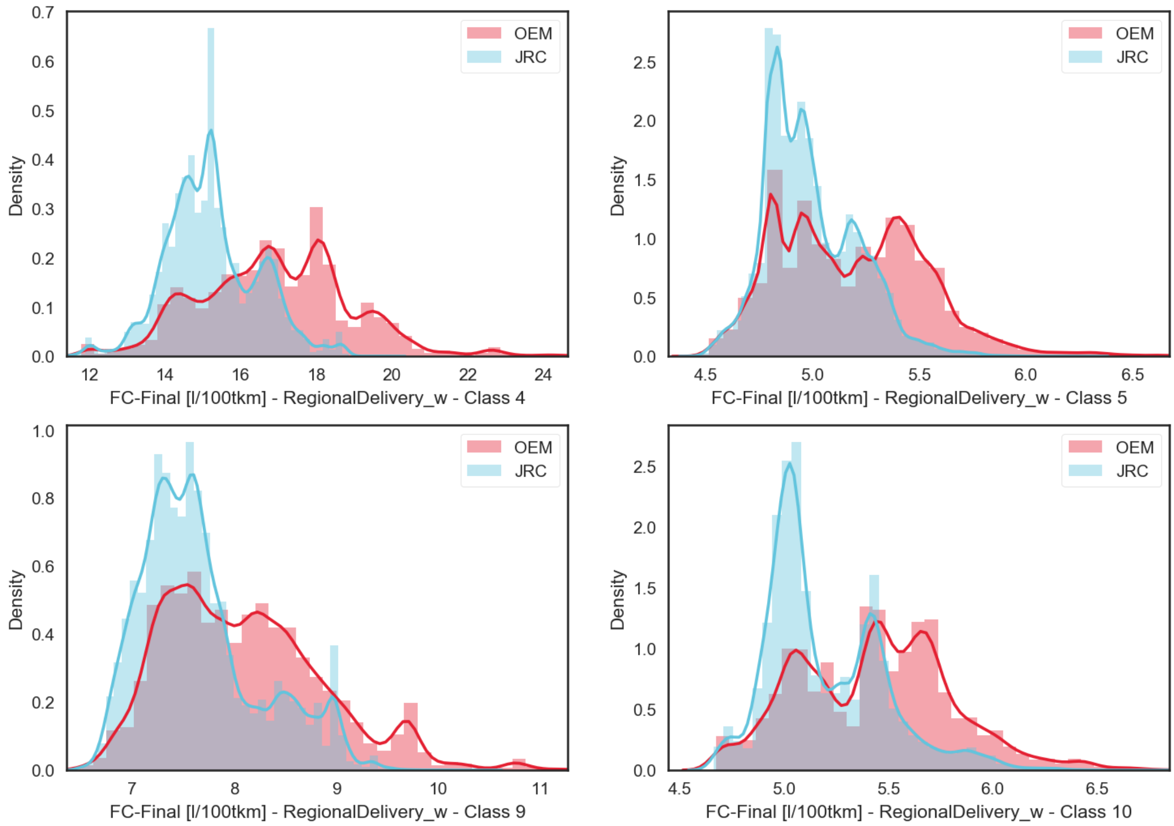


Figure 48. FC [l/100tkm] comparison between OEM declared values and JRC normalisation. Regional Delivery, weighted

Table 34. Distribution statistics. FC [l/100tkm], Regional Delivery, weighted

	HDV class	Counts [-]	Mean [l/100tkm]	St. Dev. [l/100tkm]	Min [l/100tkm]	Median [l/100tkm]	Max [l/100tkm]
OEM	**4**	23880	16.94	2.01	11.46	16.88	28.24
	5	162936	5.19	0.35	4.45	5.17	7.89
	9	33550	8.10	0.79	6.49	8.00	13.10
	10	21841	5.44	0.37	4.67	5.45	7.80
JRC	**4**	23880	15.23	1.20	11.39	15.16	19.87
	5	162936	4.99	0.21	4.44	4.95	6.32
	9	33550	7.65	0.58	6.51	7.55	10.42
	10	21841	5.19	0.28	4.66	5.09	6.99

