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Calculating Heavy-Duty Truck Energy and Fuel Consumption Using Correlation Formulas Derived From VECTO Simulations

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Abstract

The Vehicle Energy Consumption calculation Tool (VECTO) is used in Europe for calculating standardised energy consumption and CO_2 emissions from Heavy-Duty Trucks (HDTs) for certification purposes. The tool requires detailed vehicle technical specifications and a series of component efficiency maps, which are difficult to retrieve for those that are outside of the manufacturing industry. In the context of quantifying HDT CO_2 emissions, the Joint Research Centre (JRC) of the European Commission received VECTO simulation data of the 2016 vehicle fleet from the vehicle manufacturers. In previous work, this simulation data has been normalised to compensate for differences and issues in the quality of the input data used to run the simulations. This work, which is a continuation of the previous exercise, focuses on the deeper meaning of the data received to understand the factors contributing to energy and fuel consumption. Fuel efficiency distributions and energy breakdown figures were derived from the data and are presented in this work. Correlation formulas were produced to calculate the energy loss contributions of individual components and resistances (air drag, rolling resistance, axle losses, gearbox losses, etc.) over the Regional Delivery and Long Haul cycles, given a limited number of input parameters such as vehicle characteristics and average component efficiencies. Default values and meaningful ranges of variation of these parameters obtained from the data of the fleet are also reported in this work. The importance of air drag and rolling resistance losses are highlighted since these losses account for about 70% of the energy consumed downstream the engine. Finally, based on the correlation formulas to calculate the individual energy losses, a method is presented that calculates the final energy consumption and CO_2 emissions for all the regulated HDTs classes and that does not rely on the use of VECTO.

Introduction

The CO_2 certification for Heavy-Duty Trucks (HDTs) was set to start from January 2019 [1] and the European Commission is focused on determining the current levels of CO_2 emissions of these vehicles under different operating conditions [2]. Within the context of regulating emissions, attention is also given on the primary sources of energy losses during operation and the identification of the margins for their improvement [3]. Regulators, manufacturers and other stakeholders are interested in quantifying the reduction potentials and creating realistic scenarios for technology diffusion that would promote CO_2 emissions reduction from road transport. In order to investigate the CO_2 emissions reduction potential, it was required to define a reliable reference basis for certification and monitoring, which was achieved with the development of the Vehicle Energy Consumption calculation Tool (VECTO) [4–6]. VECTO is a vehicle simulation software that calculates energy consumption (EC), fuel consumption (FC) and CO_2 emissions from HDTs. To comply with this task, and with the accuracy requested, VECTO adopts a sophisticated simulation approach that is based on certified component data and officially declared vehicle characteristics. The accuracy of this approach has been demonstrated [5,7], thus making the application of a simulation-based CO_2 regulation possible. As a second step to CO_2 emissions monitoring and reporting, the European Commission proposed future CO_2 targets for:

- HDTs class 4 (4x2 rigid trucks of above 16 tons),
- HDTs class 5 (4x2 tractor trucks of above 16 tons)
- HDTs class 9 (6x2 rigid trucks of all weights)
- HDTs class 10 (6x2 tractor trucks of all weights)

as defined in regulation (EU) 2017/2400 [8] and synthesized in Sub-Appendix 1. Within this framework, the European Heavy-Duty Vehicle (HDV) manufacturers were asked to perform VECTO simulations to calculate CO_2 emissions of their vehicle sold in the European market in 2016, as if they would have done under the upcoming CO_2 certification scheme. This exercise produced a considerable amount of data that the European Commission Joint Research Centre (JRC) processed and reported in [2]. The same database was further processed to provide more detailed information on how the energy is used in HDTs and the vehicle fleet distributions of FC and CO_2 emissions were reported. Building on the data and the findings of the study mentioned above, the present paper provides a methodology for EC, FC and CO_2 emissions of HDT without the need to run full VECTO simulations. The motivation for developing such a methodology is to create a basis for quick calculations of HDT energy efficiency when the necessary data to run VECTO simulations are not available. Furthermore, the approach can be potentially used to compare a posteriori the results of different VECTO simulations. The method is based on correlation formulas and other simple calculations derived from the VECTO data provided to the JRC for the 2016-model-year vehicles and reflects the fleet-wide performance and energy efficiency. In addition, it requires a smaller number of inputs compared to VECTO and no tabular data (such as component efficiency maps). Indicative default values are proposed for consultation and use in case appropriate input data is missing. The study first focuses on the models developed to calculate the contributions to total energy consumption. Subsequently, it also proposes a methodology for producing the final FC and CO_2 emissions for the metrics of interest. A first validation of the method is presented together with an analysis of the expected accuracy. The paper concludes with the main observations drawn from the activity.

Reference 2016-fleet data

The database of VECTO simulation results from the manufacturers contains 1 716 928 records; it includes the simulation results for every vehicle introduced in the EU market in 2016 over different mission profiles (different cycle-loading combinations). Just 985 014 records of this sample are related to the cycles of interest of this study: the Regional Delivery (low and reference loading) and the Long Haul (low and reference loading). These cycle-loading combinations are referred to as RegionalDelivery_LL, RegionalDelivery_RL, LongHaul_LL and LongHaul_RL.

Energy consumption

The data-treatment process described in [2] resulted in a collection of EC data of individual components/sources of energy loss and CO_2 emissions from vehicles. This information was also used to calculate how energy is dissipated in the different vehicles and what are the CO_2 emissions for each cycle-loading and HDV class (4, 5, 9 and 10) combination. There are wide variations in energy consumption depending on the various vehicle types and mission profiles. Figure 1 provides a generalised EC picture for the Regional Delivery and the Long Haul cycles considering all loading conditions and vehicle classes. For more representative EC scenarios, please refer to the results for each of the subgroups mentioned above reported in Sub-Appendix 2.

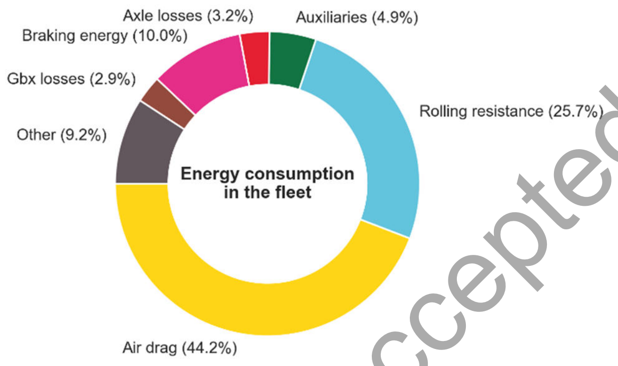

Figure 1. Fleet-averaged energy consumption downstream the engine

The picture highlights the impact that air drag and rolling resistance have on EC, which account for about 70% of the total EC downstream the engine (engine energy conversion efficiency not taken into account), and as a consequence also on the final FC (Fuel Consumption) and CO_2 emissions. According to this finding, we can conclude that to calculate the fuel efficiency of an HDT with reasonable accuracy, the way the air drag and rolling resistance losses are modelled and the quality of the input data are of high importance.

Fuel consumption and CO_2 emissions

Figure 2 presents the distribution of fuel consumption by class and loading conditions, while Figure 3 presents the respective CO_2 emissions distributions. Additional statistical values that describe the distributions (mean, standard deviation, min and max) are reported in Sub-Appendix 3. From the presented distributions, we can conclude that:

- Increased loading turns into an increase of the average value of the distribution, while the shape is preserved
- The Long Haul cycle has a higher energy request compared to the Regional Delivery cycle
- FC/CO_2 is lower for rigid trucks in the Regional Delivery cycle (the simulation is performed without trailers) and for tractors in the Long Haul cycle, as they generally have lower CdA

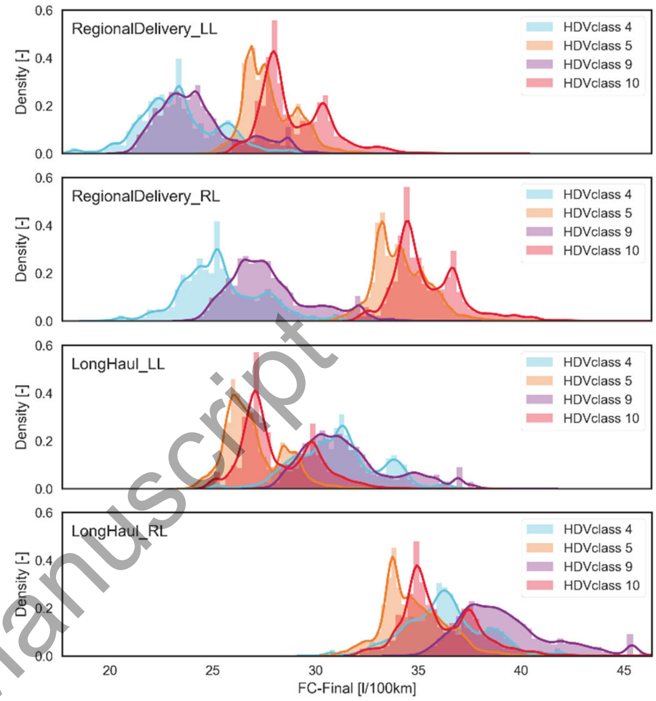

Figure 2. Fuel consumption [l/100km] distributions

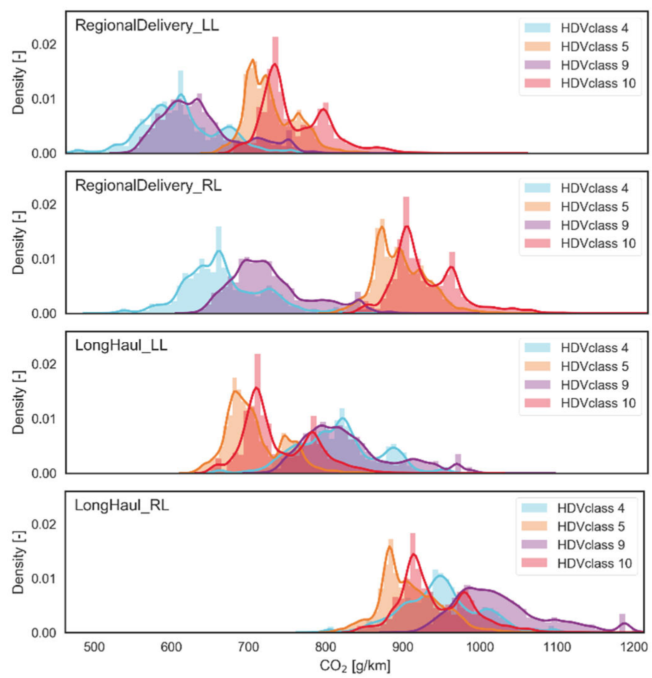

Figure 3. CO_2 emissions [g/km] distributions

Some of the distributions are multi-modal, e.g. HDV class 10. The factor triggering this behaviour was found to be the air drag losses, which are also multi-modal. The authors assume that the vehicles of this class are clustered in two different groups having significantly different CdA values, but the reason lying behind these differences could not be investigated further due to lack of information. When calculating CO_2 emission from HDT, measures have to be taken in order to address correctly the estimation of losses by capturing all the factors that might account for big deviations in the results. In this case, knowing the vehicle CdA ensures that this behaviour is captured.

