Service Request 9
under Framework Contract no CLIMA.C.2./FRA/2013/0007
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Final Report

Support for preparation of the impact assessment for CO_2 emissions standards for Heavy Duty Vehicles

Version 13-09-2018

TNO innovation for life | TU Graz Graz University of Technology | CE Delft | icct THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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1 Introduction

1.1 General

The Service Request 9 (SR9) project is aimed at providing support to the European Commission for the preparation of an impact assessment for setting CO_2 emission standards for heavy duty vehicles. The project has been carried out by a consortium consisting of TNO, TU Graz, CE Delft and ICCT under the Framework Contract nº CLIMA.C.2./FRA/2013/0007.

This report, including the annexes, presents results in the different tasks of Service Request 9. Results that were used by the Commission in its impact assessment[1] are presented in the main chapters. Results that were not directly used in the impact assessment can be found in the annexes. Additional background and supportive information derived during execution of the project can be found in the annexes as well.

1.2 Objectives of the SR9 project

The objectives of Service Request 9 are:
1. To provide provisional baseline fuel consumption values covering HDV groups above 7.5 tons, and assessing these fuel consumption values for the relevant mission profiles.
2. To provide an assessment of the technical and cost effective potential of measures to reduce fuel consumption and CO_2 emissions from HDVs.
3. To provide an assessment of social and economic impacts of various policy options regarding CO_2 standards, based on the Commission's guideline for impact assessments.

1.3 Overview of Tasks

The project was divided in four main tasks, see Table 1. Each task is reported separately in this final report; the respective chapter numbers are indicated in the table.

Table 1: Project breakdown in tasks and in which chapters and/or annexes the results can be found.

	TASK	Chapter	Annex
1	Determination of the EU baseline fuel consumption and CO_2 emissions for the main categories of lorries	2	
	Survey and analysis of on-road records of fuel consumption for the most recent lorries (2014-2016 Euro VI of the main categories)		A
	Determination of baseline vehicles and fuel consumption and CO2 emission data for the main categories of lorries		A, B
	VECTO based calculation of the baseline fuel consumption and CO2 emissions of the main categories of lorries		A
	Comparison of fuel consumption records and VECTO calculations		A
	Methodology on possible baseline for engine-only		C
	Determination of baseline and best performer fuel consumption and CO2 emissions for the main categories of lorries in 2016-2017		A
2	Survey and assessment of the CO_2 emission abatement potential of available and new technologies	3	
	Survey of the main technologies and their individual potential to improve lorries' energy efficiency, and reduce fuel consumption and CO2 emissions	3	D
	Determination of the fuel consumption and CO2 emission reduction potential with the uptake of combined HDV fuel saving technologies for the main categories of lorries	3	D
3	Determination of the cost-effective potential for reducing HDV fuel consumption and CO_2 emissions in 2025 and 2030	4	

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=comnat:SWD_2018_0185_FIN

	Evaluation of the marginal incremental cost of each technology identified under section task 2	4	E, F
	Determination of marginal abatement cost curves for 2025-2030 of the identified technologies for the main categories of lorries	4	E
	Determination of the cost-effective potential of technology improvements for reducing fuel consumption and CO2 emissions for the main categories of lorries	4	E
4	Assessment of potential impacts related to the introduction of CO_2 emission standards (i.e. limits) for lorries	5	G, H
	Identification -in close liaison and after agreement with the Commission- of options for lorries' fuel consumption and CO2 emission standards to be assessed	5	
	Assessment of economic and social impacts of selected options	5	G,H
	Assessment of sectoral and national distribution of impacts within the EU of selected options, in particular for automotive manufacturing and transport services, and of impacts on SMEs, notably for transport services.	5	G,H
	Assessment of international competitiveness impacts of selected options	5	G,H
	Assessment of environmental impacts of selected options	5	G,H
	Consultation and dialogue with stakeholders on findings on all tasks	2, 3, 4, 5	A, D, E