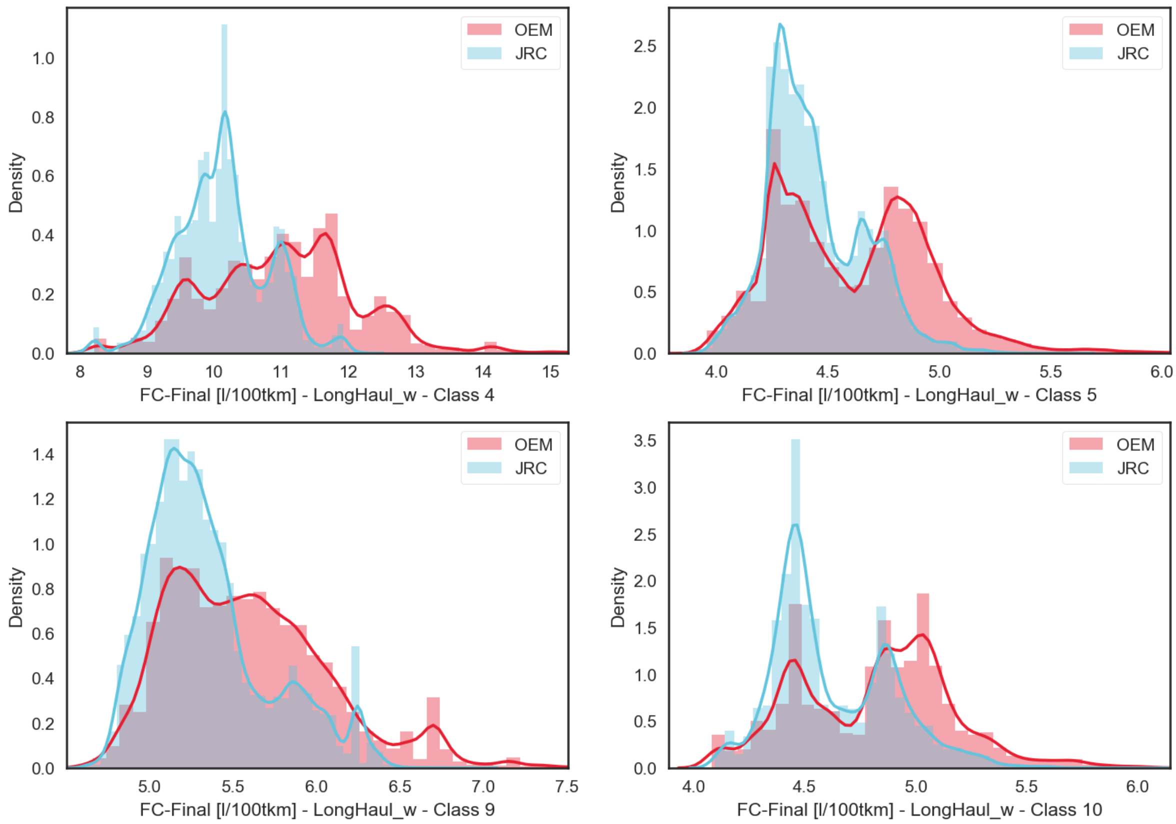


Figure 49. FC [l/100tkm] comparison between OEM declared values and JRC normalisation. Long Haul, weighted

Table 35. Distribution statistics. FC [l/100tkm], Long Haul, weighted

	HDV class	Counts [-]	Mean [l/100tkm]	St. Dev. [l/100tkm]	Min [l/100tkm]	Median [l/100tkm]	Max [l/100tkm]
OEM	**4**	23880	11.01	1.14	8.03	11.03	17.09
	5	162936	4.61	0.34	3.89	4.58	7.20
	9	33550	5.60	0.49	4.59	5.54	8.58
	10	21841	4.82	0.35	4.08	4.86	6.97
JRC	**4**	23880	10.11	0.67	7.95	10.11	12.27
	5	162936	4.44	0.22	3.91	4.39	5.63
	9	33550	5.35	0.36	4.62	5.27	6.96
	10	21841	4.62	0.27	4.10	4.53	6.23

Specific FC at wheels [g/kWh]