Methodology

This section summarises the methodology developed to estimate the EC and FC of HDTs of the Classes 4, 5, 9 and 10 without the need for detailed component efficiency maps and the use of time- and resource-consuming simulations. The approach relies on simple correlation formulas between individual EC sources and vehicle/components/mission parameters. The correlation formulas have been derived from the received VECTO data from the vehicle manufacturers for corresponding model year 2016. A filtering of the data was applied to remove outliers that would affect the accuracy of the developed fitting functions. The assumptions made are explained in the subsequent sections.

Overview, datasets and main assumptions

The methodology follows a step-wise process that begins with the calculation of the individual component energy consumptions that take place downstream of the driveline, at wheels level, and follows the energy flow upstream, ending with the calculation of the total positive energy produced at the engine and the related FC and CO_2 emissions. All the definitions used in this work to refer to vehicle/component technical specifications and energy balance are presented in Table 6 (Sub-Appendix 1). Some assumptions had to be made with respect to the driveline architecture in order to be consistent with the calculation of losses. Figure 4 presents the driveline layout in consideration and the location where energy losses take place. In particular, the retarder was considered to be of the "secondary retarder" type, as appears in VECTO; the component is named "transmission output retarder" in Commission Regulation (EU) 2017/2400 [8], meaning that its position in the driveline lies between the gearbox and the axle. No angle drive component was considered to be part of the driveline, because of their marginal share in the truck fleet. Vehicles equipped with fully automatic gearboxes (defined "ATSerial" in [8]) were excluded from the study since the amount of data available in VECTO simulations was not enough to draft a reliable correlation formula. Hence, losses related to these components were not considered (E_angle for angle drives, E_tc_loss and E_shift for fully automatic gearboxes). For vehicles equipped with manual transmission (MT) or automated manual transmission (AMT), the energy loss due to the operation of the clutch was considered to be negligible and for this reason, excluded from the calculation. Since the cycles considered for the analysis are exclusively the Long Haul and the Regional Delivery ones, the energy losses due to Power Take-Off (PTO) devices was also neglected at this stage. The following criteria were used to filter out possible outliers and non-valid simulation runs from the original 2016 sample:

1. Aborted simulations (exclusion of 5 447 records)
2. Simulations with very low average cycle speed (exclusion of 7 671 records)
3. Unrealistic axle losses (exclusion of 361 624 records)
4. Missing vehicle CdA (exclusion of 101 870 records
5. Automatic gearboxes (exclusion of 5 002 records).

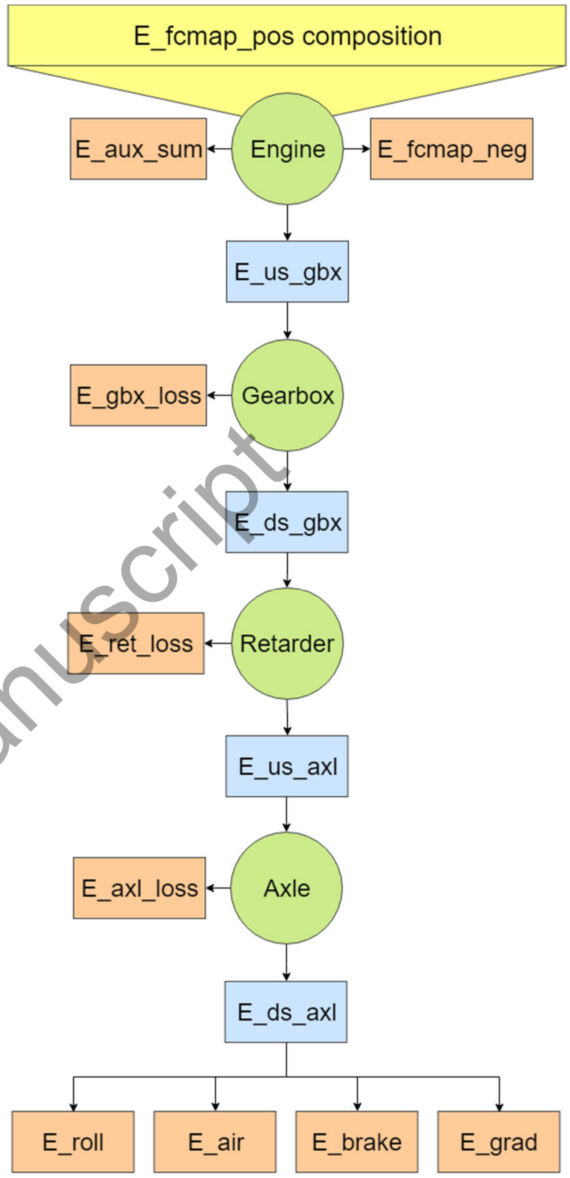

Figure 4. Driveline scheme and energy loss points

A detailed explanation for point 3 can be found in [2], which analyses how the use of default input values in manufacturers' simulations led to an inflation of the energy consumption. Concerning point 4, the criteria excludes the cases for which it was not possible to calculate a trusted vehicle CdA, needed for the correlation with air drag losses. The filtering process resulted in the rejection of 481 614 records, ending up with a dataset of 503 400 simulations that was used for extracting the relationships and building the methodology.

The Python programming language was used to handle and analyse the datasets and create plots, mainly using *pandas*, *numpy* and *matplotlib* libraries. To perform the fits *scipy.optimize.curve_fit* tool was used.

Applicability and limitations

The methodology presented in this section can be applied to estimate the positive energy demand at the vehicle engine (E_fcmap_pos), FC and CO_2 emissions that VECTO would calculate for the following mission profiles:

- Regional Delivery, low and reference loading
- Long Haul, low and reference loading

for the following classes of HDT (*vehicle group code*)

- HDTs class 4, 5, 9, 10

and for vehicles complying to the following characteristics

- Vehicles equipped with MT or AMT not featuring angle drives
- Vehicles that would manage to run the mission profiles with average speeds above specific limits
    - 58 km/h in the Regional Delivery Cycle
    - 75 km/h in the Long Haul Cycle

Vehicles whose characteristics and performances are distinctively different from what listed above might end up with very big deviations from the result that VECTO would calculate. Nevertheless, the applicability of the method can be extended by revising the calculation process, fitting it to out-of-design conditions. Each of the sub-models described in this paper can be replaced with other models fitted ad-hoc by the user, the calculation process can be started again from that point and followed until the calculation of the final results or the step where another model is replaced.

As part of the study, this paper introduces also generic data in the form of formulas, distributions, punctual values and/or ranges, which are presented in the Appendix.

Individual sources of energy loss

This section explains how to calculate the relevant sources of energy loss in HDTs over the regulated mission profiles. A flow chart summarising the process is available in Sub-Appendix 4 (Figure 21). The order used for presenting the models starts from the losses occurring downstream the driveline (bottom of Figure 4) and proceeding towards the engine. The accuracy of the individual modelling approaches is presented in the Results section.

Rolling Resistance Losses (E_roll)

As discussed before, rolling resistance is a major source of energy dissipation in HDTs, and for this reason, its calculation should be as accurate as possible. For the development of the correlation formula, the study investigated the dependency of E_roll with two input parameters: total vehicle Rolling Resistance Coefficient (RRC) and total vehicle mass (m). Total RRC calculation formula is presented in [9] and partly explained in [2], while the definitions of the parameters needed are reported in [8]. Since rolling resistance is a matter of primary importance, Sub-Appendix 5 presents a detailed explanation of the process.

E_roll, the energy consumed for rolling resistance is correlated to total RRC and total vehicle mass as depicted in Figure 5. The simpler and better performing correlation was found to be the following:

$$\text{E\_roll fit} = a * RRC * m \quad (1)$$

where E_roll fit is in kWh, RRC is non-dimensional, m is in kg and a is the parameter obtained with the fit (a = 0.272677).

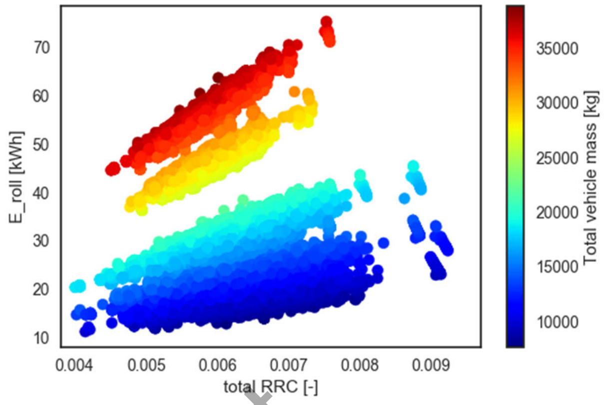

Figure 5. E_roll correlation with total RRC [-] and Total vehicle mass [kg]

Aerodynamic Losses (E_air)

Aerodynamic resistance is also a major source of EC in HDTs. To capture the energy consumed to overcome aerodynamic resistances (E_air value), the dependency of the air-drag (product of frontal area with aerodynamic drag coefficient – CdA) and average vehicle speed was considered for all simulated vehicles. Since for different truck types, rigid trucks or tractors, the mission profiles simulated imply different vehicle configurations and different speed profiles (rigid trucks are simulated with a trailer in the Long Haul, while just the rigid body is considered for the Regional Delivery), a set of fitting parameters for each truck-type and cycle combination was produced. An example of the correlation for rigid vehicles in the Long Haul cycle is reported in Figure 6.

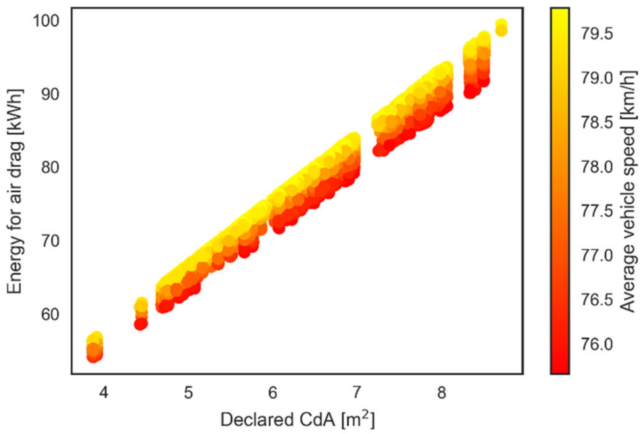

Figure 6. E_air correlation with CdA [m^2] and actual average vehicle speed [km/h] for rigid trucks in the Long Haul cycle

The fitting formula, which applies to all the sets of parameters is

$$\text{E\_air fit} = a + b * CdA + c * \overline{speed} + d * CdA * \overline{speed} \quad (2)$$

where E_air fit is in kWh, CdA is the drag area in m^2 of the vehicle without any trailer (*Declared CdxA [m²]* field from VECTO simulation output), $\overline{speed}$ is the actual average speed in the cycle in km/h (*speed [km/h]* field from VECTO simulation output) and a, b, c, d are the parameters obtained with the fit for every truck-type and cycle combination (4 sets of parameters, reported in Sub-Appendix 6).

