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Estimating the CO_2 Emissions Reduction Potential of Various Technologies in European Trucks using VECTO simulator

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Abstract

Heavy-duty vehicles (HDVs) account for some 5% of the EU's total greenhouse gas emissions. They present a variety of possible configurations that are deployed depending on the intended use. This variety makes the quantification of their CO_2 emissions and fuel consumption difficult. For this reason, the European Commission has adopted a simulation-based approach for the certification of CO_2 emissions and fuel consumption of HDVs in Europe; the VECTO simulation software has been developed as the official tool for the purpose. The current study investigates the impact of various technologies on the CO_2 emissions of European trucks through vehicle simulations performed in VECTO. The chosen vehicles represent average 2015 vehicles and comprised of two rigid trucks (Class 2 and 4) and a tractor-trailer (Class 5), which were simulated under their reference configurations and official driving cycles. The effects of aerodynamics, auxiliary systems, curb-weight, tyre rolling resistance, engine internal losses, and engine and gearbox efficiency were investigated. Factors exhibited a varying reduction potential that depended on the vehicle category and the driving cycle. Results indicate where focus should be given for improving the energy performance of trucks in view of the Commission's future efforts to propose CO_2 reduction targets for HDVs.

Introduction

Road CO_2 emissions in the European Union account for about 24% [1] of the region's total emissions a quarter of which is attributed to heavy-duty vehicles, a term attributed to trucks and buses [2,3]. Committing to climate change mitigation, the European Commission has set a target to reduce road emissions by 60% by 2050 with respect to 1990 levels [4]. For this reason, in the field of road transportation, it has set mandatory CO_2 targets for passenger and light commercial vehicles and is currently working on a strategy to reduce emissions in heavy-duty vehicles [3]. In contrast to light-duty vehicles, heavy-duty vehicles present a large variety of configurations that are tailored to the needs of the desired application. It is therefore difficult to assess CO_2 emissions using chassis dynamometer measurements as a basis for monitoring compliance of heavy-duty vehicles. In heavy-duty vehicles the possible number of configurations could be expected to increase as there is a wide variety of fuel improving/CO_2 reducing technologies [5] which could be potentially deployed in the future. Any policy initiatives should foster the introduction of such technologies and address factors that may slow down the uptake of fuel-efficient innovations. The European Commission is addressing these issues by developing the Vehicle Energy Consumption Calculation Tool (VECTO), which will be used to calculate fuel consumption and CO_2 emissions of heavy-duty vehicles through vehicle simulation. The aim of the tool is to provide a standardized method to calculate fuel consumption and CO_2 emissions by modelling the operation of vehicles over realistic driving cycles [6].

The European Commission has chosen to develop a methodology that will be based on vehicle simulation in order to eventually cover all the possible vehicle configurations in an effective way [7] and allow the calculation of vehicle fuel consumption in a way that realistically reflects their real world performance. Additionally, this approach enables a standardized CO_2 emissions estimation that permits comparison between different vehicle configurations. To achieve this, two issues had to be addressed: first, the development of the software that could effectively simulate fuel consumption and second, the development of a standardized methodology for certifying individual components and setting representative reference values for components that will not be measured (e.g. standard bodies). The first task is addressed with the development of VECTO, which will be described in more detail in the following paragraphs, while a group of experts consisting of the JRC, DG Clima, vehicle manufacturers and external consultants, is focusing on the second task [8]. Finally, a series of operating cycles, reflecting the different usages of vehicles in real world operation have been developed in collaboration with vehicle manufacturers, which are attributed the term *mission profiles*. Each mission profile describes a representative driving scenario and reference vehicle type and configuration. This work is described in the *technical annex* of the developing legislation with newer updates published by the European Commission on regular intervals [9].

The mission profiles correspond to typical transportation scenarios and include a distance based driving cycle and road grade. The available mission profiles for trucks are the following [10]:

- **Urban delivery** represents an urban route with low average speed, increased number of stop events and stop time share.
- **Regional delivery** represents an inter-urban route with portions of urban and highway driving.
- **Long haul** represents a transport application for long distances that consists mostly of highway driving.
- **Construction** represents the speed and route profile of a vehicle that is deployed in a construction site.
- **Municipal utility** represents the mission profile in an urban route for refuse trucks.

In contrast with the monitoring scheme for light-duty vehicles, currently there are limited publicly available data on CO_2 emissions from heavy-duty vehicles [11–16]. For this reason there is uncertainty on the average emissions and the effect of fuel saving technologies on what it could be considered a typical heavy-duty vehicle. Research in the field has been on-going in Europe and in other regions of the world in order to assess the issue. The current study aims to explore the effect of various vehicle parameters on the CO_2 emissions with the use of simulations by looking into the available research and data and set it within the context of VECTO. Also the study focuses on EURO VI vehicles and it is expected to assist stakeholders into assessing future potential reductions. The examined three truck configurations are considered to be representative of 2015 model year European vehicles. A series of simulation cases were formulated in order to assess the effect of these technologies over the corresponding vehicles' mission profiles.

The investigated cases were grouped into categories and focused on the effect on CO_2 emissions using grams per tonne-kilometer (g/tkm) as a metric. This metric refers to the CO_2 emitted per unit of cargo (payload) and distance travelled and is more relevant for measuring freight transportation efficiency than the metric of vehicle fuel consumption (l/100km) [17]. Additionally, a factor sensitivity analysis was conducted.

Methods

VECTO description

VECTO is a simulation tool for heavy-duty vehicles, which includes trucks and buses. The tool estimates CO_2 emissions and the capacity of VECTO to accurately capture fuel consumption of vehicles and energy flows within HDV powertrains has been demonstrated in previous studies, which also describe the simulation scheme and calculation algorithms [7,8]. The tool offers two modes for vehicle simulation; Declaration and Engineering mode. In the Declaration mode, a vehicle configuration is chosen and many of the underlying parameters (e.g. axle weight distribution) are predefined based on the technical specifications foreseen by the European legislation. On the other hand in Engineering mode, users can adjust more parameters for experimenting and validating their vehicle models [6].

The operation of vehicle components is simulated using tabulated input in the form of maps (e.g. engine fuel maps transmission torque loss maps), scalar values (e.g. rolling resistance) or a combination of these (e.g. air drag at zero yaw angle is a scalar value accompanied by a table providing the effect of sidewinds on air drag at different yaw angles). Map type inputs include information over dynamic parameters that change depending on engine or vehicle speed, while data that are considered constant during the route, such as mass and air drag area is inputted directly into the tool. Drop-down menus contain mostly categorical data such as axle configuration (e.g. 4x2, 6x2) and transmission type (e.g. Manual, AMT).

The investigated cases in the current study were simulated in Engineering mode and the analysis utilized the summary results in estimating the changes in CO_2 grams per tonne-kilometre (g/tkm). The second-by-second results were used in an energy audit for estimating the energy distribution for the baseline vehicles.

The vehicle models were developed and run in version 3.1.0.683. Figure 1 presents the main job file tab and Figure 2 the vehicle tab as sample of the tool's interface.

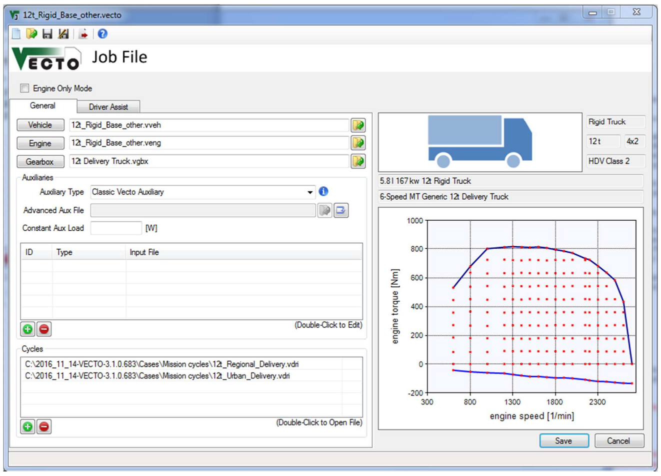

Figure 1: VECTO job file main tab.