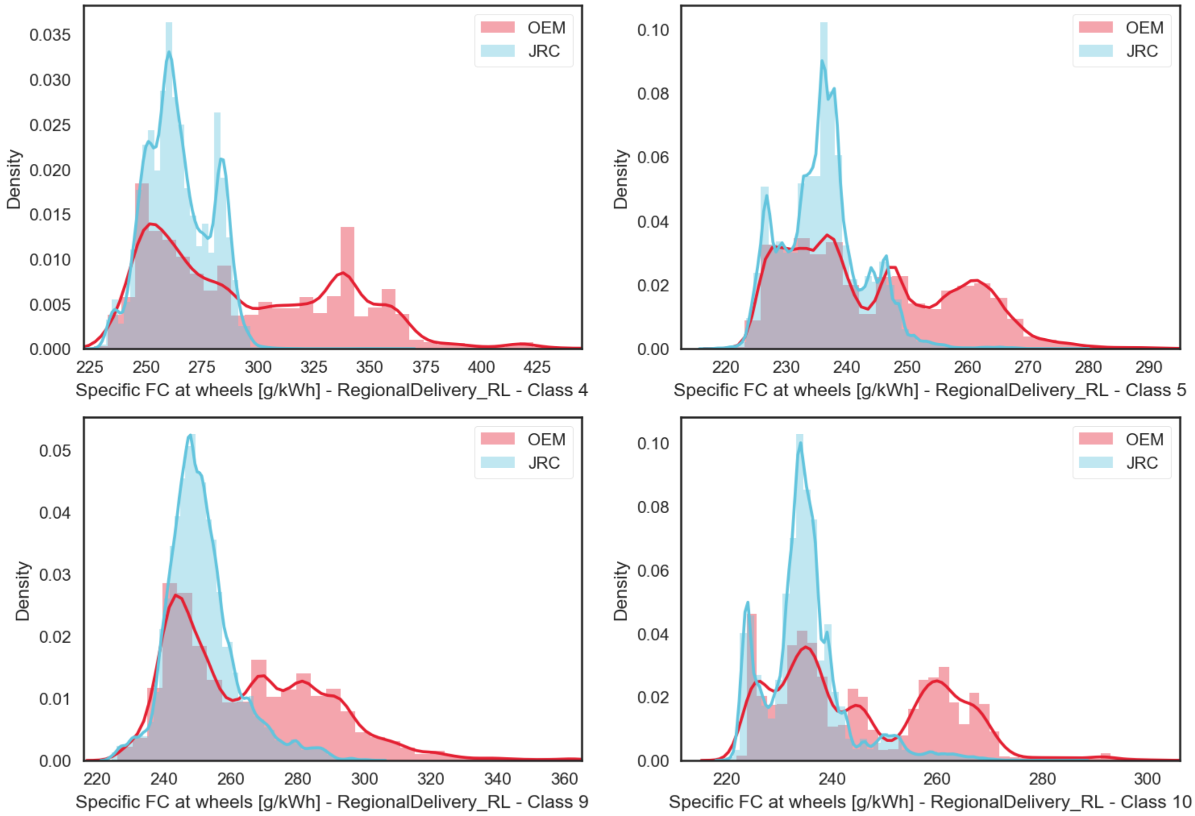


Figure 50. Specific FC at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Regional Delivery, reference load

Table 36. Distribution statistics. FC at wheels [g/kWh], Regional Delivery, reference load

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	295.2	43.4	226.9	284.4	533.3
	5	162936	244.4	13.7	220.3	240.8	356.1
	9	33550	265.3	23.5	226.1	260.9	448.9
	10	21841	245.6	15.6	221.9	242.2	317.9
JRC	**4**	23880	264.4	14.3	229.4	262.3	364.1
	5	162936	236.0	6.6	217.3	235.9	278.4
	9	33550	251.3	10.5	224.3	249.8	303.2
	10	21841	234.8	7.8	219.9	234.2	286.7

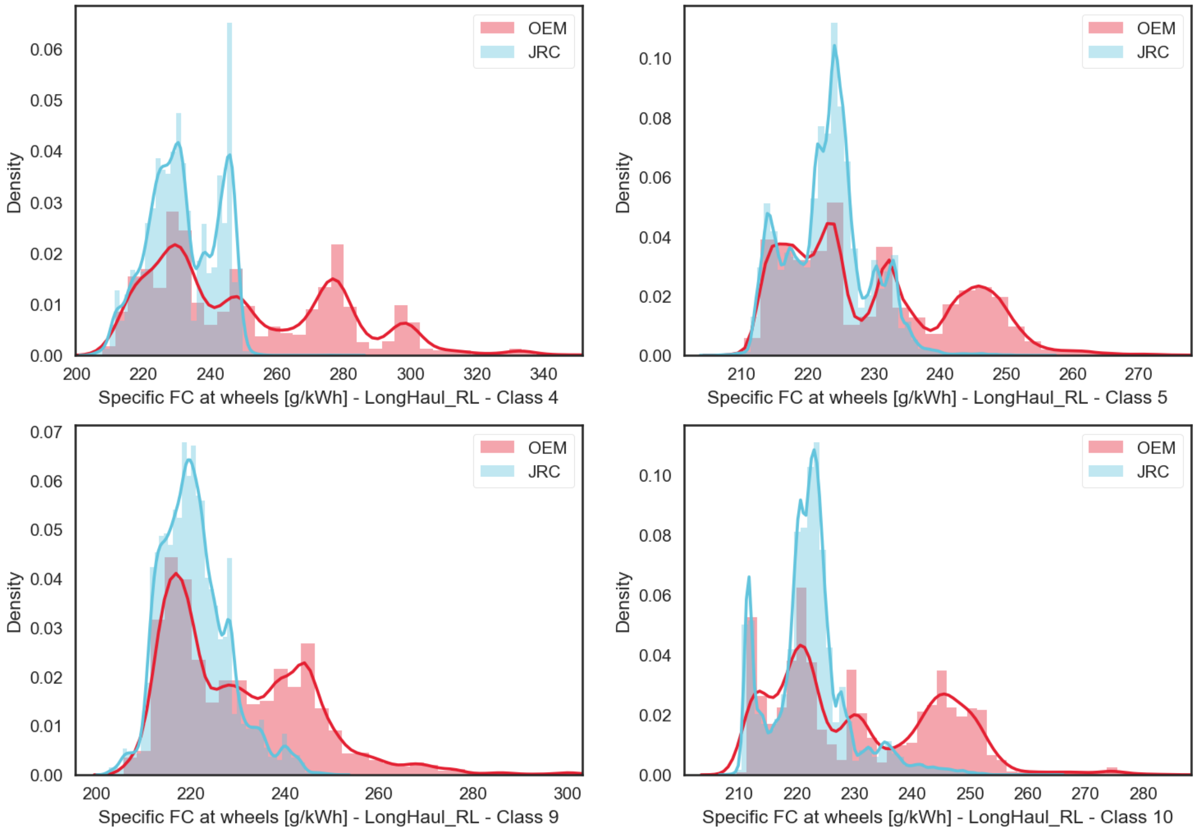


Figure 51. Specific FC at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Long Haul, reference load