Energy dissipated during braking (E_brake)

The energy dissipated in braking is the third most important source of energy losses. This quantity is for sure influenced by how much the driving cycle is dynamic, which defines the frequency and intensity of braking phases, the weight of the vehicle, that influences the kinetic energy to be dissipated, but also the total vehicle resistance to motion was found to have a contribution. This finding can be explained by the fact that vehicles with very high rolling resistance and air drag resistance will have high natural deceleration force that will contribute to braking operations. As a consequence, the braking power required will be reduced. To better correlate the braking energy with the variables described, and to account for differences in cycle dynamics, a set of fitting parameters was produced for every cycle-loading combination (4 sets). The correlation formula took into consideration, for the aforementioned reasons, the total vehicle mass (with standard bodies and loading) and the sum of the E_roll and E_air, as shown in Equation (3). The E_roll and E_air values were taken from VECTO simulations and not from the fits presented in the previous sections since for the development of the correlation it was required to reach the best possible accuracy.

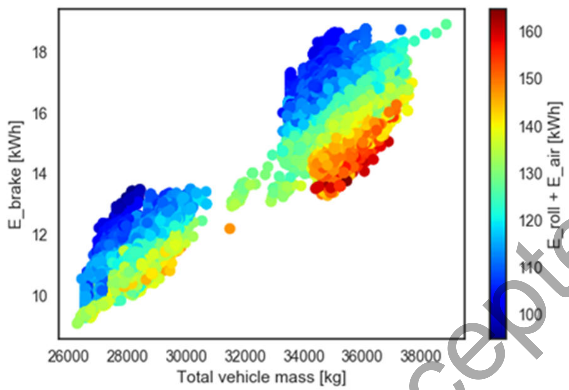

Figure 7. E_brake correlation with total vehicle mass [kg] and the sum of E_roll and E_air [kWh] from VECTO simulations for the Long Haul Reference Load cycle

Equation (3) describes the formula that was used for the fit:

$$\text{E\_brake fit} = a + b * m + c * (\text{E\_roll+E\_air}) + d * m * (\text{E\_roll+E\_air}) \quad (3)$$

Where m is the total vehicle mass (vehicle with standard bodies and trailers) in kg, E_roll + E_air is expressed in kWh, and a, b, c, d are the parameters produced with the fit (one set for each cycle-load combination, reported in Sub-Appendix 5). When applying the method to calculate E_fcmap_pos, Equation (3) will have to be used with the sum of E_roll and E_air calculated in equations (1) and (2).

Potential energy (E_grad)

This EC source is only justified when the application of the method has the goal of getting as close as possible to the VECTO result. In the case the method is applied to estimate the EC for mission profiles different from the cycles presented in this paper, the E_grad will have to be adjusted accordingly to reflect the difference in potential energy from the specific condition. The E_grad that VECTO calculates, as expected, was found to be correlated to the cycle and to the total vehicle mass, according to Figure 8. As can be seen in the charts, the contribution to the total EC is small. Nevertheless, it is possible to improve the accuracy of the estimation of the EC at the end of the driveline, where any source of inaccuracy will propagate in the calculations of the upwards energy terms. The formula to calculate the E_grad is presented here:

$$\text{E\_grad} = m * g * h \,/\, 3.6\text{E+6} \quad (4)$$

where m is the total vehicle mass in kg, g is the gravitational acceleration (9.81 m/s^2) and h is the difference in height specific of the cycle, which from the calculations results in 7.33 m for the Regional Delivery and -2.42 m for the Long Haul.

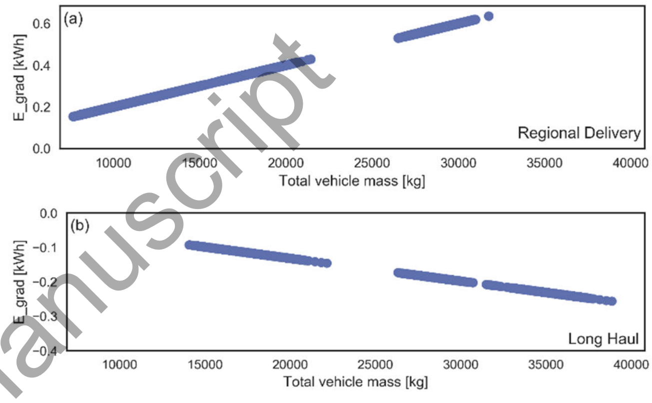

Figure 8. E_grad correlation with total vehicle mass [kg] for the Regional Delivery (a) and Long Haul (b)

Axle losses (E_axl_loss)

The energy flow downstream (E_ds_axl) of the axle is the sum of the previously discussed energy losses.

$$\text{E\_ds\_axl} = \text{E\_roll} + \text{E\_air} + \text{E\_brake} + \text{E\_grad} \quad (5)$$

Axle losses (E_axl_loss) have been found to be a function of the energy flowing inside the axle component, and hence linked to the energy upstream the axle (E_us_axl), as shown in equation (6):

$$\text{E\_us\_axl} = \text{E\_ds\_axl} + \text{E\_axl\_loss} \quad (6)$$

Axle losses were linked to average axle efficiency η_{axl} as well, as calculated in [2] and reported here:

$$\eta_{axl} = \frac{\text{E\_ds\_axl}}{\text{E\_us\_axl}} = 1 - \frac{\text{E\_axl\_loss}}{\text{E\_us\_axl}} \quad (7)$$

Finally, the correlation between E_axl_loss, E_us_axl and η_{axl} is presented in Figure 9. The formula used for the fitting of the data is the following:

$$\text{E\_axl\_loss fit} = a + b * \eta_{axl} + c * \text{E\_us\_axl} + d * \eta_{axl} * \text{E\_us\_axl} \quad (8)$$

where a, b, c, d are the parameters generated with the fitting. The correlation is good, as the parameters used for the correlation are both linked to the same E_axl_loss.

For the development of the E_axl_loss correlation, the mutual dependency of its inputs and outputs was not an issue, since both values were known. This is not the case when the method has to be applied to move from the energy consumed downstream the axle to the one upstream the axle. A way to get out of this self-referencing loop is by iterating the calculation of axle losses until convergence is reached. At the start of the iteration process, E_us_axl is set equal to E_ds_axl, and by knowing the η_{axl} a first value of E_axl_loss is found. In the second iteration, the resulting E_axl_loss from the previous iteration is added to E_ds_axl, the sum of the two is used as the E_us_axl value for the correlation, returning an updated value of E_axl_loss. This process can be repeated as many times the user wants to reach higher accuracy. Usually, one or two iterations are enough to reach an accuracy that complies with the objective of the method. The final value obtained for E_axl_loss is the one summed to E_ds_axl to obtain the E_us_axl. With regards to the value to use for η_{axl}, this can be taken from other sources that the users might have at disposal, such as VECTO simulations of similar trucks for which such parameter can be calculated, or specific axle models or efficiency values taken from literature or through another approach. Sub-Appendix 6 contains a pivot table of axle efficiency statistics (per cycle-loading combination and HDV class) found for a subset of the database, where the condition used for filtering excludes the records associated with low quality input for axle losses simulation. Such measure should return a meaningful picture of real-use axle efficiency, from which default values can be derived according to the preferences of the user.

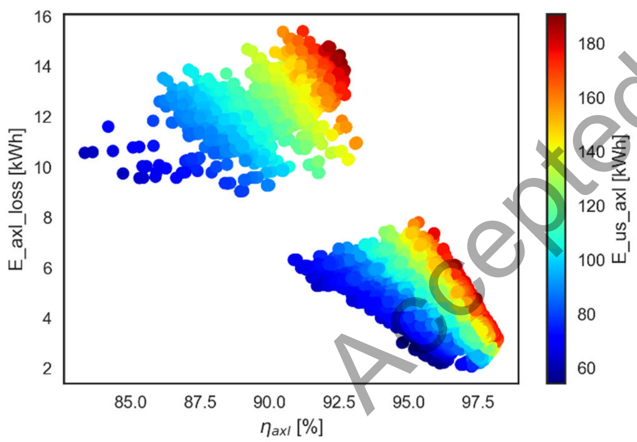

Figure 9. E_axl_loss correlation with η_{axl} [%] and E_us_axl [kWh]

Energy dissipated in the retarder (E_ret_loss)

VECTO provides three ways to calculate energy losses from retarders, according to the retarder type defined in the input files: *None* implies that the energy loss is zero, *Included in Transmission Loss Maps* implies that the energy loss is taken into account elsewhere, lastly *Secondary Type* that triggers the calculation of losses for a secondary retarder. The analysis performed on the impact of the retarder type on total losses from gearbox and retarder (to account for retarder losses included in the transmission loss map) returned an unclear trend. However, analysing a subset of records in which the retarder losses are linked to specific retarder models available on the market (hence losses were not produced by using default retarder losses models), it was possible to understand that E_ret_loss are small compared to total vehicle EC from the Long Haul and Regional Delivery cycles. In most of the cases, E_ret_loss was found to be between 0.2 and 0.5 kWh, values obtained by selecting the records associated with the best data quality for transmission losses, to ensure accuracy. Interestingly, the analysis revealed that vehicles that are equipped with retarders showed increased energy losses at the gearbox. Values of energy losses from retarders and from retarders and gearboxes combined are reported in Table 14. It is expected that whenever a retarder is considered, default values from Table 14 with regards to E_ret_loss are derived and that the energy dissipated in the gearbox (E_gbx_loss, presented in the next step) complies with the ranges presented in the same table (sum of E_gbx_loss and E_ret_loss).

Gearbox losses (E_gbx_loss)

The calculation of the energy losses at the gearbox is similar to the one presented for axle losses. Energy downstream the gearbox is calculated as follows:

$$\text{E\_ds\_gbx} = \text{E\_us\_axl} + \text{E\_ret\_loss} \tag{9}$$

Gearbox losses are also in this case function of the energy upstream the gearbox presented in equation (6):

$$\text{E\_us\_gbx} = \text{E\_ds\_gbx} + \text{E\_gbx\_loss} \tag{10}$$

Gearbox losses were linked to average gearbox efficiency η_{gbx} as well, as calculated in [2] and reported here:

$$\eta_{gbx} = \frac{\text{E\_ds\_gbx}}{\text{E\_us\_gbx}} = 1 - \frac{\text{E\_gbx\_loss}}{\text{E\_us\_gbx}} \tag{11}$$

The correlation between E_gbx_loss, E_us_gbx and η_{gbx} is presented in Figure 10. The formula used for the fitting of the data is the following:

$$\text{E\_gbx\_loss fit} = a + b * \eta_{gbx} + c * \text{E\_us\_gbx} + d * \eta_{gbx} * \text{E\_us\_gbx} \tag{12}$$

where a, b, c, d are the parameters generated with the fitting that apply to every vehicle type and mission profile.