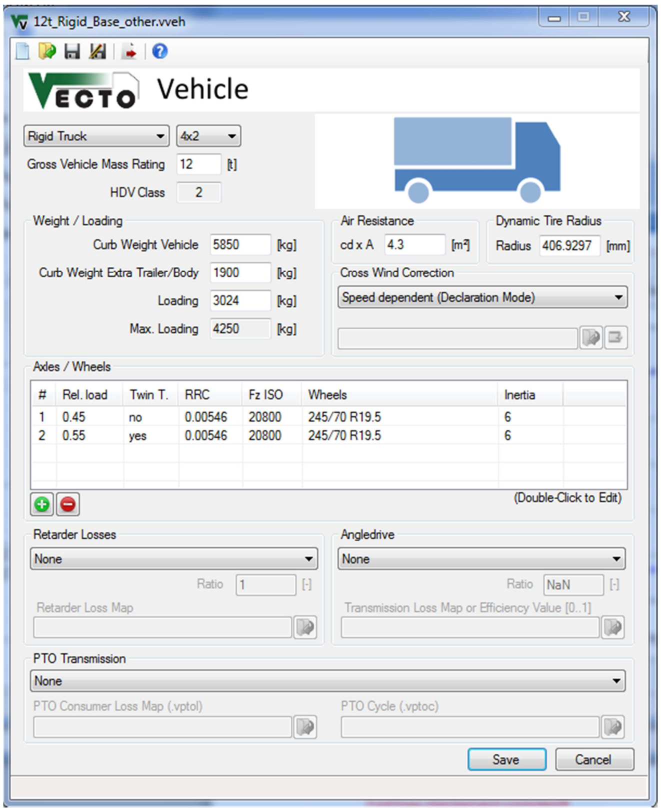

Figure 2: VECTO vehicle file tab, which is accessed from the job file main tab.

Baseline vehicles

The simulation analysis focused on three baseline vehicles, two rigid trucks and a tractor-trailer truck corresponding to HDV Classes 2, 4 and 5. The rigid trucks corresponded respectively to Classes 2 and 4, while the tractor trailer was a Class 5 vehicle. The baseline vehicles' characteristics were estimated based on the weighted average values of the most popular models sold in the European Union in 2015 [18], without singling out a specific model or brand. Where relevant data were not available, the VECTO generic values were used, such as in the cases of CdA and auxiliary power demand. Also, the generic gearboxes were used as the baselines for configuring torque losses based on the guidelines of the technical annex. Additional vehicle configurations were in accordance to the reference testing conditions for the respective standard body types of the test vehicles, which are specified by the technical annex's guidelines [9,19], the VECTO documentation [20] or by utilizing the Declaration mode parameters.

Table 1 presents the results of the analysis of the database [18] for the market weighted average technical characteristics, along with the range of values for each vehicle category. The table includes the gross vehicle weight for each baseline which will be used in the current document to reference accordingly the vehicle types.

Table 1: Engine technical characteristics of baseline vehicles. Class 5 transmission type was retrieved from [21].

Vehicle		Class 2	Class 4	Class 5
Capacity (cm3)	Average	5800	6755	12706
	Minimum	3920	4249	10677
	Maximum	12777	16353	16353
Power (kW)	Average	167	184	320
	Minimum	95	100	301
	Maximum	345	485	537
Transmission type		Manual	Manual	AMT

The first step was to create generic engine maps for the baseline vehicles, which would be representative of the current technology in Europe. The research took into consideration the estimated average engines' characteristics and subsequently the engine maps were formulated based on data available to the JRC from in house engine measurements. An extended Willans model was used to rescale the engine maps to the required capacities according to the methodology based in the literature [22,23]. Equation 1 presents the mathematical representation of the Willans method [22]:

$$P_{out} = e_{ice} \times P_{in\_ice} - P_{loss\_ice} \quad (1)$$

P_{out}: Indicated power output (W)

P_{in_ice}: Engine input power (W)

e_{ice}: Intrinsic efficiency (%)

P_{loss_ice}: Loss in power (W), it is a function of constant and engine speed related losses.

In order to ensure that the engine rescaling process would deliver realistic engine maps a comparison was made against key technical characteristics (engine capacity, stroke, power and maximum torque) of real engines available on-line from the respective Original Equipment Manufacturers (OEMs). Table 1 presents the engine characteristics for each baseline vehicle, while related market-available engines for each vehicle type can be found from Table 7 to Table 9 in the Appendix.

Baseline vehicle parameters were based on the technical annex guidelines, in values retrieved from the literature and from VECTO's generic vehicles. VECTO provides generic vehicles which are in compliance with the technical annex's specifications, but these vehicles do not necessarily reflect representative models of the year in focus. However, as these values were validated by OEMs are considered realistic and they were used whenever it was not possible to obtain fleet representative values.

Many of the reference parameters such as the payload and the power demand of auxiliary systems depend on the vehicle type and the mission profile [20].

Mission profiles

The vehicle models were tested over the regional delivery and the long haul cycles, with the Class 2 truck being additionally tested over the urban delivery cycle. Since the cycles are distance based, each vehicle has a different running time and average speed than the others. Table 5 in the Appendix presents the main characteristics of the cycle for each vehicle type.

An overview of the tested cycles shows that long haul cycle has the highest average speed and the lowest stop time share followed by regional and urban delivery. The long haul was also the least transient cycle with the lowest accelerating time share, while urban delivery cycle had the highest transient conditions. These findings will assist in interpreting the differences of the simulation results.

Input description

The following paragraphs describe the inputs used in the analysis along with the average values for each vehicle type.

The product of the aerodynamic coefficient and cross sectional area (CdA) is estimated through vehicle constant speed tests. Aerodynamic resistance is proportional to the square of the vehicle speed so its effect is more apparent at higher speeds than at lower ones. As it was difficult to retrieve data on CdA values, the respective VECTO generic values were used as an approximation for each vehicle type. These values have been approved as realistic by the OEMs due to their involvement in the development of VECTO.

The mass input consists of three mass values: curb weight, extra curb weight and payload. The curb weight corresponds to the mass of the chassis and the cabin of the vehicle, while the extra curb weight corresponds to the mass of the truck body and/or the trailer. In the case of rigid trucks the mass of the standard body was considered in all cycles, while the vehicles were also considered to be towing a trailer in the long haul cycle, as foreseen by the technical annex. In this case the term gross combined weight is used instead of gross vehicle weight in order to denote the increase in the vehicle payload capacity. The trailer type is determined to be a T1 standard trailer for the Class 2 truck and T2 for the Class 4 baselines, while the tractor-trailer was allocated an ST1 standard semi-trailer [6]. Accordingly, the reference payloads are determined by the driving cycle depending on the gross vehicle weight of the vehicle (see Table 6 in the Appendix).

Rolling resistance represents the energy losses due to tyre deformation as result of road contact and it is expressed by the rolling resistance coefficient [24]. A rolling resistance coefficient (RRC) value of 5.46 kg/tonne was chosen which corresponds to an energy class “C” tyre and was proposed by ACEA as a representative value for 2016 vehicles [17]. This value is considered realistic despite that the average RRC of both new and replacement tyres sold in Europe in 2015 was estimated at 6.13 kg/tonne [25]. The latter value is expected to decrease in the future as since 1st November 2016 the maximum rolling resistance allowed in Europe is 6.5 kg/tonne [26].

The auxiliary power value corresponds to the total energy demands of the generic auxiliaries of VECTO and includes fan, steering pump, HVAC, electric system and pneumatic system [20]. More specifically the individual components considered in the simulations were the following:

- **Fan:** Belt driven or driven via transmission – electronically controlled viscous clutch.
- **Steering pump:** Fixed displacement with electronic control.
- **HVAC:** default VECTO configuration.
- **Electric system:** Standard technology.
- **Pneumatic system:** Medium supply 1-stage with Energy Saving System (ESS) and Air Management System (AMS) for the rigid trucks and medium supply 2-stage with ESS and AMS for the tractor-trailer.

The power demand depends on the mission profile and vehicle type and it was considered to be constant over each cycle. The power demand values were retrieved by running the baseline cases in declaration mode, where they are also considered to pose a constant load on the engine (see Table 6).

According to the analysis in Table 1 manual transmissions are more common in Class 2 and 4 trucks, with Automated Manual Transmission (AMT) being more prominent in Class 5. In the current study, the baseline vehicles’ configuration used the generic VECTO 6-speed manual and 12-AMT gearbox maps which were configured according to the vehicle’s engine output torque. Additionally, the gearbox losses were re-estimated according to the technical guidelines in order to set efficiency to 98% for the axle and to 96% and 99% for the indirect gears the direct one, respectively.