Table 37. Distribution statistics. FC at wheels [g/kWh], Long Haul, reference load

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	251.0	28.6	207.7	244.9	398.2
	5	162936	229.7	12.6	207.9	225.2	332.6
	9	33550	230.6	15.7	205.7	227.5	350.9
	10	21841	230.8	14.3	209.6	228.7	296.2
JRC	**4**	23880	231.8	10.3	205.1	230.8	282.0
	5	162936	223.1	6.0	205.3	223.4	255.9
	9	33550	220.8	7.2	202.7	220.0	251.0
	10	21841	222.2	6.8	208.2	222.1	264.5

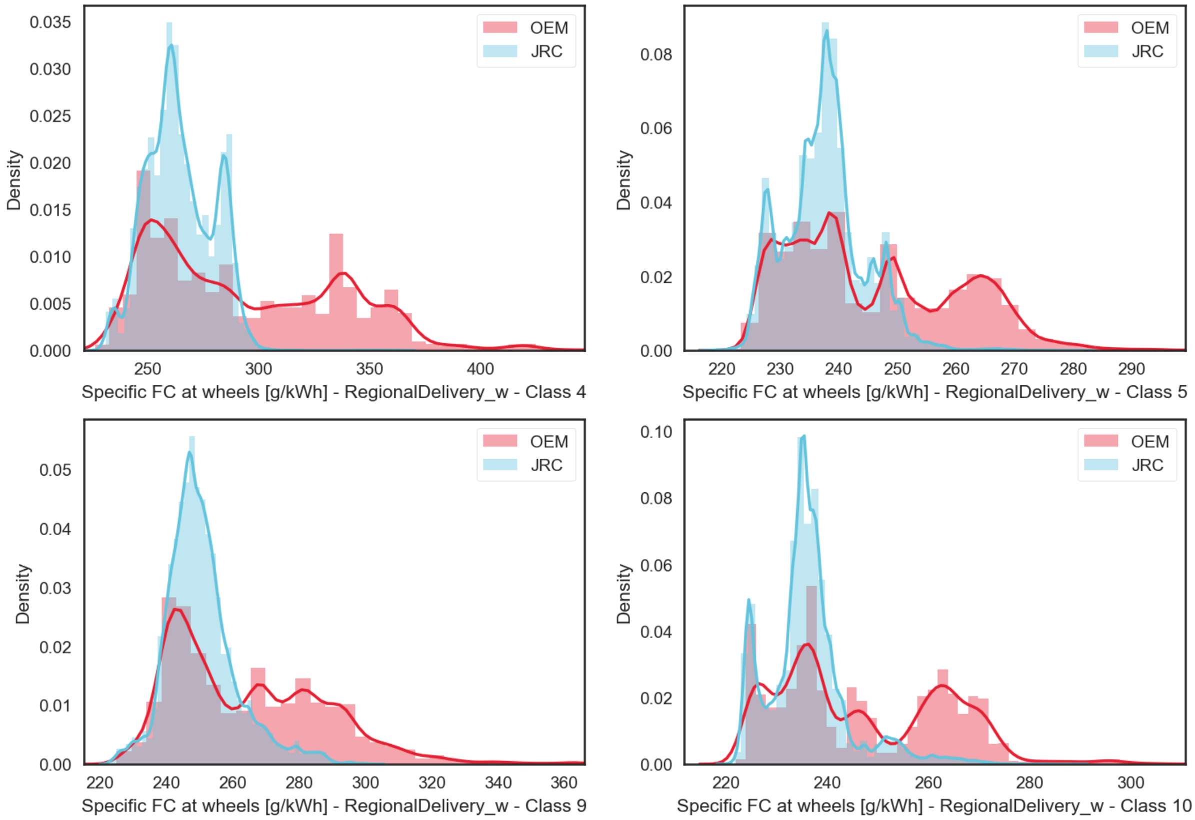


Figure 52. Specific FC at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Regional Delivery, weighted

Table 38. Distribution statistics. FC at wheels [g/kWh], Regional Delivery, weighted

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	295.1	44.1	226.7	284.6	536.0
	5	162936	246.0	14.5	220.3	241.6	368.5
	9	33550	264.8	23.9	225.0	260.3	449.9
	10	21841	247.1	16.5	221.9	244.3	321.9
JRC	**4**	23880	264.4	14.6	228.7	262.3	363.9
	5	162936	237.4	6.8	217.8	237.5	282.0
	9	33550	250.5	10.5	223.2	249.1	302.4
	10	21841	236.1	8.1	220.2	235.5	289.5