1.4 Vehicle groups considered in this report

For analytical purposes in VECTO, and as part of the formal procedure for certification of CO_2 emission values based on VECTO, the heavy duty vehicle fleet is characterised by their size, configuration and use pattern. This resulted in the vehicle groups listed in Table 2.
Ten main vehicle groups can be distinguished, on the basis of their axle configuration, chassis configuration, maximum vehicle weight and the presence of a trailer. Vehicle group numbers that are between brackets in the table are not considered as main categories. During the execution of the project information from the main categories were gathered.
For the vehicle groups 4, 5, 9 and 10, responsible for the largest part of the HD CO_2 emissions, sufficient amount of fuel consumption information and details was available to further analyse and process during the execution of the individual tasks.

Table 2: Overview of VECTO vehicle groups, and (coloured) mission profiles.

Axles	Axle configuration	Chassis configuration	Maximum GVW	Vehicle group		Long haul	Regional delivery	Urban delivery	Municipal utility	Construction	Standard body	Standard trailer	Standard semitrailer
2	4x2	Rigid	>3.5 - 7	(0)			R	R			B0		
		Rigid or tractor	**7.5 - 10**	**1**			**R**	**R**			B1		
		Rigid or tractor	**>10 - 12**	**2**		**R+T**	**R**	**R**			B2	T1	
		Rigid or tractor	**>12 - 16**	**3**			**R**	**R**			B3		
		Rigid	**>16**	**4**		**R+T**	**R**		**R**		B4	T2	
		Tractor	**> 16**	**5**		**T+ST**	**T+ST**						ST1
	4x4	Rigid	7.5 - 16	(6)					R	R	B2		
		Rigid	>16	(7)						R	B5		
		Tractor	all weights	(8)						T+ST			
3	6x2/2-4	**Rigid**	**all weights**	**9**		**R+T**	**R**		**R**		B5	T2	
		Tractor	**all weights**	**10**		**T+ST**	**T+ST**						ST1
	6x4	**Rigid**	**all weights**	**11**		**R+T**	**R**		**R**	**R**	B5		
		Tractor	**all weights**	**12**		**T+ST**	**T+ST**			**R**			ST1

	6x6	Rigid	all weights	(13)						R			
		Tractor	all weights	(14)						R			
4	8x2	Rigid	all weights	(15)						R			
	8x4	Rigid	all weights	**16**						R			
	8x6 8x8	Rigid	all weights	(17)						R			

R = Rigid & Body
R+T = Rigid & Body & Trailer
T+ST = Tractor & Semitrailer

2 Determination of the EU baseline fuel consumption and CO_2 emissions (Task 1)

2.1 Introduction

The purpose of Task 1 was to determine baseline fuel consumption and CO_2 emission figures for different types of heavy duty vehicles in the European fleet. Such baseline data serve as a reference against which reduction potentials can be assessed and as a baseline for setting target values. In the end the results from Task 1 have not been used for the impact assessment and the regulatory proposal of the European Commission. Instead the Commission's proposal and the associated impact assessment were based on a report by the JRC [Fontaras, 2018][2]. The results from task 1 are documented and summarised in Annex A.

The consortium has supported the work in [Fontaras, 2018] by collection of data on VECTO results for the 2016 fleet. The results of this work are described in detail in the JRC report [Fontaras, 2018].

In Task 1 also a study has been performed in support of the possible development of engine-only standards. These results were also not retained by the Commission's impact assessment for its current legal proposal on HDV CO_2 emission standards. The results of this study on engine-only standards are summarised in Annex C.

2.2 References

[Fontaras, 2018]	*Analysis of VECTO data for Heavy-Duty Vehicles (HDV) CO_2 emission targets",* EUR 29283 EN, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/analysis-vecto-data-heavy-duty-vehicles-hdv-co2-emission-targets

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[2] The CO_2 emission reduction targets of the Commission proposal COM/2018/284 are based on actual monitoring data collected for the year 2019.