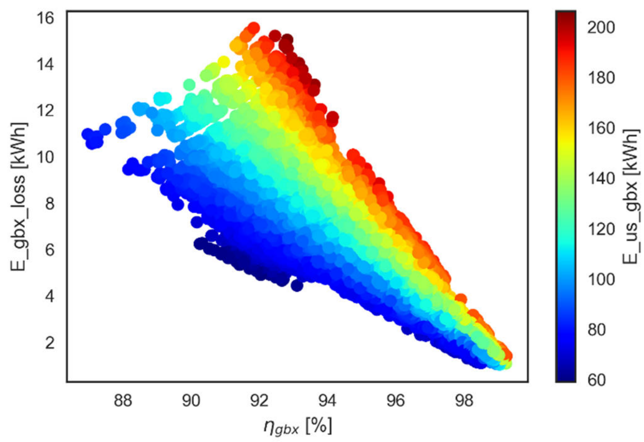

Figure 10. E_gbx_loss correlation with η_{gbx} [%] and E_us_gbx [kWh]

Also, in this case, the calculation of E_gbx_loss has to be performed iteratively as explained in the axle losses section (see also Figure 21). In this case, one or two repetitions are enough to reach acceptable accuracy. Sub-Appendix 6 includes a pivot table of gearbox efficiency statistics (per cycle-load combination and HDV class) that should be representative of real-use condition, from which default values can be derived.

Auxiliaries (E_aux_sum)

EC from auxiliaries depends on the cycle and the combination of auxiliaries used. VECTO foresees five auxiliary system types: pneumatic system (PS), steering pump (STP), engine fan (FAN), electric system (ES) and air conditioning (AC). The solution chosen for the last two has a small impact on the final E_aux_sum, so they were excluded from the analysis. A table reporting the different E_aux_sum for each combination of PS, STP and FAN auxiliaries is reported in Sub-Appendix 6 (Table 17). In order to generalise the EC from auxiliaries, baseline energy consumptions of 5.6 and 6.6 kWh could be considered for the Long Haul and Regional Delivery cycle respectively. In case the PS technology "Large Supply" is used, without being complemented with other energy saving systems (ESS, AMS or clutches), these values have to be incremented by 4.7 kWh approximately[1].

Engine motoring (E_fcmap_neg)

Energy dissipated during engine motoring phases (E_fcmap_neg) is particularly important for HDTs. E_fcmap_neg is different for each engine and difficult to generalise. The correlation of E_fcmap_neg with engine size (power or displacement) and operating conditions during the VECTO simulation was attempted, and the formula that best fitted was found to be the following:

$$\text{E\_fcmap\_neg fit} = a + b * P_{eng} + c * \text{n\_eng\_avg} + d * P_{eng} * \text{n\_eng\_avg} \qquad (13)$$

Where P_{eng} is engine maximum rated power in kW, n_eng_avg is average engine speed in the cycle in rpm, and a, b, c, d are the parameters obtained from the fit (one set of parameters for each cycle-load combination, reported in Sub-Appendix 6). When the average engine speed is unknown or cannot be estimated, the information of Figure 22 in Sub-Appendix 6 could be used. The correlation existing among the variables is presented in Figure 11 for the Long Haul Reference Load cycle. As shown in the figure, combining engine rated power and average engine speed over the different cycles does not fully reproduce the friction losses, and still, a dependency from the engine model can be seen (each vertical cluster corresponds to a different engine model). Anyhow, the use of engine rated power captures the increasing trend of E_fcmap_neg, whereas the impact of n_eng_avg is clear for some operational points associated with very high engine speeds and unclear for low engine speeds. A more complex physical model that takes into account engine characteristics would have to be developed to obtain good accuracy from the calculation of E_fcmap_neg. However, this is outside of the scope of this paper since the deviations between the simulated E_fcmap_neg and the one obtained with the fitting did not exceed ±2 kWh for 98% of the observations, thus the method was considered to be good enough for the accuracy required.

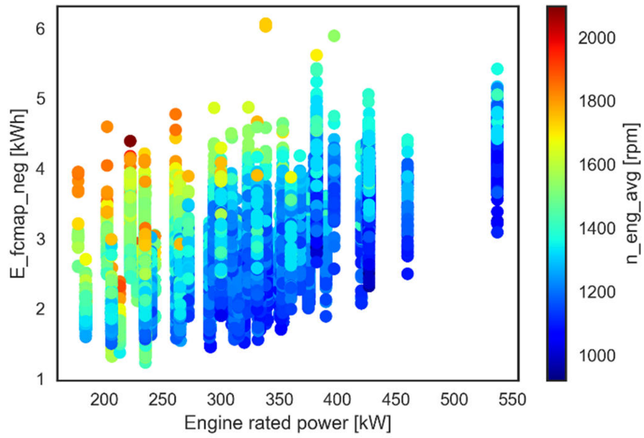

Figure 11. E_fcmap_neg correlation with engine rated power [kW] and n_eng_avg [rpm]

Engine positive energy output

The positive work produced by the engine over the cycle (E_fcmap_pos), is the sum of all energy losses presented in this section.

$$\text{E\_fcmap\_pos method} = (\text{E\_roll} + \text{E\_air} + \text{E\_brake} + \text{E\_grad} + \text{E\_axl\_loss} + \text{E\_ret\_loss} + \text{E\_gbx\_loss} + \text{E\_aux\_sum} + \text{E\_fcmap\_neg}) \qquad (14)$$

The E_fcmap_pos obtained can be used to calculate the relative weight of each of the energy loss sources calculated in the previous steps to check for consistency (see for example the charts in Sub-Appendix 2).

Calculation of CO_2 emissions

Once the E_fcmap_pos is calculated, it is possible to obtain the respective fuel consumption (FC) and CO_2 emissions by considering a meaningful value for the engine efficiency and by applying conversion formulas. Given the average engine efficiency over the cycle η_{eng}, the total energy that the fuel has to provide is calculated as follows:

$$\text{E\_fuel}\ [kWh] = \frac{\text{E\_fcmap\_pos}}{\eta_{eng}} \qquad (15)$$

Given a fuel type, the relative Low Heating Value (LHV) and carbon to hydrogen ratio, and considering the distances driven in the regulated cycles (which is 100 km both for Regional Delivery and Long Haul in the latest VECTO versions), is then possible to derive all the metrics of interest. Generic values for engine efficiency are

[1] These values have been derived by considering the first six rows of Table 17, which account for 91.5% of the vehicles considered in the analysis, and the seventh row, which is the special case of PS auxiliary of the "Large Supply" type, which has increased EC and accounts for 1% of the considered fleet, approximately. The remaining vehicles have EC from the auxiliaries very similar to the one of the baseline condition.

presented in [2] (Annex 4, page. 60) for every cycle-loading, HDV class, and input data quality for engine losses.

For a more detailed engine modelling approach, which takes into consideration the engine operating condition for the estimation of the efficiency, the authors suggest to consult [10]. This approach relies on the concept of BMEP-FuMEP lines explained in [2], in which these lines were produced for every engine found in the VECTO data of the fleet, and whose result is an FC map that ensures good accuracy in estimating FC of HDTs in VECTO cycles. In the new approach from [10], the slopes and offset of the lines obtained for every engine of the fleet were generalised and presented for engine clusters. With such a model, it is possible to generate an FC map by knowing just two inputs: engine capacity and maximum torque.

Evaluation of the method

In this section, it was first analysed the goodness of the fits and as a second step, the capacity of the method to reproduce the original CO_2 emissions of the fleet was investigated.

Goodness of the fits

For every record of the database of vehicles simulations, the EC was calculated using the models based on fittings: E_roll, E_air, E_brake, E_axl, E_gbx and E_fcmap_pos. For the obtained values, it was calculated the relative error from the same VECTO value. The distributions of such errors were calculated as the relative difference between the value from the fit and the value from VECTO as presented in Figure 12.

Table 1 presents the statistics for the same distributions, where the statistics of the errors obtained with the other models (E_grad and E_aux_sum) are also presented. No results for the energy loss in the retarder (E_ret_loss) have been presented since the investigation was unable to develop a methodology with the available data to generalise this aspect with reasonable accuracy, which was considered however to have a minor impact. All the proposed models have a mean relative error close to zero, with the exceptions of E_aux_sum and E_fcmap_neg, which might need some further tweaking. The accuracy of the results is still considered to be acceptable for the purpose of the method proposed in this paper.

Validation of the method on the data of the fleet

The method explained in the previous section and presented in the flow chart in Figure 21, was applied to the entire database of vehicles that was used to derive the EC data and the correlations. The inputs used to test the method, according to the section in which the methodology is presented, are listed here: HDT class and type (rigid or tractor), total RRC, total vehicle mass, CdA, average speed in the cycle, axle and gearbox average efficiency, retarder type, average engine speed in the cycle, engine rated power and auxiliary technology PS type. The calculation started with the estimation of the energy losses at wheel level and followed upwards the driveline. Each of the subsequent steps was based on the values calculated in the previous ones. The assumption taken regarding the E_ret_loss is that this value is always zero except for those records associated with retarder of the "Secondary Retarder" type, for which the losses have been fixed to 0.3 kWh to match the two most energy consuming retarder types presented in Table 14, *Retarder B* and *Secondary water retarder*, which account for a much bigger penetration compared to *Retarder C*.

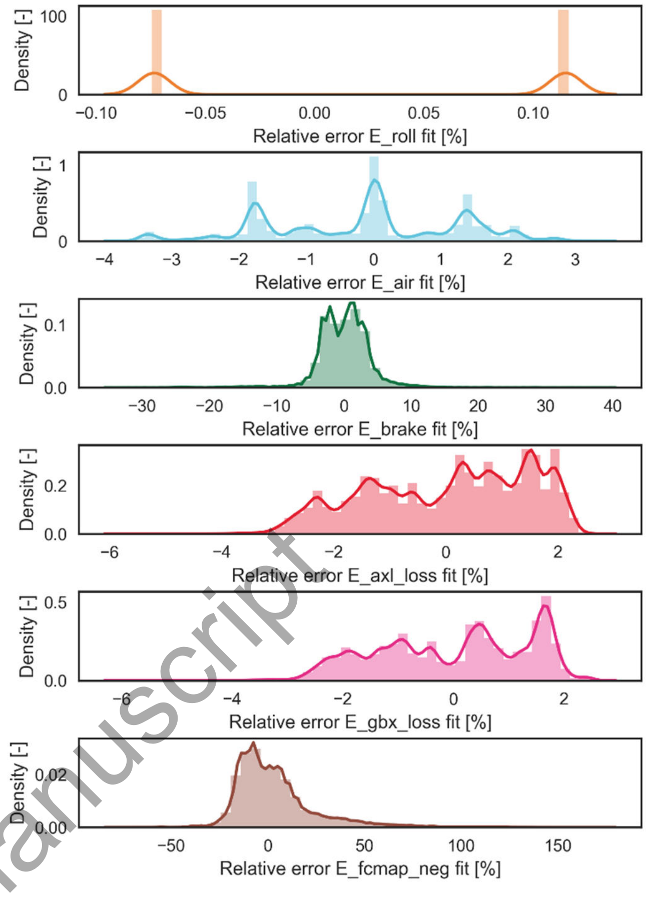

Figure 12. Distributions of energy consumption deviations between the results of the fits and VECTO

Table 1. Statistics of deviations [%] between the results of the energy consumption models and VECTO

Deviation [%]	mean	std	min	25%	50%	75%	max
E_roll	0.021	0.094	-0.074	-0.073	0.114	0.115	0.116
E_air	-0.159	1.401	-3.681	-1.445	-0.008	1.165	3.286
E_brake	0.03	3.831	-34.832	-2.199	0.222	2.236	39.683
E_grad	-0.107	0.023	-0.177	-0.124	-0.1	-0.089	-0.06
E_axl_loss	0.051	1.429	-5.765	-1.166	0.292	1.337	2.708
E_gbx_loss	-0.001	1.358	-5.997	-1.103	0.254	1.264	2.627
E_aux_sum	-1.618	9.973	-23.824	-13.902	0.805	7.356	22.095
E_fcmap_neg	3.273	20.584	-81.019	-10.332	-1.033	10.436	176.544

No correction to E_gbx_loss for the vehicles equipped with a secondary retarder was taken into account. The results produced by the method are compared with the VECTO values in Figure 13, in which a very good matching is highlighted. The method is found to be accurate for the different vehicle types and throughout all the range of E_fcmap_pos. The relative error distribution is presented in Figure 14 and additional information are presented in Table 2. The resulting mean relative error is -0.243%, meaning that the model is underestimating the EC due to a systematic error.