Table 6 in the Appendix presents an overview of the vehicles’ characteristics that were used in the simulation.

Simulation design

Overview of simulation approaches

Table 2 presents an overview of the simulation approach for each analysed technology category. The following sections provide more details on the simulation cases as they were grouped under their respective categories. The term “case” in this research describes the set of simulations that were realized to estimate the effect of each factor.

Table 2: Simulation approach by category.

Simulations	
Category	Approach
Aerodynamics	Reduction of CdA (m2) of 20% in rigid trucks and 25% in the tractor trailer CdA sensitivity analysis (% CdA change - % CO2 g/tkm change)
Auxiliaries	Sensitivity analysis for steady auxiliary loads (kW) during the cycle (% Auxiliary load change - % CO2 g/tkm change)
Engine	Downspeeding: Fuel map approach. Linearly rescaled map by reducing RPM by 100 at the cruising operation points Changed axle ratio
	Engine efficiency: Fuel map approach 50% engine indicated efficiency Sensitivity analysis for constant engine losses (bar), speed related losses bar.(m/sec)-2 and combination of the two loss types (% loss change - % CO2 g/tkm change)
Mass	Mass sensitivity analysis (kg) (% Mass change - % CO2 g/tkm change)
Rolling resistance	Fit vehicle with A energy efficiency class tyres (RRC=4 kg/t) Rolling resistance sensitivity analysis (% RRC change - % CO2 g/tkm change)
Transmission	Transmission type: Drop down menu selection AMT: Class 2 and 4 trucks
	Gearbox/ axle efficiency: Gearbox/axle map approach. Reduced torque losses by 20%

Table 16 in the Appendix presents a list of values that can be found in the literature for the each category. These values, whenever quantitative, are presented alongside the VECTO results for comparison.

Simulation approach description

The following paragraphs describe the approach for each category presented in Table 2. In all cases, the sensitivity analyses examined a range between -15% and 15% of the baseline parameters.

Engine: Two different cases regarding engine technology improvements were investigated.

- **Engine efficiency.** The engine efficiency scenario realized a sensitivity analysis by producing fuel maps based on a Willans model [23]. The model takes into consideration a combination of constant engine losses and engine speed related losses in order to estimate mean effective pressure loss. The sensitivity analysis focused independently on these two factors and then examined a combination of the two, while the values of these factors were validated experimentally by the JRC. The analysis also examined a case where engine's brake thermal efficiency was 50%, which is presented as an individual technology. This efficiency was achieved by improving also the combustion process in the model and it was examined as this efficiency value is suggested by ERTRAC [27] as a target for future vehicles.
- **Downspeeding.** The next case examined downspeeding, a term referring to lowering engine optimum operating speed to achieve better fuel efficiency [28]. A 100 revolutions per minute (RPM) reduction at the sweet spot was assumed based on the literature (speed decrease range 50 to 350 RPM), while maintaining the same power output [28]. The rescaling was applied linearly throughout the map, with no change in the idle RPMs. An adjustment in the axle ratio value was also required to ensure the same power output, which was re-estimated based on the equation (2):

$$axle\ ratio_{new} = axle\ ratio_{old} \times \frac{RPM_{new}}{RPM_{old}} \quad (2)$$

Aerodynamics: The effect of air drag change on fuel consumption was investigated by correlating changes in the CdA with CO_2 g/tkm emission changes. The analysis investigated also a case where CdA was reduced by 20% in the rigid trucks and by 25% in the tractor trailers.

Auxiliary use: The changes in power values were correlated against changes in the CO_2 g/tkm emissions.

Tyres: The investigation of the effect of tyres focused on changes of the rolling resistance coefficient that were subsequently correlated against the CO_2 emission. It should be noted, that in this case, only the vehicle's tyres were modified while the trailer's and semi-trailer's tyres retained their baseline value. Additionally, another case was investigated, where the vehicle was fitted with A energy efficiency class tyres, as an example of the RRC reduction potential.

Axles and transmission: The axle transmission investigated two cases:

- **Transmission type:** The effect of AMT on fuel consumption and CO_2 emissions was investigated through in series of test cases by selecting the respective scalar values in the tool. The traction interruption time was also adjusted to 1 s.
- **Transmission efficiency:** The case of system efficiency was approached by reducing torque losses in the gear and the axle maps by 20%, with the potential reduction reaching up to 25% in the literature [29]. The simulation cases first examined axle and gearbox efficiency individually and subsequently their combined effect.

Vehicle mass: In real-world conditions, full vehicle loading can be realized by maxing out either the payload or volume capacity. In both cases, reductions in the vehicle's curb weight result in lower CO_2 g/tkm. The current study focused on changes in the vehicle's curb weight, while the payload values remained the same. It should also be noted that the extra mass accounting for vehicle body and/or the trailer mass was also considered stable in all cases. Finally, the results were correlated as changes in vehicle mass against changes in CO_2 g/tkm emissions.

Energy audit

The energy audit investigated the vehicle's energy distribution in order to assist in prioritizing areas for future development depending on the vehicle use. With the scope to facilitate the research the various energy flows were split into *engine* and *vehicle* losses. The engine losses include engine friction, exhaust thermal energy, coolant heat rejection, heat transfer to ambient, and intercooler losses. Vehicle losses on the other hand include the losses originated in the auxiliary systems, gearbox, retarder, axle, and brakes, as well as the air drag and rolling resistance.

In the case of vehicle losses, the approach was straight forward by estimating the total energy attributed to each loss type as they were produced directly by VECTO. However, the analysis of the engine losses was realized based on an extended Willans model, which used input parameters from the second-by-second simulation results. The recorded engine speed, power output at the crankshaft and power output at the gearbox shaft were used as input in the model which subsequently estimated the friction, exhaust, cooling, intercooler losses and heat transferred to ambient The model calculated the following parameters, which were used to estimate the various loss types: actual cylinder pressure, air temperature, pre and post intercooler temperature and intake air density. Accordingly, following the air flow path, the model estimated the energy at each step in the following order: intercooler, heat transfer to environment, cooling losses and exhaust losses. A more detailed description of the aspects of the model and the approach can be found in [23,30].

Results and discussion

Baseline vehicles

Table 3 presents the fuel consumption (FC) and CO_2 emissions results by driving cycle for all baseline vehicles. Despite that the current study utilizes CO_2 metrics and more specifically g per tonne-kilometre, the table also presents fuel consumption to provide a better overview of the results. It should be also noted that the expression of metrics in l/100tkm for fuel consumption and g/tkm for CO_2 emissions refer to the fuel consumed/CO_2 emitted per tonne of transferred payload and not to the whole mass of the vehicle.

Table 3: Fuel consumption and CO2 emissions of baseline vehicles by driving cycle.

Vehicle	Cycle	FC l/100km	FC l/100tkm	CO_2 g/km	CO_2 g/tkm
Class 2	Long haul	25.1	2.5	660.6	66.9
	Regional delivery	21.3	7.0	559.9	185.2
	Urban delivery	25.9	8.6	681.5	225.4
Class 4	Long haul	30.4	2.2	798.5	57.0
	Regional delivery	24.3	5.5	637.7	144.9
Class 5	Long haul	36.8	1.9	966.3	50.1
	Regional delivery	36.8	2.9	968.8	75.1

Class 2 and 4 trucks emitted the lowest CO_2 g/tkm in the long haul cycle, which was 63% lower than in other cycles. The difference can be attributed to the fact that these vehicles are considered to tow a trailer in these cycles, which increases their payload that in turn decreases their emissions. This increase in transportation efficiency is more apparent with a closer examination of the CO_2 g/km metric. Both vehicles had lower CO_2 g/km emissions in regional delivery than in the long haul, but the difference was between 15 – 20%.

Class 5 vehicle presented lower CO_2 g/tkm emissions by 33% in the long haul cycle than in the regional delivery. However, as there were no drastic differences in the vehicle configuration and an examination of the CO_2 g/km metric in this case showed a reduction of 0.3% in the long haul for the Class 5 vehicle.