3 Survey and assessment of the CO_2 emission abatement potential of available and new technologies (Task 2)

3.1 Introduction

In Task 2 the CO_2 emission reduction potentials of single technologies (Section 3.2) as well as of combined technologies (Section 3.3) were elaborated. The potentials of the single technologies are input to the cost curves [Krause, 2018], while the simulation of technology combinations was mainly done to check if interactions between technologies exist and change the potential of the single technologies when combined with other technologies. A positive example is the CO_2 reduction from hybridisation, which showed higher reductions when combined with reduced air and rolling resistance[3].

To be able to calculate overall CO_2 abatement potentials from the existing technologies, it was planned to establish correction functions for such interactions. Some interactions were already considered in the design of the single technology data (e.g. the hybrid potential was simulated with an optimised 2025 HDV design as baseline and not for the 2016 baseline vehicle configuration).

In the following explanations, the reduction potential is defined as ratio of the CO_2 emissions with the technology to the CO_2 emissions of the baseline[4] vehicle:

$$\mathbf{R_i = 1 - CO_{2Technology\ i} / CO_{2baseline}}$$

With R_i ....reduction potential of a technology "i"
$CO_{2Technology\ i}$ ....[g CO_2/ton-km] and [g CO_2/km] from the VECTO simulation with a technology "i" implemented (per mission profile and for a weighted average of all mission profiles relevant for the vehicle group)
$CO_{2baseline}$ ....[g CO_2/ton-km] and [g CO_2/km] from the VECTO simulation for the baseline vehicle (also separated per mission profile)

To calculate the reduction potential of technology combinations, the fleet penetration of each technology in the HDV fleet has to be defined. For the average vehicle in the HDV fleet the overall CO_2 reduction compared to the baseline vehicle is then the result from the vector multiplication of the reduction potential and the penetration rate over all technologies considered:

$$\mathbf{CO_{2y}} = \Pi\ (\ 1 - \mathbf{R_{i,\,y}\ x\ P_{i,\,y}})$$

With CO_{2y} ....[g CO_2/ton-km] and [g CO_2/km] of the new vehicle fleet in the year "y" (also separated per mission profile)
$P_{i,\,y}$ ....fleet penetration rate of a technology "i" (0 = no share, 1 = 100% share) in the newly registered vehicle fleet in the year y.

The penetration rates for the relevant years and scenarios are based for the year 2016 on data gathering from fleet operators, from OEMs and expert assessments from the project team supported by interviews with other stakeholders.

The CO_2 levels of the HDV fleets in the scenarios for 2025 were calculated with the same approach. Only difference with the 2016 scenario, is that the fleet penetration rates per technology have been adjusted. This approach was applied per HDV group and for each mission profile.

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[3] lower driving resistances of a vehicle leave more energy for recuperation during braking phases, thus more electric energy is available for propulsion the lower the rolling and air resistance are.

[4] If not defined differently for specific technologies, as e.g. for hybrids and ADAS. Exceptions are described in the corresponding chapter to each technology.

3.2 Individual potential of CO_2 abatement measures (Task 2.1)

The work to elaborate the CO_2 reduction potentials for the single technologies covered:

- Set up of a “technology list” which gives an overview on all technologies which were proposed to be considered in the study
- Definition of VECTO input data sets for different vehicles within the HDV groups 4, 5, 9 and 10 for:
    - the typical vehicle, which represents the typical configuration in long haul operation in the year 2016. This vehicle data is used in the comparison with the results from fleet operator data (Annex A.2)
    - the baseline vehicle, which is defined as a vehicle designed for long haul operation but with none of the technologies on board, which had to be simulated. This baseline vehicle is therefore a virtual reference vehicle, which e.g. has no roof spoiler.
    - the average vehicle for 2016 and 2025, which represents the average long haul vehicle per group with the fleet penetration rates defined for 2016 and in a given scenario for 2025 per technology.
- Defining the effects from each single technology on the VECTO input data set (e.g. reduction of the CdxA value by xy% as effect from a technology changing aerodynamics). The magnitudes of the effects were gained from existing measurements, literature or simulations and are described in Annex D of this report.
- Elaboration of the methods to simulate effects from technologies yet not covered in the VECTO software (e.g. hybrid vehicles). The methods are described in Annex D.
- Collecting data from literature on effects on fuel consumption and/or CO_2 emissions per technology and per mission profile as basis for a comparison with the VECTO results
- Filling in reduction potentials and fleet penetration rates for each technology in the “technology list” to compute resulting CO_2 emission levels for different scenarios.