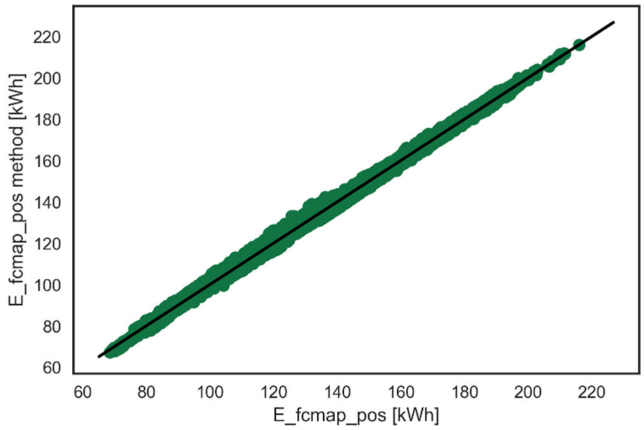

Figure 13. Comparison between E_fcmap_pos obtained from VECTO simulations (x axis) and from the method (y axis)

This is probably due to the systematic error in the estimation of E_air, which is also on the negative side and accounts for a large part of total vehicle EC downstream the engine. Despite this deviation, the result can still be considered acceptable.

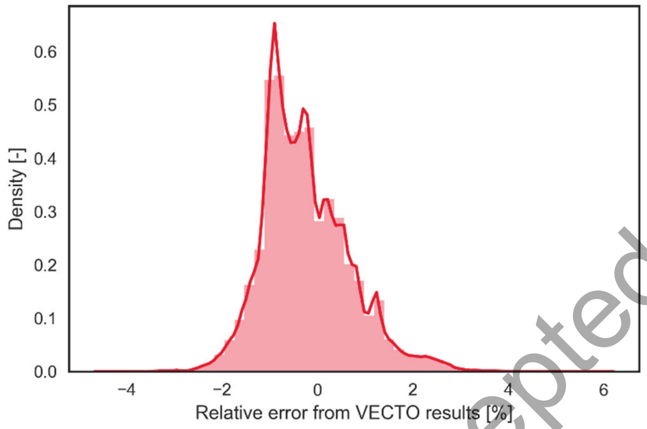

Figure 14. Distribution of the relative error of E_fcmap_pos calculated with the method

Table 2. Statistics for the distribution of the relative error of E_fcmap_pos calculated with the method

	Relative error [%]
mean	-0.243
std	0.901
min	-4.459
25%	-0.892
50%	-0.366
75%	0.301
max	5.998

Validation of the method on VECTO generic vehicle

The method was also tested using the data of the class 5 generic vehicle that is included with the VECTO installation files. The information needed to apply the method was derived from the VECTO input files, complemented with other engineering guesses and is presented in Table 3.

Table 3. Inputs for VECTO class 5 generic vehicle

Total RRC [-]	RegionalDelivery_LL	0.006266
	RegionalDelivery_RL	0.005873
	LongHaul_LL	0.006256
	LongHaul_RL	0.005984
Total vehicle Mass [kg]	RegionalDelivery_LL	18329
	RegionalDelivery_RL	35029
	LongHaul_LL	18329
	LongHaul_RL	28629
Declared CdA [m^2]	5.3	
Average speed [km/h]	60 for Long Haul, 80 for Regional Delivery	
Axle efficiency	96% (derived from tables in Sub-Appendix 6)	
Gearbox efficiency	98% (derived from tables in Sub-Appendix 6)	
Retarder type	'Secondary Retarder' type	
Engine rated power	325 kW	
Engine max torque	2134 Nm (taken from engine full load curve)	
Auxiliary technology PS	Not of the 'Large Supply" type	

For this validation, some of the default values and suggestions from Sub-Appendix 6 were taken in order to derive some input values as if they were not available. Axle and gearbox efficiencies were derived from Table 13 and 16, as well as n_eng_avg (engine average speed), that was calculated using the approach described in Figure 22. As average cycle speeds were taken indicative values of 60 and 80 km/h for the Regional Delivery and the Long Haul respectively. Regarding the calculation of air drag and rolling resistance losses, the best quality input was used since these loss sources are of primary importance for the calculation of total EC. The energy consumed downstream the engine was calculated for the four cycle-loading combinations, using the correlation formulas and compared with the full VECTO simulations. The results are presented in Table 4, which reports the E_fcmap_pos obtained with the two solutions, and in Table 5, which reports the relative error obtained for the individual losses (with respect to E_fcmap_pos calculated with VECTO).

Table 4. Comparison of E_fcmap_pos obtained with VECTO and with the method for the VECTO class 5 generic vehicle

E_fcmap_pos [kWh]	Long Haul Low Load	Long Haul Ref. Load	Regional Delivery Low Load	Regional Delivery Ref. Load
VECTO	114.44	151.77	118.49	148.81
Method	104.58	142.90	106.12	136.93

Table 5. Relative error of the method with respect to VECTO full simulation for the VECTO class 5 generic vehicle

Relative error [%]	Long Haul Low Load	Long Haul Ref. Load	Regional Delivery Low Load	Regional Delivery Ref. Load
E_roll	-0.02%	-0.03%	0.03%	0.04%
E_air	0.31%	0.70%	-0.39%	-0.08%
E_brake	0.14%	0.21%	0.45%	0.51%
E_grad	0.00%	0.00%	0.00%	0.00%
E_axl_loss	-4.37%	-2.84%	-4.40%	-3.17%
E_ret_loss	-1.40%	-1.05%	-1.31%	-1.04%
E_gbx_loss	-3.00%	-2.45%	-3.73%	-3.39%
E_aux_sum	0.01%	-0.04%	-0.24%	-0.21%
E_fcmap_neg	-0.26%	-0.32%	-0.81%	-0.59%
E_fcmap_pos	-8.62%	-5.84%	-10.44%	-7.98%

The method calculates an acceptable solution also when some of the inputs are derived from the default values and the approaches reported in the appendix. The deviation obtained for gearbox and axle losses is high since the average efficiencies adopted differ consistently from the ones that feature the VECTO simulation: on average, the generic vehicle shows axle and gearbox efficiencies of 91.7% and 94.7% in the simulation run. Despite the two inputs being consistently off the real ones, the method still provides a total energy consumption downstream the engine that is comparable and that closely reflects how the way the energy is dissipated.

Conclusions

JRC received a database of VECTO simulation results covering the 2016 HDT fleet, containing different vehicle types and different mission profiles. The data were analysed in order to quantify how the energy is distributed depending on the different mission profiles and vehicle classes. The impact of air drag and rolling resistance losses was highlighted, pointing up that an accurate modelling is of primary importance in order to reach acceptable accuracy in the calculation of total EC. FC and CO_2 emissions were also presented, in the form of distributions and tables, for each of the mission profiles into consideration and each regulated HDV class. A method to calculate the total EC without the need to run the full VECTO simulations was developed based on the results. The goal was to provide insight and information to build the energy consumption tree when certain proprietary inputs are missing in order to run VECTO or when it is necessary to quickly compare VECTO results of different vehicles under a common basis. The proposed method was found to be satisfying in terms of accuracy, showing relative errors within ±3% compared to VECTO results, that are obtained after a time-based simulation is performed, and within a slightly bigger band when default input values are used. The accuracy and lightness of the method can be useful features for anyone in need of making large-scale calculations with many different vehicle configurations.

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Disclaimer

The views expressed are purely those of the authors and shall not be interpreted as an official position of the European Commission under any circumstance.

Definitions/Abbreviations

AMS	Advanced Mechatronics System
BMEP	Brake Mean Effective Pressure
CdA	Drag coefficient x Drag Area
CO_2	Carbon Dioxide
EC	Energy Consumption
ES	Electric System
ESS	Energy Saving System
FAN	Vehicle engine fan
FC	Fuel Consumption
FuMEP	Fuel Mean Effective Pressure
HDT	Heavy-Duty Truck

HDV	Heavy-Duty Vehicle	**RL**	Reference Loading
JRC	Joint Research Centre	**RR**	Rolling Resistance
LHV	Lower Heating Value	**RRC**	Rolling Resistance Coefficient
LL	Low Loading	**STP**	Steering Pump
PS	Pneumatic System	**VECTO**	Vehicle Energy Consumption Calculation Tool
PTO	Power Take-Off		

Appendix

Sub-Appendix 1 -> Definitions

Table 6. Description of VECTO outputs and other definitions from the authors

Name	Unit	Description
E_roll	kWh	Energy for rolling resistance
E_air	kWh	Energy for air drag
E_brake	kWh	Energy wasted during braking
E_grad	kWh	Difference in potential energy
E_wheels	kWh	Energy at wheels
E_angle	kWh	Energy for angle drive losses
E_ds_axl	*kWh*	*Energy downstream the axle*
E_axl_loss	kWh	Energy for axle losses
E_us_axl	*kWh*	*Energy upstream the axle*
E_ret_loss	kWh	Energy for retarder losses
E_ds_gbx	*kWh*	*Energy downstream the gearbox*
E_gbx_loss	kWh	Energy for gearbox losses
E_clutch	kWh	Energy lost in the clutch
E_shift	kWh	Energy for gear shifts (AMT, AT)
E_tc_loss	kWh	Energy for torque converter losses
E_us_gbx	*kWh*	*Energy upstream the gearbox*
E_aux_sum	kWh	Sum of auxiliaries consumption
E_fcmap_neg	kWh	Energy for engine frictions
E_fcmap_pos	kWh	Positive energy produced at the engine
Declared CdA	m^2	Cross-sectional area of the vehicle w/o trailer(s)
speed	km/h	Actual average vehicle speed during the cycle
Total vehicle mass	kg	Total mass of the vehicle including standard bodies
total vehicle RRC	-	Total RRC of the vehicle including standard bodies