Individual technologies

The current section presents the results on CO_2 emissions of CdA decrease, A energy efficiency class tyres, 50% engine brake thermal efficiency, engine downspeeding, AMT and transmission efficiency. The impact on CO_2 emissions in all cases represents a change in g/tkm, while all the estimated CO_2 g/tkm values.

Figure 3 presents the results a reduction of 20% in the CdA in the rigid trucks and 25% in the tractor trailer.

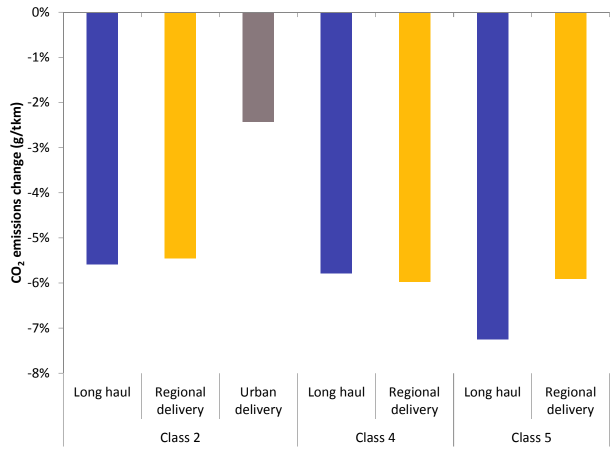

Figure 3: Effect of CdA reduction on CO2 emissions by vehicle type (Class 2 and 4: 20% reduction. Class 5: 25% reduction).

Reduction in the CdA delivered the highest benefits in the cycles with the higher speed, with an estimated reduction of 5.6% in the Class 2 vehicles and 7.2% in the Class 5 in the long haul cycles. The effect diminished in the urban delivery cycle for the Class 2, as it has the lower average speed, but nonetheless showed a reduction of 2.4%.

Figure 4 presents the effect of fitting A class tyres in the vehicles on CO_2 emissions and shows that the effect is more apparent in the long haul cycles and this could be attributed to the higher payload in these cycles. The dependence on the payload can be shown in the difference between long haul and regional deliver cycles in the Class 5 vehicle were is was smaller compared to the rigid trucks.

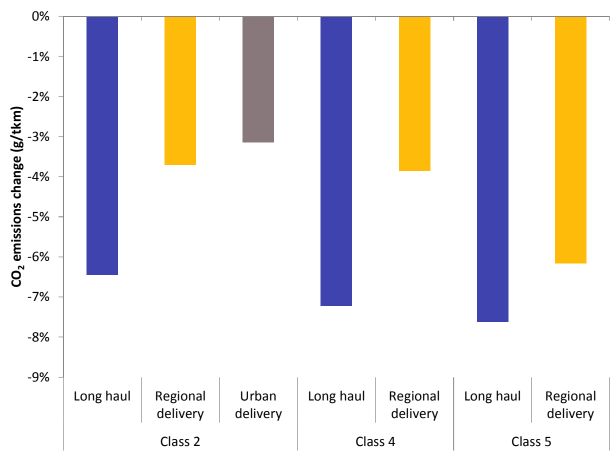

Figure 4: Use of A energy efficiency class tyres on CO_2 emissions by vehicle type.

The application of A energy efficiency class led to a reduction of 6.5% in the Class 2 and 7.6% in the Class 5 in the long haul cycle, while in the regional cycle the CO_2 reduction was 3.7% and 6.2% respectively.

Figure 5 presents the results for 50% engine brake thermal efficiency, where the effect is more apparent in the more transient cycles. Vehicles in these cycles operate longer outside their optimum operational range, where engine efficiency is nonetheless high. In this sense improvements in the less efficient operational points have a higher impact on CO_2 emissions.

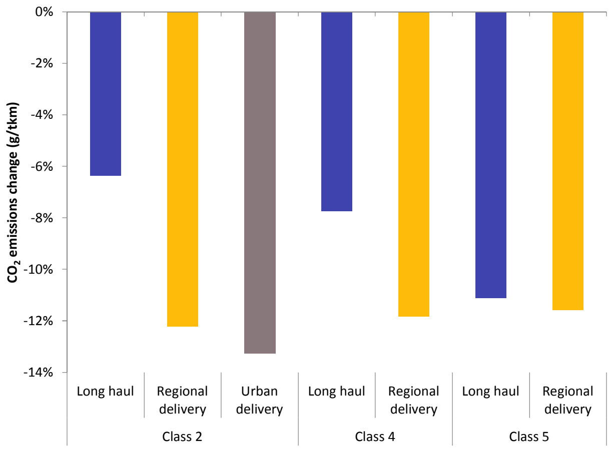

Figure 5: Effect of 50% engine brake thermal efficiency on CO_2 emissions by vehicle type.

The highest reduction in CO_2 emissions is observed in the urban delivery cycle and it was estimated at 13%. Reductions in the regional delivery cycle were estimated at 12.2% in the Class 2 and 11.6% in the Class 5. In general, engine efficiency seems to be highly influencing factor on CO_2 emissions as a study suggested that increase in energy peak efficiency can decrease fuel consumption between 14 and 17% [31].

Figure 6 presents the effect of engine downspeeding for all the investigated vehicles over the tested cycles and show that the CO_2 decrease is higher in the regional delivery than in the long haul cycle in the rigid trucks, while the tractor-trailer presents a slightly different trend. The effect of downspeeding in this case is higher in the long-haul cycle than in the regional delivery, but the benefits in both cycles are below 1%. The urban delivery cycle was not investigated as without being ruled out, downspeeding according to the literature focuses on long haul and regional routes [28,32]. The estimated reduction for the Class 2 truck is 3.5% for the regional cycle and 2.9% for the long haul cycle, with the Class 4 following a similar trend. In comparison to the rigid trucks the figures are lower for tractor-trailer with a reduction of 0.5% in the long haul cycle and 0.2% in the regional cycle for the Class 5 vehicle.

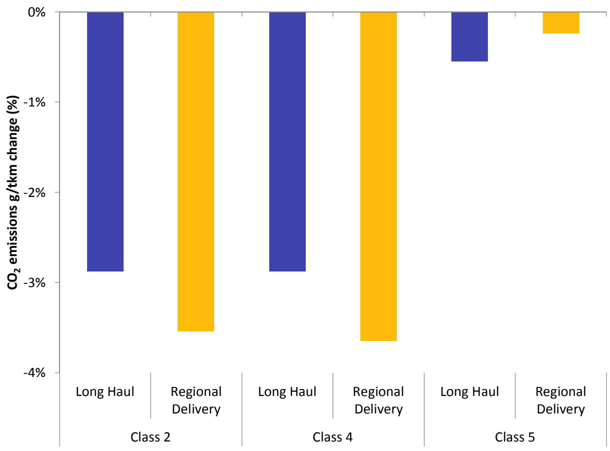

Figure 6: Effect of engine downspeeding on CO_2 emissions.

Engine downspeeding in Classes 2 and 4 has shown a higher decrease in emissions in the regional delivery than in the long haul cycle. The vehicles' fuel maps were rescaled linearly, resulting in a downspeeding even in the less efficient operating points, which could provide significant benefits when the vehicle operates within this range. The downspeeding effect therefore could be more apparent in transient cycles than in the less transient ones, such as the long haul where the vehicle could nonetheless be operating mostly within its most efficient range. An NHTSA study suggests that the benefits of downspeeding could be over 4% in low speed cycles, with low payload, while at higher speeds the benefits are about 2% [32]. It could be suggested, however that stronger downspeeding (>100 RPM) could be examined for Class 5 vehicles, as the potential for higher benefits could lie in this range.

Downspeeding, on the other hand, could pose an additional stress on the driveline due to the application of higher torque, which in some cases can increase by up to 29% [33]. The use of additional material to strengthen components in this case could potentially increase the manufacturing costs in order to maintain the component's weight close to their non-downsped counterparts.

Figure 7 presents the results for AMT transmission types compared to the baselines. The effect was more prominent in transient cycles due to the increased gear shifting that could be performed more efficiently by the AMT.