Methodology
For all technologies, which can be simulated with VECTO, the effects of the single technology were introduced into the VECTO input data of the baseline vehicle (e.g. a reduction of the CdxA value by xy%). Then Then the fuel consumption over relevant mission profiles has been calculated with VECTO for this input data set. The reduction potential of a technology is then calculated as ratio of the CO_2 emissions with the technology to the CO_2 emissions of the baseline vehicle.

For hybrid and for ADAS (Advanced Driver Assistant Systems) VECTO does not simulate the fuel consumption reduction. Therefore for hybridisation the model PHEM from TUG was used instead of VECTO to calculate the CO_2 reduction for each HDV group, mission profile and payload condition. As with VECTO, the baseline vehicle and the hybrid vehicle were simulated and the relative change in CO_2 emissions are used to define the reduction potential. Since hybrids have a higher potential with lower air and rolling resistance due to the higher brake energy recuperation possible at such vehicles, the hybrid drive train was also implemented in an optimised 2025 vehicle version in PHEM.

The potential from ADAS technology (engine start-stop, eco-roll and predictive cruise control in its possible combinations) could not be simulated with available software tools. The reduction potential for these driver assistance systems therefore were calculated by an Excel application in a post-processing of VECTO modal result files.

This method gives CO_2 reduction values in line with the future CO_2 certification. In contrary, using CO_2 reduction potentials directly from literature implies the risk that the data in the literature was produced for other driving conditions (cycle, loading, gear shifts, etc.) than the standard VECTO conditions and thus may state quite different reduction potentials than one would get from a VECTO calculation.

All methods are described in more detail later in this chapter or in Annex D for the single considered technologies.

VECTO

VECTO (Vehicle Energy Consumption Calculation Tool) is a software tool developed on behalf of the European Commission DG CLIMA for certification of fuel consumption and CO_2 emissions of HDV vehicles. VECTO uses input data on CO_2 relevant vehicle components like engines, transmissions, axles, tyres and air drag from certified component tests to cost efficiently simulate the performance of the complete vehicle. An extensive description of VECTO can be found in [Rexeis, 2017].

Since future CO_2 limits will be based on VECTO results, in this study the assessment of the actual fleet CO_2 level as well as the assessment of CO_2 reduction potentials are based on VECTO calculation results. The software version used was the final VECTO software version from the LOT4/SR7 contract (VECTO 3.2.0.940 from July 2017) and set of generic data as laid down in the “declaration mode”. These data cover mission profiles (driving cycles), driver model settings, vehicle payloads and generic data on power consumption from auxiliary units.

The VECTO version as available to this study did not cover several future technologies, either because the actual legislation does not cover specific input for certain vehicle components (e.g. air drag or tyre data for non-standard bodies and trailers) or because procedures for component testing and/or simulation modules have not been elaborated so far (e.g. hybrid vehicles, ADAS). For these technologies alternative approaches have been used, which were chosen in a way that the results are as close to possible to a probable future extended version of VECTO. Considering any of these technologies in a CO_2 limit scenario implies, that the VECTO approach has to be extended accordingly until the limits come into force.

It has to be mentioned explicitly, that any future change in VECTO (both in the simulation models and also in the sets of generic data like cycles, payloads, driver- and gear shift models) will result in changes of results for absolute fuel consumption and CO_2 levels and also in the reduction potential of single fuel saving technologies. A flexible approach to align the definitions made in the context of the CO_2 limits to possible future updates in VECTO methods could be to use a set of generic vehicle models (like the ones elaborated in Task 1.3). These models can be used to simulate CO_2 emissions before and after VECTO updates to compute the relative changes in results and to adapt the CO_2 limit accordingly.