Table 7. Definition of regulated HDV classes according to regulation (EU) 2017/2400

HDV class	Axle configuration	Chassis configuration	Max. laden mass (tons)	Allocation of mission profile and vehicle configuration	
				Long haul	Regional Delivery
4	4x2	Rigid	>16	Rigid + Trailer	Rigid
5	4x2	Tractor	>16	Tractor + Semi-Trailer	Tractor + Semi-Trailer
9	6x2	Rigid	all weights	Rigid + Trailer	Rigid
10	6x2	Tractor	all weights	Tractor + Semi-Trailer	Tractor + Semi-Trailer

Sub-Appendix 2 -> Heavy-Duty Trucks energy consumption

Cycle-loading subgroups (all HDVclasses)

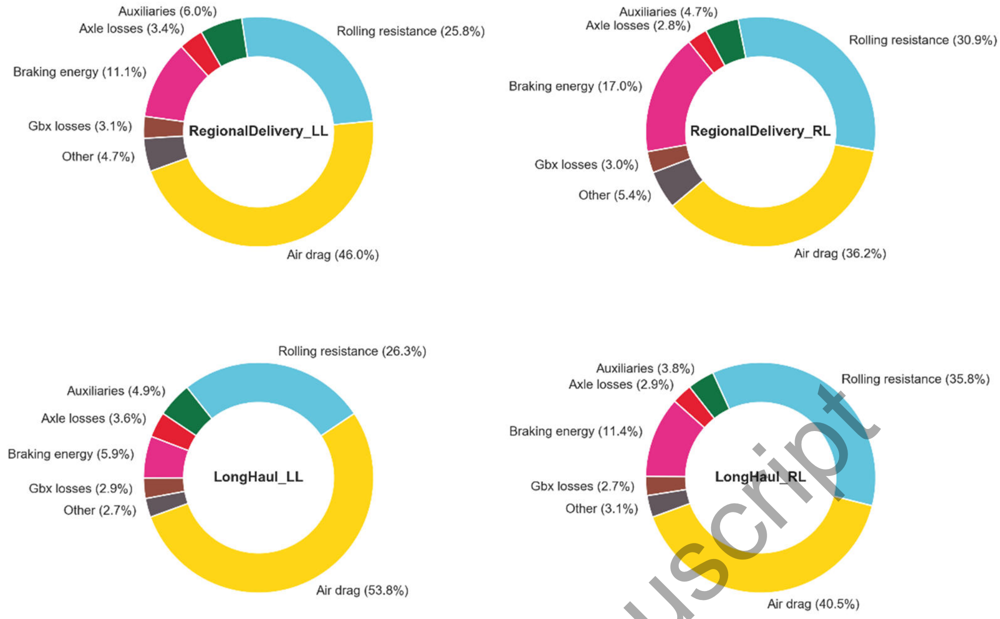

Figure 15. Energy consumption shares presented for each cycle-loading combination

HDVclass subgroups (all cycle-loadings)

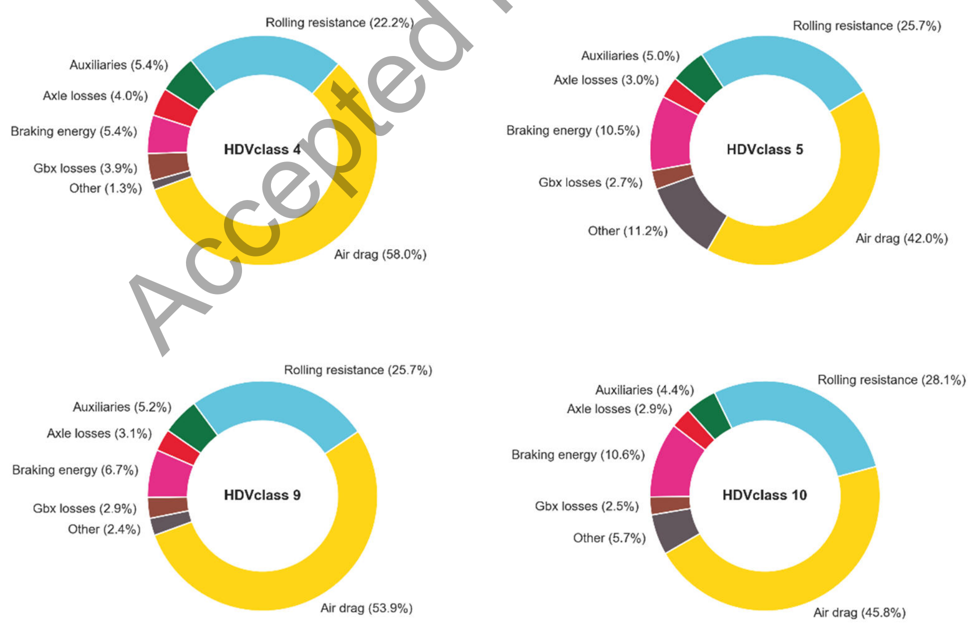

Figure 16. Energy consumption shares presented for each HDV class

Cycle-Loading-HDVclass subgroups

HDV class 4 (4x2 rigid trucks above 16 tons)

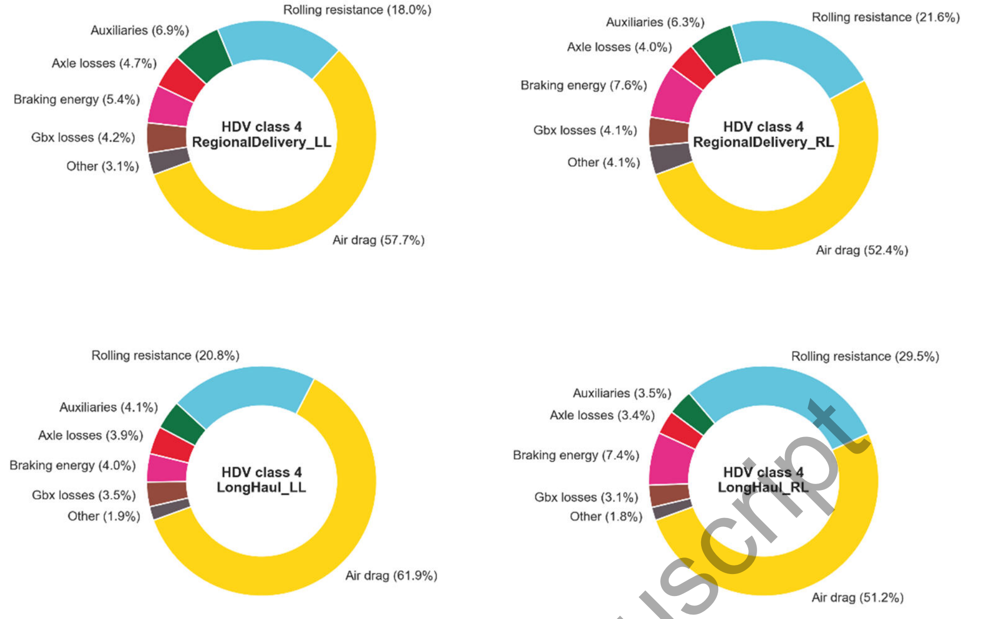

Figure 17. Energy consumption shares presented for HDV class 4 and each cycle-loading combination

HDV class 5 (4x2 tractor trucks above 16 tons)

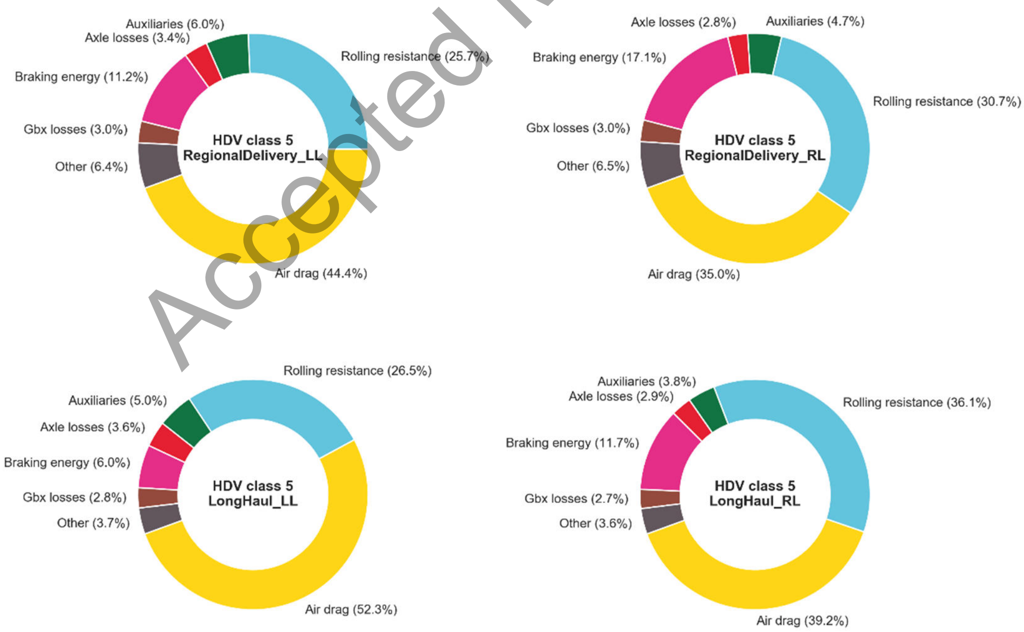

Figure 18. Energy consumption shares presented for HDV class 5 and each cycle-loading combination

HDV class 9 (6x2 rigid trucks above 16 tons)

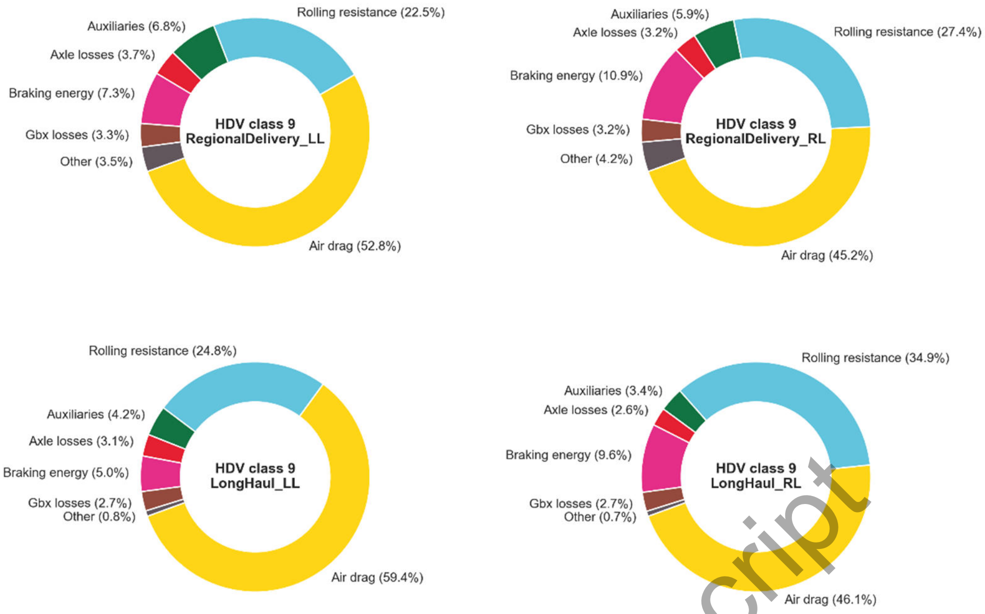

Figure 19. Energy consumption shares presented for HDV class 9 and each cycle-loading combination