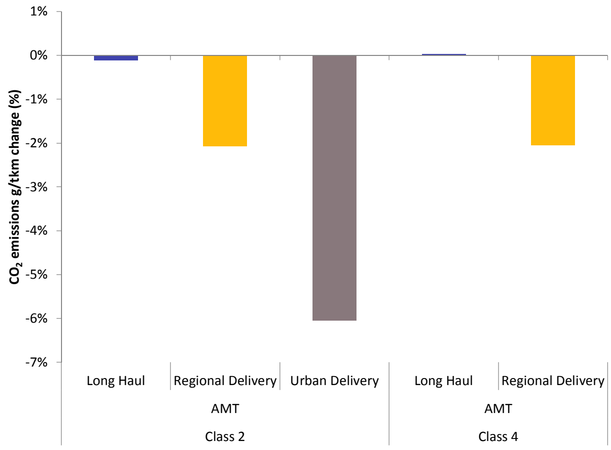

Figure 7: Effect of AMT on CO_2 emissions.

Changing from manual to AMT showed a reduction in the regional and urban delivery cycles in the rigid trucks. The effect of the AMT was more apparent in these cases as the more transient conditions with increased gearshifting offered a better proving ground for demonstrating the gearbox capabilities. It could be concluded that in general a switch from manual to AMT would be beneficial in any of the investigated mission profiles. NHTSA suggests improvements between 3 – 10% in the fuel economy for the US [32], where AMT has a lower market penetration [21]. Switching to AMT is also an enabler to achieve a certain level of downspeeding as there would be a demand for increased shifting, which could be unachievable with a manual gearbox.

It should also be pointed out that more research is required to investigate other transmission options such as automatic transmission, while Infinite Variable Transmission (IFV) has been suggested as an option in the case of city buses for a 11 t vehicle [34]. Although, implementation of this technology could be difficult in heavier vehicles due to the increased torque in the driveline components, its use could be examined in lighter trucks for urban delivery.

Figure 8 present the results of increased transmission efficiency for all vehicle types for reduced torque losses by 20%. The reduction is almost equal in all cases between an improved axle and an improved gearbox, while as it could be expected, the combination of an improved axle and gearbox delivers the highest reduction. The improvement for a combined improved axle and gearbox for the Class 2 truck was 2.8% in the long haul and around 3% in both the regional and urban delivery. The reductions were similar in the Class 4 truck and they were estimated at 2.5% in the long haul cycle and 2.9% in the regional delivery. In the case of tractor-trailers, the reduction is a bit lower and it was estimated at 1.7% in the long haul cycle and 1.9% for the Class 5 vehicle.

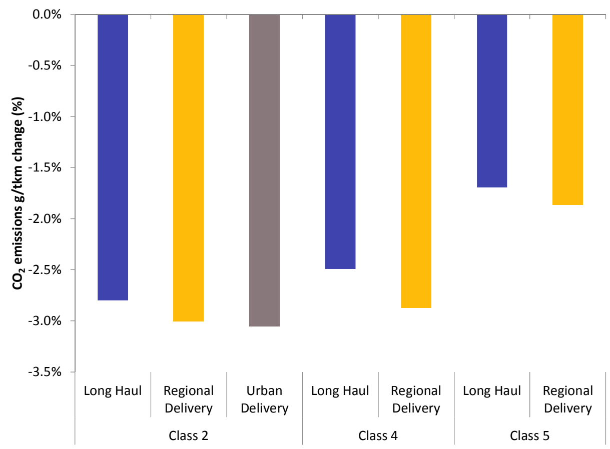

Figure 8: Effect increased gearbox and axle efficiency on CO_2 emissions.

Sensitivity analysis

The current section presents the results of the series of the sensitivity analyses on aerodynamics, auxiliaries, curb weight, rolling resistance and engine losses. The analysis found that there were similar trends between the vehicles so that presentation will focus on some typical examples and extend whenever is needed.

Table 4 presents the regression coefficients for the all vehicles by driving cycle, which serve as a direct metric for the sensitivity analysis. The CO_2 emissions can be estimated by multiplying the relative factor change with the respective regression coefficient value. Statistical regression showed that all factors are linearly correlated to CO_2 emissions, with R^2 being very close to 1 and for this reason only the regression coefficients are provided.

Table 4: Regression coefficient by driving cycle for all vehicles. Correlation of relative factor change to relative CO2 emissions (g/tkm) change.

Vehicle	Case	Cycle		
		Long haul	Regional delivery	Urban delivery
Class 2	Aerodynamics	0.29	0.28	0.12
	Auxiliaries	0.04	0.05	0.08
	Curb weight	0.10	0.14	0.23
	Rolling resistance	0.13	0.14	0.12
	Engine constant and speed related losses	0.21	0.26	0.31
	Engine constant losses	0.08	0.11	0.14
	Engine speed related losses	0.13	0.15	0.17
Class 4	Aerodynamics	0.28	0.30	-
	Auxiliaries	0.03	0.05	-
	Curb weight	0.09	0.13	-
	Rolling resistance	0.13	0.15	-
	Engine constant and speed related losses	0.22	0.27	-
	Engine constant losses	0.08	0.11	-
	Engine speed related losses	0.13	0.15	-
Class 5	Aerodynamics	0.29	0.22	-
	Auxiliaries	0.04	0.03	-
	Curb weight	0.09	0.12	-
	Rolling resistance	0.12	0.10	-
	Engine constant and speed related losses	0.20	0.24	-
	Engine constant losses	0.10	0.12	-
	Engine speed related losses	0.10	0.11	-

Figure 9 present a graphical representation of the vehicle regression coefficients presented in the Table 4 for the Class 2 truck over the long haul cycle, as a typical example of the sensitivity analyses.

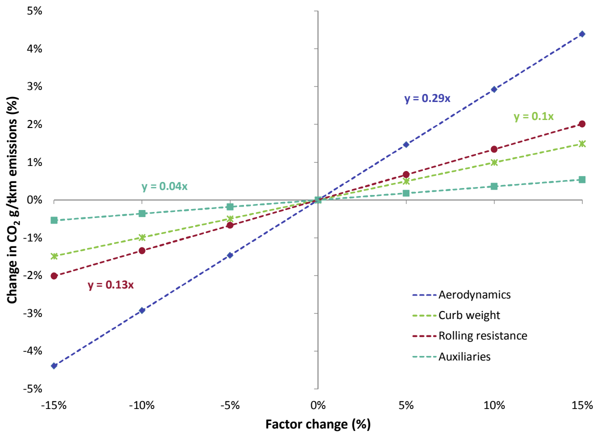

Figure 9: Sensitivity analysis of vehicle related factors for the Class 2 truck over the long haul cycle.

Regarding vehicle related factors, the highest reduction is observed for aerodynamic improvements for all vehicles in all cycles, except for the urban cycle of the Class 2 truck, where curb weight reductions are more sensitive. This could be expected, as the aerodynamic resistance is affected significantly by the vehicle speed, whereas in the case of the urban cycle the effect is less prominent due to the lower speeds. A study on the effect of boat tails has shown a decrease of 9.4% in drag coefficient through a simulation approach [35], while another study suggested a decrease between 5-10% [36]. These values, based on the sensitivity analysis would deliver a decrease between 1.5 and 2.9% in CO_2 emissions, while improvements in the aerodynamic characteristics are considered to be the easiest first step in increasing transportation efficiency [5]. From a fuel consumption point of view, a study [37] suggested that boat tails could deliver a reduction between 2-3%, while another one estimated a reduction of 3.9% in long-haul application for a tractor-trailer. In these cases if the fuel consumption metric is taken into consideration then it would need a CdA reduction between 7 and 12%. Higher reduction in fuel consumption (7%) was found with the use active air flow systems that increase the pressure in the low pressure points in the truck [37], which could effectively reduce CdA by up to 21%.

Rolling resistance was more sensitive in the transient cycles than in the less transient ones A study has shown that a drastic decrease in RRC of about 25% in both tractor and trailer tyres would result in 5% lower CO_2 g/tkm emissions [38]. Based on the sensitivity analysis the reduction in CO_2 would be about 3%. Two more sources point out that reduction in fuel consumption for low rolling resistance tyres is 2% [39] and 5% [40], without giving further information on the rolling resistance values of the tested tyres.

It should be pointed out that the trailer's tyres were considered to maintain the same rolling resistance value in the respective sensitivity analysis, as the investigation focused on vehicles and not trailers. In general the study did not take specifically into consideration any changes on trailer that could have an impact on CO_2 emissions and it is suggested that modifications in this field should be investigated further.