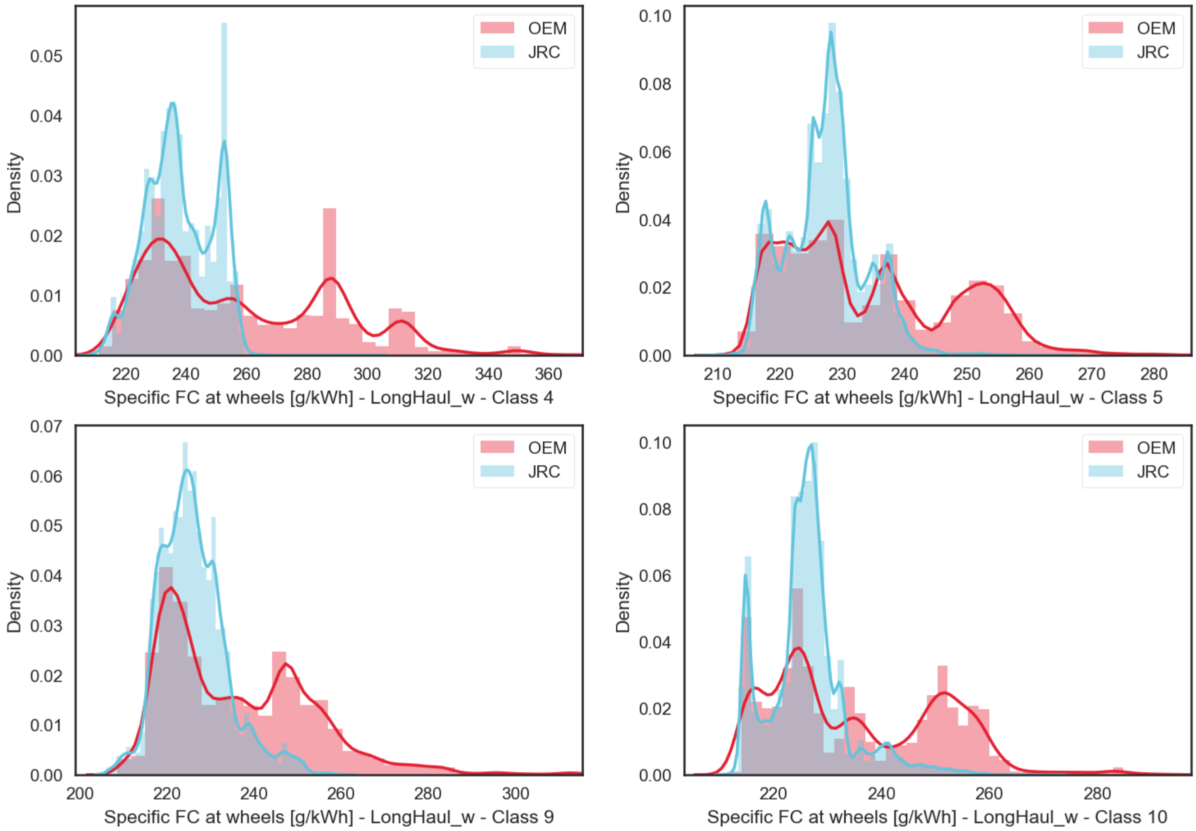


Figure 53. Specific FC at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Long Haul, weighted

Table 39. Distribution statistics. FC at wheels [g/kWh], Long Haul, weighted

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	259.1	31.9	211.1	252.3	429.2
	5	162936	234.4	13.8	210.4	229.8	352.8
	9	33550	236.5	17.4	208.5	233.0	370.3
	10	21841	235.6	15.7	212.1	232.4	305.8
JRC	**4**	23880	237.9	10.9	209.4	236.7	301.5
	5	162936	227.3	6.4	208.4	227.5	265.6
	9	33550	226.0	7.7	206.2	225.2	260.7
	10	21841	226.2	7.3	211.1	226.1	272.2

Specific CO_2 at wheels [g/kWh]