HDV class 10 (6x2 tractor trucks above 16 tons)

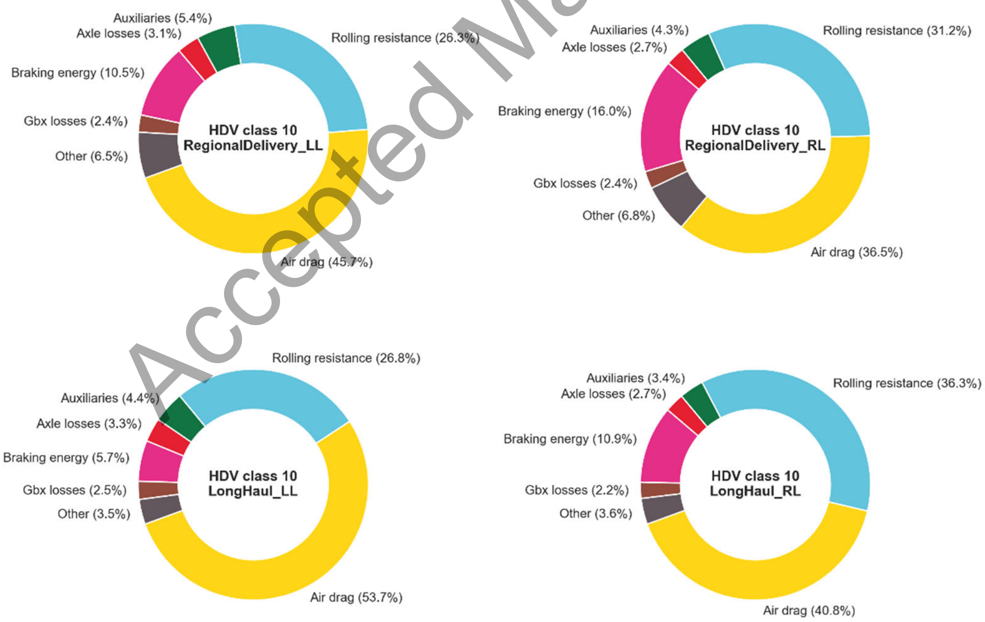

Figure 20. Energy consumption shares presented for HDVclass 10 and each cycle-loading combination

Sub-Appendix 3 -> Heavy-Duty Trucks fuel consumption and CO_2 emissions

Table 8. Fuel consumption and CO_2 emissions distributions specifics

		Fuel consumption [l/100km]				CO2 emissions [g/km]			
Cycle_Load	**HDV class**	**mean**	**std**	**min**	**max**	**mean**	**std**	**min**	**max**
LongHaul_LL	**4**	31.3	2.1	24.5	37.3	818.7	55.6	641.6	975.2
	5	26.5	1.3	23.7	34	694.4	34	619.7	890.8
	9	31.6	2.1	27.1	41	827.7	55.6	710.3	1073.8
	10	28.4	1.9	24.8	35.4	743.4	49.7	648.6	926.1
LongHaul_RL	**4**	36.4	2.1	29.9	42.9	951.9	55.9	781.4	1121.4
	5	34.3	1.4	30.7	42.2	898.1	37.9	802.5	1104.5
	9	39.2	2.1	34.1	49.4	1025.2	56.2	891	1293.8
	10	36.2	1.9	32.1	43.7	947.5	50.2	840.8	1144
RegionalDelivery_LL	**4**	23.7	1.9	17.3	30.7	618.9	50.7	452.7	803.8
	5	27.5	1.2	24.7	34.6	718.8	31	646.1	906.5
	9	24.5	1.9	20.5	33.5	639.9	49.2	536.8	875.8
	10	29.2	1.8	25.9	36.6	765.3	46.6	678.8	956.4
RegionalDelivery_RL	**4**	25.6	1.9	19.4	33.1	671.1	50	508.6	865
	5	33.9	1.3	30.5	41.4	886.8	34.2	799	1082.5
	9	27.9	1.9	23.8	37.4	729.8	49.7	623.8	977.9
	10	35.7	1.8	32	43.1	933.3	47.7	838.1	1127.8

Sub-Appendix 4 -> Flow chart explaining the HDT CO_2 calculation

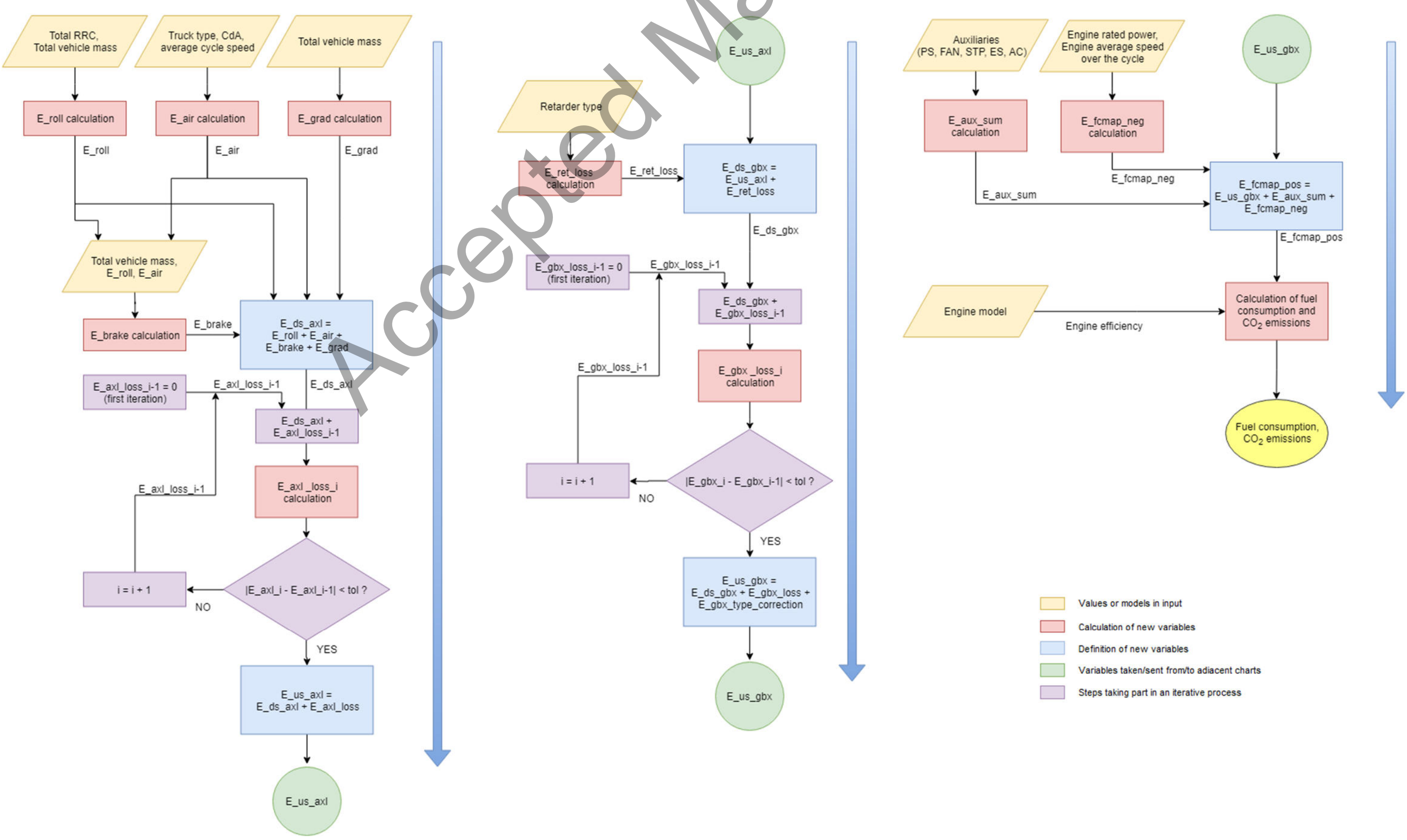

Figure 21. Flow chart of the process to calculate HDTs CO2 emissions

Sub-Appendix 5 -> Calculation of vehicle total Rolling Resistance Coefficient (RRC)

As reported in the manual of VECTO, the calculation of vehicle total rolling resistance is performed as follows:

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

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 [-].

This method accounts for the impact that each of the axles has, for this reason the weight repartition and the tire configuration (whether single or double) and rolling resistance on each axle has to be known. The total vehicle weight and the weight distribution change accordingly to the vehicle configuration and cycle. The first is to be calculated by adding to the vehicle curbed mass the weight of the standard bodies applicable for the specific vehicle type and cycle, whether for the second the values are reported in the *SegmentTable.csv* file inside the VECTO installation folder. For the standard bodies (trailers and semitrailers) VECTO assumes that RRC_iso is equal to 0.0055 and Fz_iso is equal to 37500.

An example of calculation of total RRC is here reported.