In the more transient cycles, the analysis found that the curb weight has a more significant influence. This difference could be attributed to the more transient conditions where mass differences would affect more the required energy during acceleration. A study suggested that a reduction of 400 kg could reduce fuel consumption by 0.7%, while another one suggested that lightweighting could decrease emissions by 2.2% [31], without specifying the exact extend of the mass reduction. However, a source suggested that lightweighting a tractor-trailer vehicle by 1800 kg is a feasible solution [41]. Taking into account this reduction in the Class 5 vehicle then the decrease would be estimated at ~1.5% both in the g/tkm and the g/km CO_2 metrics.

Auxiliaries were found to have a lower impact on the emissions compared to other factors. However, auxiliaries were considered to have constant power requirements throughout the cycle, derived from VECTO generic values, while a more dynamic approach could deliver different results. It is noticeable that auxiliary sensitivity is higher in the more transient cycles (urban and regional delivery), despite the lower baseline load in these cycles. An explanation for this difference could be attributed to the auxiliary power consumption during the stopping events as they pose a constant load to the engine which results in an increased power share compared to other factors. It was found that improvements in the cooling fan can reduce fuel consumption between 2-3% [42], while LED lighting [43] and electrohydraulic steering [44] are suggested in order reduce fuel consumption.

The engine related factors results have shown that a reduction in engine speed dependent losses yielded higher benefits in the case of rigid trucks. In the Class 2 truck the two types of losses converged in the urban delivery cycle, but engine speed related losses still had a higher impact. The case of tractor-trailer showed a convergence between the two types of losses, but it seemed to be more dependent on constant engine losses. According to the literature, a reduction in engine parasitic and friction reduction is suggested to deliver a CO_2 decrease between 1 – 1.5% for regional and highway driving [42]. The latter value it could be translated approximately in a 5-7.5% internal friction reduction in the case of the tractor-trailer.

Energy audit

The analysis presents first the total energy distribution as it was estimated from the VECTO second-by-second results followed by the engine energy break down as it was estimated by the extended Willans model. The rigid trucks showed a similar trend as a group and for this reason, the discussion focused mainly on Class 2 and 5 vehicles and whenever needed it extended into more details.

Figure 10 presents the total energy distribution in rigid trucks and shows that the majority of the energy, apart from the engine losses, was attributed to overcoming aerodynamic resistance in the long haul and regional delivery cycles. In the case of the Class 2 truck, the losses due to air drag were estimated at ~16% for both the long haul and regional delivery. Rolling resistance was the second most influencing factor in these cycles with estimated energy distribution of 12.3% for the long haul and 7.6% for the regional delivery cycles of the Class 2 truck. Brake losses had the highest energy share for the Class 2 vehicle in the urban delivery cycle amounting to 8.9% of the total losses, followed by air drag (6.8%) and rolling resistance (6.2%). In the same vehicle, auxiliary losses were also increased compared to the other cycles reaching up to 4.6% in the urban cycle, while in the long haul and regional delivery cycles were estimated at 3.1% and 1.9% respectively.

Figure 11 presents the engine energy break down for the rigid trucks. The majority of the energy in all cases was lost to the exhaust gases accounting for 32% in the long-haul cycle and 39.4% in the regional delivery cycle for the Class 2 truck. The second highest losses are attributed to cooling; these were estimated at 16.4% and 11.5% in the long haul and regional delivery cycles respectively for the Class 2 truck. On the other hand, exhaust losses were found to be significantly high in the urban delivery cycle, reaching up to 47.7% while losses attributed to cooling were estimated at 5.9%.

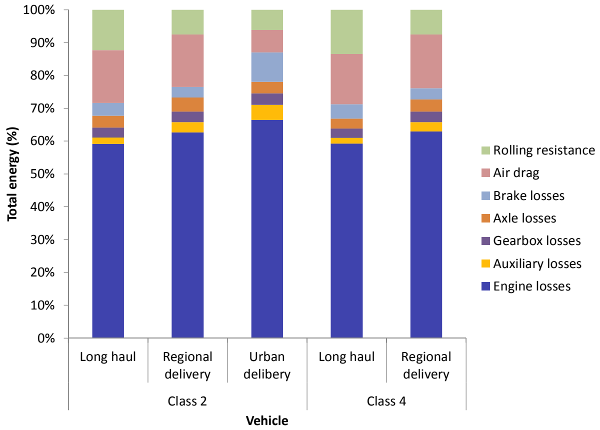

Figure 10: Total energy distribution in rigid truck baselines.

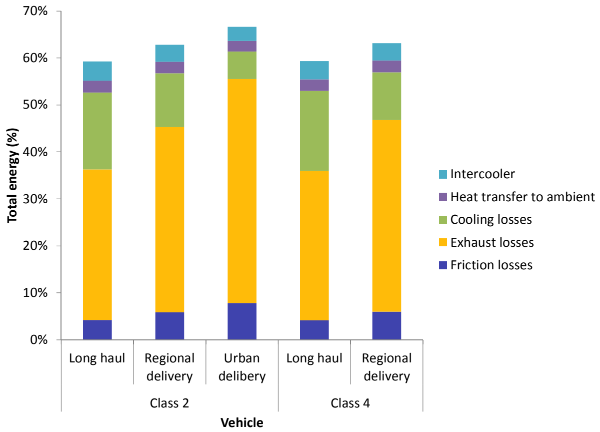

Figure 11: Breakdown of engine energy losses for the rigid truck baselines.

Figure 12 presents the energy distribution in the tractor-trailer and shows that about 60% of the total energy was attributed to engine losses, which are analysed further in the following paragraphs. The next more influencing factor was the aerodynamic resistances which were estimated at 16.5% and 13.8% in the long haul and regional delivery cycles respectively. The attributed energy to rolling resistance was also high and it was estimated at 14.3% for the long haul cycle and 11.8% for the regional delivery.

Figure 13 presents the engine energy losses break down, where the majority of the losses were attributed to exhaust gases, which were found to be at 35.6% in the long haul and 39.8% in the regional delivery. Subsequently, intercooler exhibited high losses, which were estimated at ~6% in both cycles. Cooling losses were lower compared to rigid trucks and were found to be 9% in the long haul and 6.2% in the regional delivery.

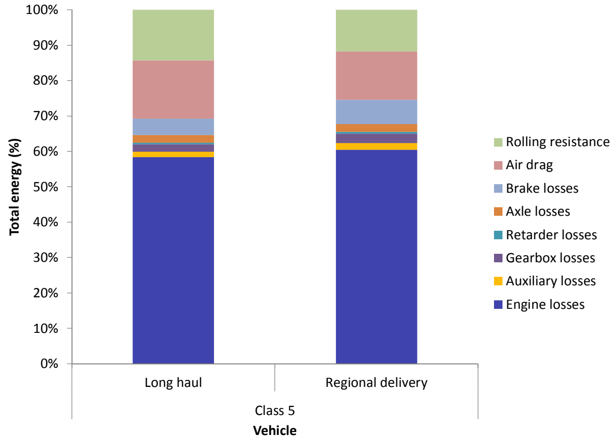

Figure 12: Total energy distribution in tractor-trailer baselines.

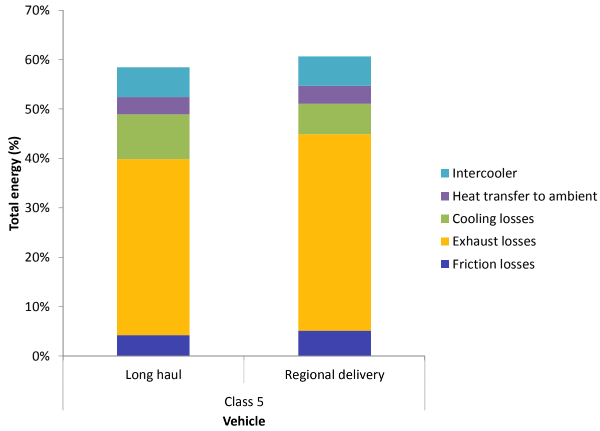

Figure 13: Breakdown of engine energy losses for the tractor-trailer baselines.