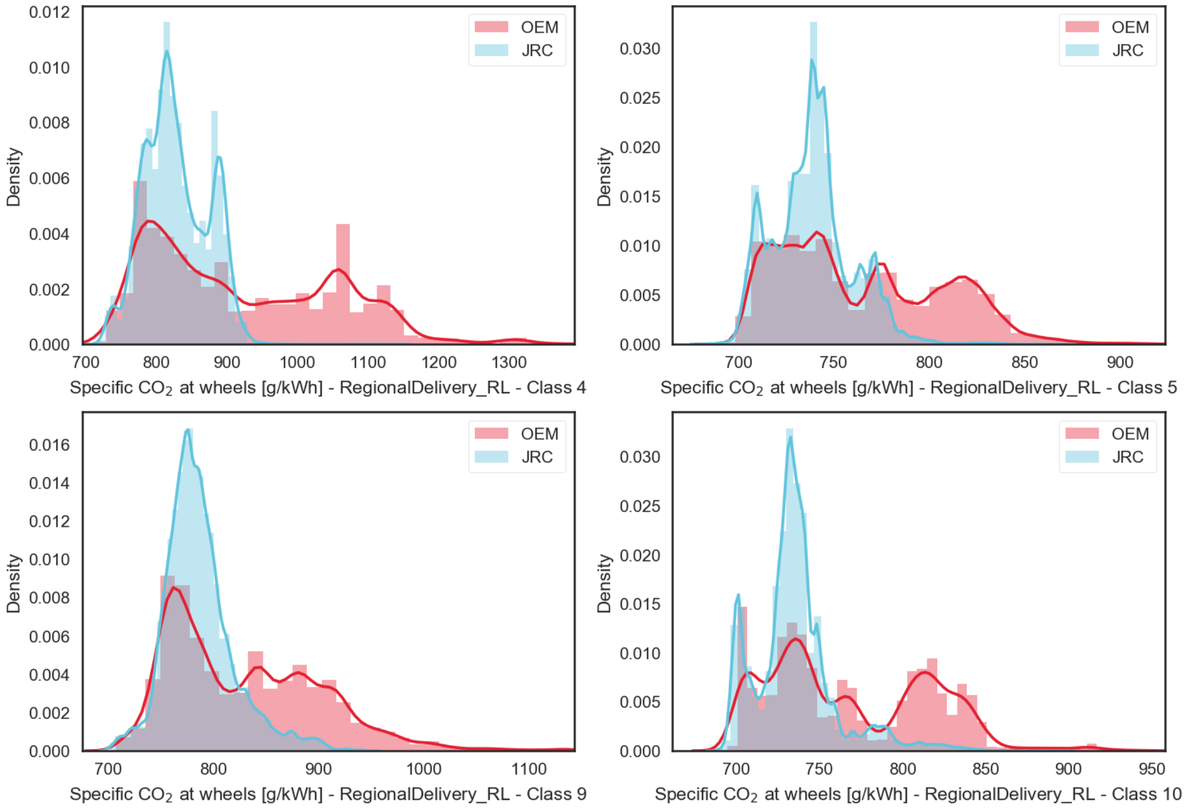


Figure 54. Specific CO_2 at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Regional Delivery, reference load

Table 40. Distribution statistics. Specific CO_2 at wheels [g/kWh], Regional Delivery, reference load

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	923.9	135.9	710.0	890.1	1669.2
	5	162936	764.9	42.9	689.6	753.7	1114.7
	9	33550	830.3	73.7	707.7	816.8	1405.1
	10	21841	768.6	48.8	694.5	758.2	995.2
JRC	**4**	23880	827.7	44.6	718.2	821.1	1139.5
	5	162936	738.7	20.8	680.0	738.5	871.4
	9	33550	786.6	33.0	702.0	782.0	948.9
	10	21841	735.0	24.5	688.2	733.2	897.4