<u>DATA:</u>

HDV class: 5

Mission profile: Long Haul, low loading

$m = vehicle\ curbed\ mass +$ weight of standard body ST1 + low loading = 10000 + 7500 + 2600 = 20100 kg

s (i) = [0.2, 0.25, 0.55/3, 0.55/3, 0.55/3] (first value is the front axle, the second is the rear axle, the last three the three axles of the semitrailer)

RRC_iso = 0.004 (upper limit of class A of the tire labelling system 1222/2009)

Fz_iso = 35000 (both RRC_iso and Fz_iso have to be provided by the tire manufacturer)

Class	Configuration	LongHaul	RegionalDelivery
4	combination	B4 +T2	B4
	total weight (kg)	7500	2100
5	combination	ST1	ST1
	total weight (kg)	7500	7500
9	combination	B6 +T2	B6
	total weight (kg)	7600	2200
10	combination	ST1	ST1
	total weight (kg)	7500	7500

Class	Body	Weight
4	B4	2100
	T2	5400
5	ST1	7500
9	B6	2200
	T2	5400
10	ST1	7500

<u>CALCULATION:</u> the single contribution from each axle has to be calculated.

$$RRC1 = 0.2 * 0.004 * \left(\frac{0.2 * 20100 \cdot 9.81}{2 \cdot 35000}\right)^{\beta-1}$$

$$RRC2 = 0.25 * 0.004 * \left(\frac{0.25 * 20100 \cdot 9.81}{4 \cdot 35000}\right)^{\beta-1}$$

$$RRC3 = RRC4 = RRC5 = 0.55/3 * 0.004 * \left(\frac{0.55/3 * 20100 \cdot 9.81}{2 \cdot 35000}\right)^{\beta-1}$$

RRC = RRC1 + RRC2 + RRC3 + RRC4 +RRC5

Sub-Appendix 6 -> Correlation parameters for the fitting formulas and material for deriving default values

Rolling resistance (E_roll)

Table 9. Parameters to be used in the correlation formula for the calculation of E_roll

	a
fleet	0.272678

Air Drag (E_air)

Table 10. Parameters to be used in the correlation formula for the calculation of E_air

Truck type	**Rigid**				**Tractor**			
Parameters	**a**	**b**	**c**	**d**	**a**	**B**	**c**	**d**
Regional Delivery	12.099	-0.642	-0.153	0.135	45.289	-8.132	-0.655	0.260
Long Haul	17.638	-4.496	0.061	0.167	16.341	-3.367	-0.128	0.153

Energy for braking (E_brake)

Table 11. Parameters to be used in the correlation formula for the calculation of E_brake

	a	**b**	**c**	**d**
RegionalDelivery_LL	-6.2409	0.0013	0.0184	-3.98E-06
RegionalDelivery_RL	-8.3637	0.0015	-0.0153	-3.18E-06
LongHaul_LL	-1.2354	0.0006	-0.0219	-1.73E-07
LongHaul_RL	-14.1412	0.0011	0.0358	-3.00E-06

Axle losses (E_axl_loss)

Table 12. Parameters to be used in the correlation formula for the calculation of E_axl_loss

Parameters	**a**	**b**	**c**	**d**
fleet	2.710837	-0.02677	0.991148	-0.00991

Table 13. Axle efficiency statistics for each cycle-loading and HDV class combination

Cycle_Load	**HDV Class**	**Max [%]**	**mean [%]**	**median [%]**	**min [%]**	**std [%]**
LongHaul_LL	**4**	97.96	96.29	96.83	88.69	1.21
LongHaul_LL	**5**	97.88	96.19	96.12	93.97	0.93
LongHaul_LL	**9**	98.04	96.84	97.15	93.88	0.72
LongHaul_LL	**10**	97.63	96.55	96.87	93.91	0.82
LongHaul_RL	**4**	98.1	96.7	97.03	90.35	1.02
LongHaul_RL	**5**	98.1	96.93	96.9	95.33	0.66
LongHaul_RL	**9**	98.2	97.33	97.56	94.96	0.56
LongHaul_RL	**10**	97.97	97.19	97.34	95.14	0.6
RegionalDelivery_LL	**4**	97.58	95.18	95.91	84.2	1.74
RegionalDelivery_LL	**5**	97.87	96.28	96.23	94.24	0.86
RegionalDelivery_LL	**9**	97.73	95.9	96.29	91.75	1
RegionalDelivery_LL	**10**	97.67	96.61	96.87	94.12	0.74
RegionalDelivery_RL	**4**	97.67	95.64	96.25	85.81	1.48
RegionalDelivery_RL	**5**	98.04	96.86	96.84	95.28	0.66
RegionalDelivery_RL	**9**	97.86	96.38	96.71	93.27	0.81
RegionalDelivery_RL	**10**	97.91	97.11	97.24	95.07	0.58

Retarder losses (E_ret_loss)

Table 14. Table describing the impact of the presence of a retarder both on E_ret_loss and on E_ret_loss+E_gbx_loss

		E_gbx_loss + E_ret_loss [kWh]					E_ret_loss [kWh]				
Retarder type [-]	**Retarder model [-]**	**count**	**max**	**mean**	**min**	**Std**	**count**	**max**	**mean**	**min**	**std**
Included in Transmission Loss Maps	**Ret. A**	32	4.1446	3.491125	3.0657	0.301688	32	0	0	0	0
None	**Ret. A**	2460	4.3662	1.574346	1.0379	0.557852	2460	0	0	0	0
Secondary Retarder	**Ret. B**	60324	9.6792	6.03553	1.3888	1.408821	60324	0.5371	0.297017	0.2698	0.02234
	Ret. C	972	4.5519	3.755294	3.2575	0.31534	972	0.2304	0.198333	0.1883	0.009995
	Secondary water retarder	26144	7.0826	4.156047	3.1319	0.494364	26144	0.4764	0.279847	0.2323	0.021014

Gearbox losses (E_gbx_loss)

Table 15. Parameters to be used in the correlation formula for the calculation of E_gbx_loss

Parameters	**a**	**b**	**c**	**d**
fleet	3.060891	-0.03086	1.006445	-0.01006

Table 16. Gearbox efficiency statistics for each cycle-loading and HDV class combination

Cycle_Load	**HDV Class**	**max [%]**	**mean [%]**	**median [%]**	**min [%]**	**std [%]**
LongHaul_LL	**4**	99.23	96.29	96.81	92.15	1.57
LongHaul_LL	**5**	99.08	97.27	98.2	92.75	1.52
LongHaul_LL	**9**	99.2	97.32	97.16	92.59	1.25
LongHaul_LL	**10**	99	97.69	98.24	93.68	1.05
LongHaul_RL	**4**	99.21	96.73	96.99	93.27	1.36
LongHaul_RL	**5**	99.14	97.58	98.32	94.19	1.28
LongHaul_RL	**9**	99.24	97.5	97.26	93.79	1.09
LongHaul_RL	**10**	99.1	97.87	98.34	94.93	0.91
RegionalDelivery_LL	**4**	98.85	95.38	95.92	89.58	1.77
RegionalDelivery_LL	**5**	98.85	96.94	97.92	92.84	1.64
RegionalDelivery_LL	**9**	98.82	96.5	96.42	90.53	1.55
RegionalDelivery_LL	**10**	98.78	97.36	97.94	93.55	1.11
RegionalDelivery_RL	**4**	98.86	95.56	96.02	90.69	1.66
RegionalDelivery_RL	**5**	98.85	97.15	97.97	93.6	1.46
RegionalDelivery_RL	**9**	98.86	96.68	96.5	91.52	1.41
RegionalDelivery_RL	**10**	98.81	97.46	97.98	94.16	1.01

Energy for auxiliaries (E_aux_sum)

Table 17. Energy consumption for auxiliaries (E_aux_sum [kWh]) for relevant combinations of technologies

Combination of most affecting auxiliaries			E_aux_sum [kWh]		Share [%]
Auxiliary technology STP [-]	**Auxiliary technology FAN [-]**	**Auxiliary technology PS [-]**	**Long Haul**	**Regional Delivery**	
Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 2-stage + ESS	5.57	6.48	26.0
Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Large Supply + mech. Clutch	5.19	6.06	22.8
Fixed displacement with elec. control	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 1-stage	6.74	7.77	20.5
Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 1-stage + ESS + AMS	5.51	6.63	12.5
Variable displacement mech. controlled	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	5.38	6.61	5.9
Variable displacement mech. controlled	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 1-stage + mech. clutch + AMS	4.79	5.82	2.1
Variable displacement mech. controlled	Belt driven or driven via transm. - Electronically controlled visco clutch	Large Supply + ESS + AMS	5.93	6.82	1.6
Fixed displacement with elec. control	Belt driven or driven via transm. - Electronically controlled visco clutch	Large Supply	10.14	11.36	1.3
(1) Fixed displacement (2) Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	6.51	7.71	1.1
Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 1-stage	6.30	7.06	1.0
Variable displacement elec. controlled	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	5.25	6.45	0.84
(1) Fixed displacement (2) Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Large Supply + ESS + AMS	7.05	7.95	0.64
Fixed displacement with elec. control	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 1-stage	6.25	7.03	0.47
Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Large Supply + ESS + AMS	6.11	7.05	0.47
(1) Fixed displacement (2) Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	6.05	7.10	0.42
Fixed displacement with elec. control	Crankshaft mounted - Bimetallic controlled visco clutch	Medium Supply 1-stage	6.54	7.35	0.41
Variable displacement mech. controlled	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	4.88	5.94	0.41
Variable displacement elec. controlled	Belt driven or driven via transm. - Electronically controlled visco clutch	Large Supply + ESS + AMS	5.80	6.71	0.32
Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Large Supply + ESS + AMS	5.67	6.49	0.27
Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	5.58	6.81	0.25
(1) Fixed displacement (2) Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Large Supply + ESS + AMS	6.54	7.34	0.21
(1) Fixed displacement (2) Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 1-stage + ESS + AMS	6.46	7.45	0.14
Fixed displacement	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	5.15	6.26	0.11
Variable displacement mech. controlled	Crankshaft mounted - Electronically controlled visco clutch	Large Supply + ESS + AMS	5.44	6.19	0.08
Variable displacement elec. controlled	Crankshaft mounted - Electronically controlled visco clutch	Medium Supply 2-stage + ESS + AMS	4.75	5.79	0.05
Variable displacement elec. controlled	Crankshaft mounted - Electronically controlled visco clutch	Large Supply + ESS + AMS	5.31	6.07	0.01
Fixed displacement	Belt driven or driven via transm. - Electronically controlled visco clutch	Medium Supply 1-stage + ESS	5.98	6.84	0.00

Energy for engine friction (E_fcmap_neg)

Table 18. Parameters to be used in the correlation formula for the calculation of E_fcmap_neg

Parameters	a	b	c	d
RegionalDelivery_LL	5.586632	-0.0105	-0.00524	2.14E-05
RegionalDelivery_RL	12.09616	-0.03715	-0.01128	5.11E-05
LongHaul_LL	2.486856	-0.00604	-0.00169	8.22E-06
LongHaul_RL	5.583181	-0.01647	-0.00419	1.99E-05

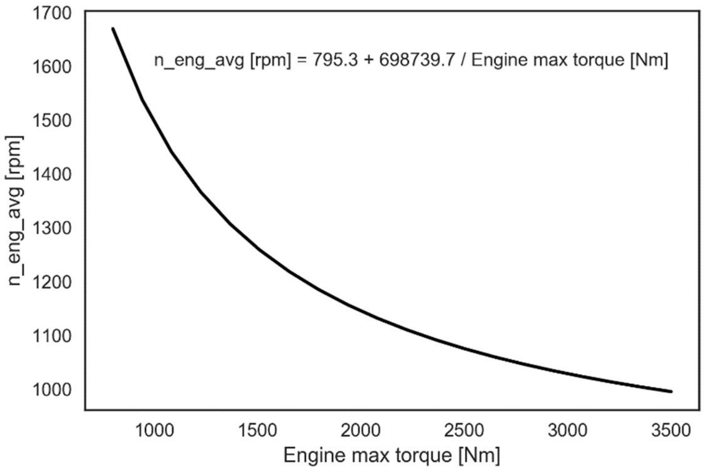

Figure 22. Approximate relationship between Engine max torque [Nm] and average engine speed (n_eng_avg [rpm]) in Long Haul and Regional Delivery cycles