The energy audit showed that the majority of the energy in the engine losses in most cases was lost in the exhaust gases in a range of 37% to 48% of the total energy, followed by cooling losses that were estimated between 10% and 17%. Exhaust losses were found to be lower in the more transient cycles (regional and urban delivery), while cooling losses had increased in these cases. In general, it was observed that overall engine losses increased in the more transient cycles, which is attributed to the engine operating longer in low efficiency points. Applications of energy recovery systems in these fields, such as waste heat recovery [45] can contribute in mission profiles that exhibit driving in high operation points.

Friction losses could appear low, but improvements in this field should be considered. A reduction in this field could be easier to address in the short-term by improving engine characteristics, such as use of low viscosity motor oil [46]. Application of low viscosity oils can be implemented in vehicles that are already in use in order to reduce CO_2 emissions, as vehicle operators could be reluctant to use low viscosity oils in past. Such oils could be recommended by the manufacturer, but it could be chosen over for a more viscous lubricant as it could be considered that would provide better protection to the engine.

Regarding the vehicle related losses, an examination of the energy audit reveals that the highest amount of energy is attributed to overcome aerodynamic resistances in all cases in the long haul and regional delivery cycles, with the brake losses having a higher share in the urban cycle for the Class 2 vehicle. The sensitivity of the aerodynamic coefficient should be taken into consideration as air drag determination in heavy-duty vehicles is realized through a constant speed test. The methodology presents a repeatability standard deviation of 1.8% and a reproducibility standard deviation of 2.2% [47], which should be taken into consideration when estimating the effect of air drag improvement devices, such as roof fairings. In this case, it could be suggested that the effect of such devices to be measured in the same tests as in the baseline measurements to reduce any type of measurement bias.

Braking losses comprise about 3-5% of the losses in the long haul cycle for all vehicles, while they slightly increase in the regional delivery up to about 7%. Also, the energy which is lost in decelerating/stopping the vehicle includes the retarder losses in the case of the tractor-trailer, which are estimated to about 0.5% of the total energy. The difference between long haul and regional delivery cycle can be attributed to the latter being more transient with higher acceleration/deceleration time and increased number of stops. Part of the energy which is lost to braking could be retrieved with hybridization of the powertrain, which in addition to energy recuperation can also reduce fuel consumption at low engine efficiency operating points [48]. However, hybrid powertrains have not been implemented into the VECTO simulation tool yet and the effect could not be quantified.

The overall auxiliary power consumption followed a trend, where a lower proportion of the total energy was attributed in the long haul and higher in the regional and urban delivery. This difference could be explained due to the higher stop time of these cycles where the engine is idling and provides energy to compensate the auxiliary loads. Also, the increased transient conditions could contribute in this increase as the engine is working longer time below its optimum efficiency.

In addition, as the study examined only standard body types, it did not take into consideration potentially more energy demanding applications such as municipal utility and trucks with fridge units. In these cases, the variations in the power demand could have a different impact on CO_2 emissions. Despite the seemingly low impact in the examined cases, improvements should be taken into consideration as vehicle's mechanical components like cooling fan and air compressor could be eventually be replaced by electrified versions [42,49]. Electrified components could reduce overall emissions and energy consumption, but they have higher power requirements which could be addressed by hybrid configurations [42].

Vehicle manufacturers offer predictive cruise control [50,51] that can assist in reducing energy consumption [44]. Predictive cruise control utilizes GPS data to anticipate the forthcoming road conditions such as slope grade and optimizes gear shifting to the most efficient way. This case was not examined as the utilized software version had not implemented this feature and it should be investigated further as it is suggested that fuel consumption can be reduced by 5% in long haul application [31].

Conclusions

The current study investigated the effect of individual technologies on the CO_2 emissions of three different vehicle configurations. Additionally, the study also showed the potential reduction by utilizing the best available choices in each technology category, which could be used to design vehicle configurations that would optimize CO_2 emissions depending on the intended vehicle use. Clearly there is a promising margin for CO_2 emissions reduction in Heavy Duty Trucks with currently available solutions. However a big question that has not been addressed by the present study is what is the economic viability of such improvements under the current fuel prices and market situation. In order to achieve real-world reductions, vehicle manufacturers should apply a combination of technologies depending on the intended vehicle use. A combination of different technologies could result in several synergies, but also in some trade-offs between the technologies. Vehicle simulation tools such as VECTO, capture these effects but a more refined study, coupled with real world measured data would be necessary in order to reach solid conclusions. The investigated 2015 "average" baseline vehicles can be used in such an exercise in order to assess the reduction potential of different technology packages also over real world operation.

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Disclaimer

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

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Definitions/Abbreviations

ACEA	European Automobile Manufacturers' Association
AMS	Air Management System
AMT	Automated Manual Transmission
CdA	Cross sectional area
ERTRAC	European Road Transport Research Advisory Council
ESS	Energy Saving System
FC	Fuel Consumption
HDV	Heavy-Duty Vehicle
HVAC	Heating Ventilation Air-Conditioning
JRC	Joint Research Centre
OEM	Original Equipment Manufacturer
RRC	Rolling Resistance Coefficient
VECTO	Vehicle Energy Consumption Tool

Appendix

Simulation characteristics

Table 5: Cycle characteristics by vehicle.

Vehicle	Cycle	Distance (km)	Time (s)	Average speed (km/h)	Acceleration time share (%)	Deceleration time share (%)	Cruise time share (%)	Stop Time Share (%)
Class 2	Long haul	100	4650	77.6	6.1%	5.3%	87.2%	1.4%
	Regional delivery	26	1581	58.8	15.4%	13.4%	63.9%	7.2%
	Urban delivery	28	3250	30.8	17.3%	14.3%	48.8%	19.7%
Class 4	Long haul	100	4755	75.9	7.5%	6.0%	85.0%	1.4%
	Regional delivery	26	1581	58.8	15.7%	13.7%	63.4%	7.2%
Class 5	Long haul	100	4574	78.8	5.2%	4.2%	89.1%	1.5%
	Regional delivery	26	1577	59.0	17.8%	14.8%	60.2%	7.2%

Table 6: Baseline vehicles' characteristics.

Vehicle		**Class 2**	**Class 4**	**Class 5**
Vehicle type		Rigid truck		Tractor trailer
Gross vehicle weight (t)		12	18	40
Gross combined weight in long haul cycle (t)		22.5	36	
Empty mass (kg)		5850	6000	7100
Extra mass (kg)	Urban/ Delivery cycles	1900	2100	7500
	Long haul	5300	7500	7500
Reference payload (kg)	Urban/ Delivery cycles	3024	4400	12900
	Long haul	9872	14000	19300
CdA (m^2)		4.3	5.1	6.1
Auxiliary use (kW)	Urban/ Regional delivery cycles	3.41/ 3.67	3.92	4.17
	Long haul	3.86	4.24	4.44
Rolling resistance coefficient (-)		0.00546	0.00546	0.00546
Axle weight distribution	Other cycles	0.45/0.55	0.45/0.55	0.25/ 0.25/0.5
	Long haul	0.225/ 0.325/0.45	0.2/0.3/ 0.5	0.2/ 0.25/0.55
Transmission	Gearbox type	6 - speed Manual		12 – speed AMT
	Gearbox ratios	6.75 -0.78		14.93 - 1.0
	Gearbox efficiency	Indirect gears: 96%		
		Direct gears: 99%		
	Axle configuration	4x2		4x2
	Axle ratio	4		2.59
	Axle efficiency	98%		
Wheels		245/70 R19.5	295/80 R22.5	315/70 R22.5

Engines

Table 7 presents the engine characteristics that were considered in the simulation, along with indicative market-available engines for comparison for the same vehicle class.

Table 7: Comparison of engine technical characteristics of baseline vehicles and market-available engines for Class 2.

Class 2						
OEM	Engine	Capacity (cm^3)	Stroke (mm)	Power (kW)	Max Torque (Nm)	Source
-	Simulation	5800	135	167	815	
DAF	PACCAR PX-5 engine	4500	135	157	850	[52]
DAF	PACCAR PX-7 engine	6700	135	172	900	[53]
Daimler	OM934 LA - 5.1L	5100		170	900	[54]
Iveco	Tector 5	4500		137	700	[55]
Iveco	Tector 7	6700		185	850	[55]
MAN	MAN D0836 CR	6900		184	1000	[56]

Table 8: Comparison of engine technical characteristics of baseline vehicles and market-available engines for Class 4.