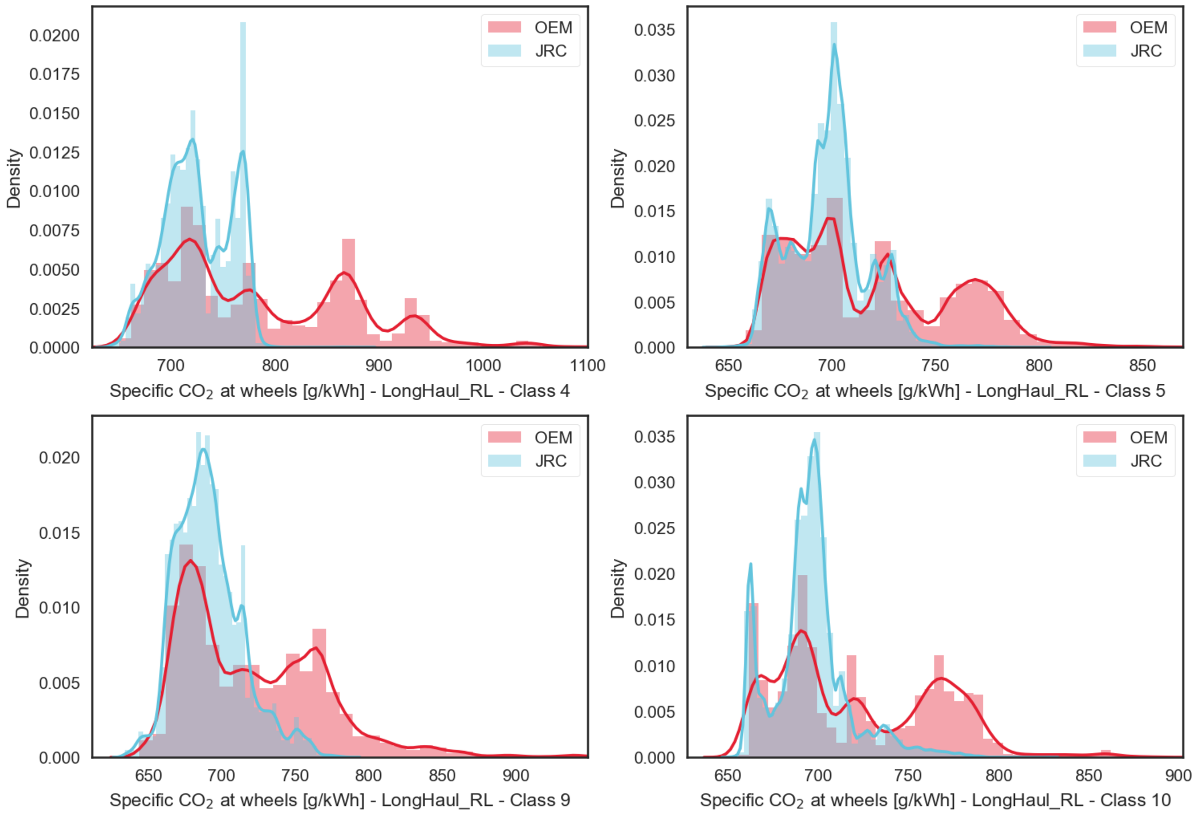


Figure 55. Specific CO_2 at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Long Haul, reference load

Table 41. Distribution statistics. Specific CO_2 at wheels [g/kWh], Long Haul, reference load

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	785.7	89.5	650.1	766.5	1246.3
	5	162936	718.9	39.5	650.6	704.7	1041.0
	9	33550	721.7	49.1	643.9	712.0	1098.2
	10	21841	722.5	44.6	656.0	715.8	927.2
JRC	**4**	23880	725.7	32.2	642.0	722.4	882.6
	5	162936	698.2	18.8	642.5	699.1	800.9
	9	33550	691.2	22.5	634.3	688.7	785.7
	10	21841	695.4	21.3	651.8	695.2	827.8

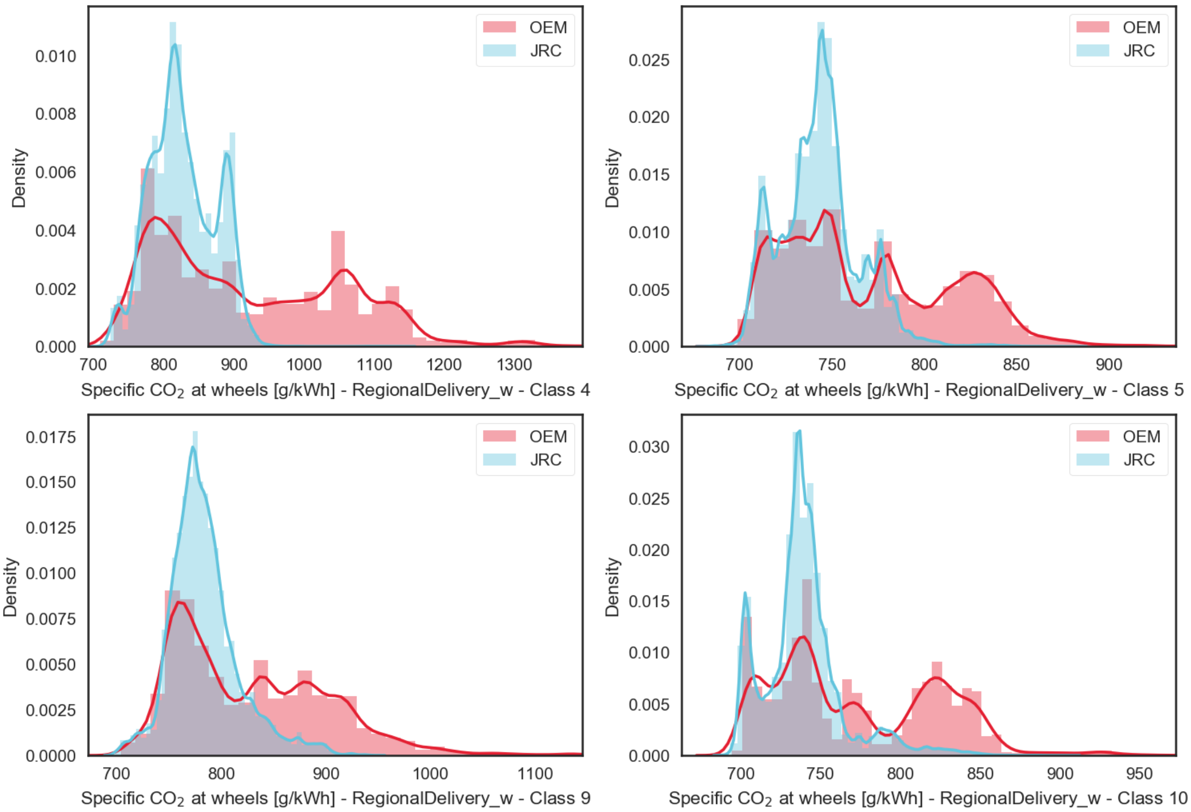


Figure 56. Specific CO_2 at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Regional Delivery, weighted