PHEM

The model PHEM (Passenger car and Heavy duty Emission Model) is used for the simulation of all hybrid concepts within this study. To assess the reduction potential from hybridisation, both, the vehicle with conventional combustion engine and the hybrid vehicle version are simulated in PHEM to ensure the comparability of the results. Certainly the same vehicle specifications and the mission profiles were used in PHEM and in VECTO. Since the VECTO model was developed with PHEM as starting point, the absolute fuel consumption levels and the reduction potentials modelled by the two different software tools are comparable.

The model PHEM is developed at IVT from TU Graz since the late 1990ies. Development is continuously ongoing to include new technologies where relevant and to improve accuracy and user friendliness. A short description is given below. More details can be found e.g. in [Hausberger, 2017], [Schreiber, 2017], [Zallinger, 2011], [Rexeis, 2009] and [Hausberger, 2003].
Similar to VECTO, PHEM is an instantaneous emission model based on equations of vehicle longitudinal dynamics and engine fuel consumption and emission maps (Figure 18).

The engine power demand is calculated in 1Hz for the cycles from the driving resistances and losses in the transmission line. The engine speed is simulated by the tyre diameter, final drive and transmission ratio as well as a driver gear shift model. Base exhaust emissions and fuel flow are then interpolated from engine maps.

The temperatures at various locations at the exhaust gas system are simulated from the engine out exhaust gas temperatures and mass flows and from simulation of the heat exchanges between gas and components and components and ambient and by a zero dimensional energy balance. Furthermore models for the efficiency of exhaust gas after treatment systems are implemented based on space velocity and the temperature levels. This part of the PHEM model was used in the engine technology assessments especially for the potential of an improved SCR and for the simulation of waste heat recovery systems. A driver model is provided by PHEM also, to simulate representative gear shift manoeuvres.