Class 4						
OEM	Engine	Capacity (cm^3)	Stroke (mm)	Power (kW)	Max Torque (Nm)	Source
-	Simulation	6755	135	167	900	
DAF	PACCAR PX-7 engine	6700	135	172	900	[53]
MAN	MAN D0836 CR	6900		213	1150	[56]
Volvo	D8K250	7700	135	184	950	[57]

Table 9: Comparison of engine technical characteristics of baseline vehicles and market-available engines for Class 5.

Class 5						
OEM	Engine	Capacity (cm^3)	Stroke (mm)	Power (kW)	Max Torque (Nm)	Source
-	Simulation	12706	164	302	2000	
DAF	MX-13 375	12900	162	303	2000	[58]
Daimler	OM 471 LA 12.8L	12800		310	2100	[59]
MAN	MAN D2676	12420	166	309	2100	[60]

Individual technologies

Table 10to Table 15 present the absolute values of CO_2 emissions and the respective change from the baseline for the investigated individual technologies.

Table 10: CO_2 emissions and relative change for aerodynamic reductions (20% in rigid trucks, 25% in tractor trailer) by vehicle type.

Truck	Cycle	CO_2 (g/km)	CO_2 (g/tkm)	CO_2 change (g/km)	CO_2 change (g/tkm)
Class 2	Long haul	623.7	63.2	-5.6%	-5.6%
	Regional delivery	529.4	175.1	-5.5%	-5.5%
	Urban delivery	664.9	219.9	-2.4%	-2.4%
Class 4	Long haul	752.3	53.7	-5.8%	-5.8%
	Regional delivery	599.6	136.3	-6.0%	-6.0%
Class 5	Long haul	897.4	46.5	-7.2%	-7.2%
	Regional delivery	914.8	70.9	-5.9%	-5.9%

Table 11: CO_2 emissions and relative change for an energy efficiency class tyres (RRC = 4 kg/t) in all wheels by vehicle type.

Truck	Cycle	CO_2 (g/km)	CO_2 (g/tkm)	CO_2 change (g/km)	CO_2 change (g/tkm)
Class 2	Long haul	618.0	62.6	-6.5%	-6.5%
	Regional delivery	539.2	178.3	-3.7%	-3.7%
	Urban delivery	660.1	218.3	-3.1%	-3.1%
Class 4	Long haul	740.8	52.9	-7.2%	-7.2%
	Regional delivery	613.1	139.3	-3.9%	-3.9%
Class 5	Long haul	893.7	46.3	-7.6%	-7.6%
	Regional delivery	912.3	70.7	-6.2%	-6.2%

Table 12: CO_2 emissions and relative change for maximum 50% brake thermal efficiency engines by vehicle type.

Truck	Cycle	CO_2 (g/km)	CO_2 (g/tkm)	CO_2 change (g/km)	CO_2 change (g/tkm)
Class 2	Long haul	618.5	62.7	-6.4%	-6.4%
	Regional delivery	491.5	162.5	-12.2%	-12.2%
	Urban delivery	591.1	195.5	-13.3%	-13.3%
Class 4	Long haul	736.7	52.6	-7.7%	-7.7%
	Regional delivery	562.2	127.8	-11.8%	-11.8%
Class 5	Long haul	859.9	44.6	-11.1%	-11.1%
	Regional delivery	859.6	66.6	-11.6%	-11.6%

Table 13: CO_2 emissions and relative change for downspeeding by vehicle type.

Truck	Cycle	CO_2 (g/km)	CO_2 (g/tkm)	CO_2 change (g/km)	CO_2 change (g/tkm)
Class 2	Long Haul	641.6	65.0	-2.9%	-2.9%
	Regional Delivery	540.1	178.6	-3.5%	-3.5%
Class 4	Long Haul	775.5	55.4	-2.9%	-2.9%
	Regional Delivery	614.5	139.7	-3.6%	-3.6%
Class 5	Long Haul	961.0	49.8	-0.5%	-0.5%
	Regional Delivery	966.5	74.9	-0.2%	-0.2%

Table 14: CO_2 emissions and relative change for AMT transmission type by vehicle type.

Truck	Cycle	CO_2 (g/km)	CO_2 (g/tkm)	CO_2 change (g/km)	CO_2 change (g/tkm)
Class 2	Long Haul	659.9	66.8	-0.1%	-0.1%
	Regional Delivery	660.6	66.9	-2.1%	-2.1%
	Urban Delivery	559.9	185.2	-6.0%	-6.0%
Class 4	Long Haul	798.8	57.1	0.0%	0.0%
	Regional Delivery	624.7	142.0	-2.1%	-2.1%

Table 15: CO_2 emissions and relative change for efficient transmission by vehicle type.

Truck	Cycle	Component	CO_2 (g/km)	CO_2 (g/tkm)	CO_2 change (g/km)	CO_2 change (g/tkm)
Class 2	Long Haul	Axle	651.2	66.0	-1.4%	-1.4%
		Gearbox	651.4	66.0	-1.4%	-1.4%
		Gearbox and Axle	642.1	65.0	-2.8%	-2.8%
	Regional Delivery	Axle	551.9	182.5	-1.4%	-1.4%
		Gearbox	552.6	182.8	-1.3%	-1.3%
		Gearbox and Axle	543.1	179.6	-3.0%	-3.0%
	Urban Delivery	Axle	670.9	221.8	-1.6%	-1.6%
		Gearbox	670.1	221.6	-1.7%	-1.7%
		Gearbox and Axle	660.7	218.5	-3.1%	-3.1%
Class 4	Long Haul	Axle	788.7	56.3	-1.2%	-1.2%
		Gearbox	787.8	56.3	-1.3%	-1.3%
		Gearbox and Axle	778.6	55.6	-2.5%	-2.5%
	Regional Delivery	Axle	628.1	142.8	-1.5%	-1.5%
		Gearbox	627.4	142.6	-1.6%	-1.6%
		Gearbox and Axle	619.4	140.8	-2.9%	-2.9%
Class 5	Long Haul	Axle	957.9	49.6	-0.9%	-0.9%
		Gearbox	958.4	49.7	-0.8%	-0.8%
		Gearbox and Axle	949.9	49.2	-1.7%	-1.7%
	Regional Delivery	Axle	960.7	74.5	-0.8%	-0.8%
		Gearbox	958.7	74.3	-1.0%	-1.0%
		Gearbox and Axle	950.7	73.7	-1.9%	-1.9%

Literature values on fuel consumption

Table 16: Literature values of the effect on the fuel consumption by category.

<table>
<tr><td>Category</td><td>Technology</td><td>Reduction on fuel consumption</td><td>Source</td></tr>
<tr><td rowspan="3">Aerodynamics</td><td>Boat tails</td><td>3 – 8%</td><td rowspan="2">[37]</td></tr>
<tr><td>Active flow control</td><td>7%</td></tr>
<tr><td>Side, underbody panels and boat tail</td><td>3.9%</td><td>[29]</td></tr>
<tr><td>Auxiliaries</td><td>Improved cooling fan</td><td>2 – 3%</td><td>[42]</td></tr>
<tr><td rowspan="3">Engine</td><td>Downspeeding: Engine’s sweet spot RPM reduction and faster gear ratios</td><td>2 – 4%</td><td>[32]</td></tr>
<tr><td>Engine efficiency: Improvements in pistons, bearings and valve trains with proper coating</td><td>1 – 1.5%</td><td>[42]</td></tr>
<tr><td>Engine efficiency: Increased aftertreatment efficiency lead to better combustion system optimization with higher cylinder pressure and injection</td><td>0.5 - 2%</td><td>[44]</td></tr>
<tr><td rowspan="2">Mass</td><td rowspan="2">Mass reduction – use of lightweight materials</td><td>0.7% for 400 kg</td><td>[61]</td></tr>
<tr><td>2.2%</td><td>[31]</td></tr>
<tr><td rowspan="3">Rolling resistance</td><td rowspan="3">Low rolling resistance tyres</td><td>5%</td><td>[40]</td></tr>
<tr><td>2%</td><td>[39]</td></tr>
<tr><td>3%</td><td>[62]</td></tr>
<tr><td rowspan="2">Transmission</td><td>AMT</td><td>3 – 10%</td><td>[32]</td></tr>
<tr><td>Low viscosity lubricants in transmission</td><td>1 – 4%</td><td>[63]</td></tr>
</table>