Table 42. Distribution statistics. Specific CO_2 at wheels [g/kWh], Regional Delivery, weighted

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	923.7	138.1	709.5	890.9	1677.8
	5	162936	769.9	45.5	689.6	756.1	1153.3
	9	33550	829.0	74.8	704.2	814.9	1408.2
	10	21841	773.5	51.7	694.6	764.7	1007.6
JRC	**4**	23880	827.6	45.7	715.9	821.1	1139.1
	5	162936	743.2	21.4	681.7	743.3	882.8
	9	33550	784.2	33.0	698.6	779.6	946.4
	10	21841	739.0	25.4	689.3	737.2	906.1

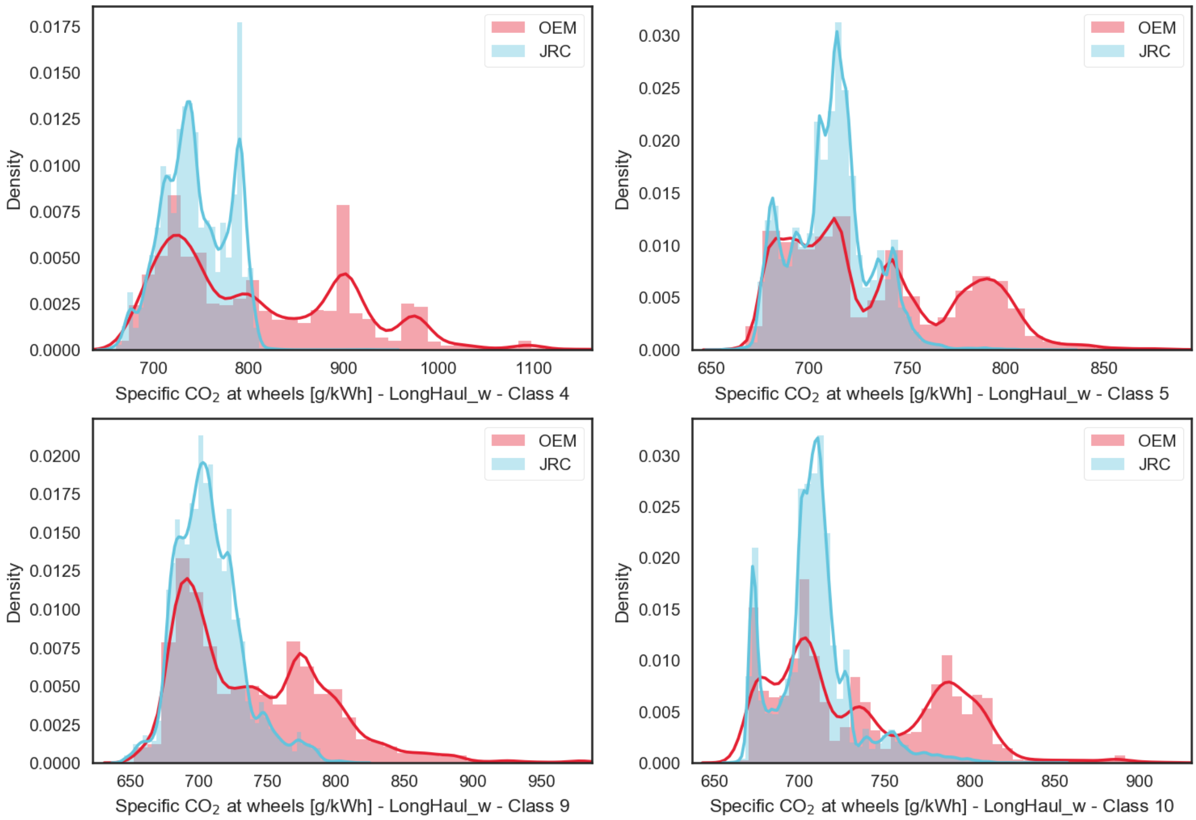


Figure 57. Specific CO_2 at wheels [g/kWh], comparison between OEM declared values and JRC normalisation. Long Haul, weighted

Table 43. Distribution statistics. Specific CO_2 at wheels [g/kWh], Long Haul, weighted

	HDV class	Counts [-]	Mean [g/kWh]	St. Dev. [g/kWh]	Min [g/kWh]	Median [g/kWh]	Max [g/kWh]
OEM	**4**	23880	811.1	99.8	660.8	789.7	1343.5
	5	162936	733.7	43.3	658.5	719.2	1104.3
	9	33550	740.2	54.4	652.7	729.4	1159.1
	10	21841	737.4	49.1	664.0	727.3	957.2
JRC	**4**	23880	744.6	34.0	655.6	740.8	943.6
	5	162936	711.3	19.9	652.2	712.2	831.2
	9	33550	707.4	24.0	645.5	704.9	815.9
	10	21841	708.0	23.0	660.7	707.6	852.0

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