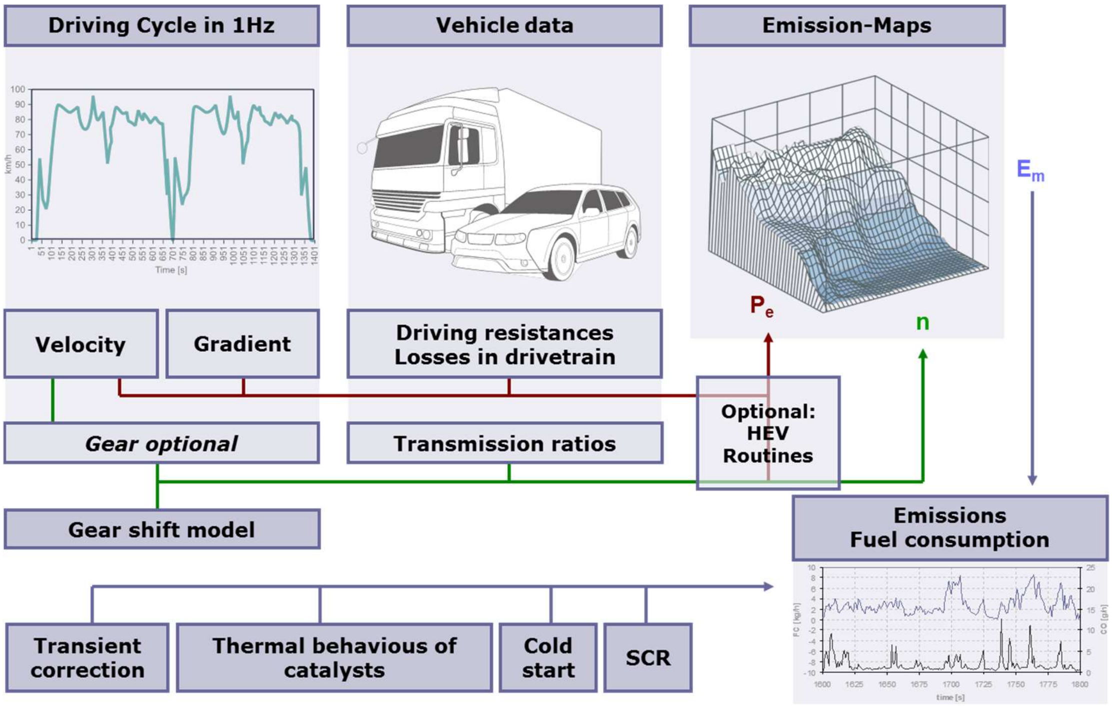

Figure 1: Scheme of the PHEM model.

Overview on reduction potentials of single investigated vehicle technologies
This section gives an overview on the reduction potentials of the single investigated fuel saving technologies. A detailed description of the principles of the technologies, the underlying data, the applied methods and the results is given in Annex D. Table 3 summarizes the fuel consumption reduction potentials for a group 5 truck. All technologies have been evaluated for the mission profiles “Long Haul” and “Regional Delivery” each with two different payloads. Payloads depend on the vehicle group and correspond to generic VECTO data used for the official CO_2 declaration (see Table 5 on page 22). To consolidate the reduction potentials to a single representative value for each technology and vehicle group, it is necessary to combine the individual results and give an appropriate weighting. Values and approach for weighting factors are described in section 3.3.

Table 3: Fuel consumption reduction potential of individual technologies for group 5.

Tech ID	Technology	FC reduction to Baseline group 5[%]				
		LongHaul low load	LongHaul representative load	Regional Delivery low load	Regional Delivery representative load	Weighted potential
Aero-T1-1	Roof spoiler plus side flaps	-6.98%	-5.14%	-5.56%	-4.27%	-5.59%
Aero-T1-2	Side and underbody panels at truck chassis	-1.59%	-1.17%	-1.20%	-0.97%	-1.27%
Aero-T1-3	Covers for rear truck wheels	-0.47%	-0.34%	-0.37%	-0.23%	-0.37%
Aero-T1-4	Closable front grille	-1.59%	-1.17%	-1.20%	-0.97%	-1.27%
Aero-T1-5	Aerodynamic mud flaps	-1.78%	-1.34%	-1.42%	-1.09%	-1.44%
Aero-T2-1	Movable 5th wheel, shortens the gap cabin to trailer	-0.93%	-0.68%	-0.73%	-0.50%	-0.73%
Aero-T2-2	Rear view cameras instead of mirrors	-2.26%	-1.67%	-1.76%	-1.34%	-1.81%
Aero-T2-3	Redesign, longer and rounded vehicle front	-2.67%	-1.96%	-2.11%	-1.57%	-2.13%
Aero-S1-1	Covers for trailer wheels	-0.67%	-0.49%	-0.53%	-0.35%	-0.53%
Aero-S1-2	Rounded front edges of trailer, if so by covers	-2.67%	-1.96%	-2.11%	-1.57%	-2.13%
Aero-S1-3	Side and underbody panels at trailer chassis	-4.43%	-3.28%	-3.61%	-2.66%	-3.56%
Aero-S1-4	Boat tail by variable height of trailer body	-3.12%	-2.30%	-2.45%	-1.86%	-2.50%
Aero-S1-5	Boat tail trailer (50cm)	-3.50%	-2.59%	-2.76%	-2.10%	-2.81%
Tyres-1	Low rolling resistance tyres on truck/tractor	-5.05%	-6.72%	-4.72%	-5.96%	-6.15%
Tyres-2	Low rolling resistance tyres on truck/tractor + trailer	-10.45%	-13.84%	-9.56%	-11.12%	-12.60%
Tyres-3	Tyre pressure monitoring systems (TPMS) on truck	-0.20%	-0.24%	-0.19%	-0.16%	-0.22%
Tyres-4	Tyre pressure monitoring systems (TPMS) on truck and trailer	-0.34%	-0.45%	-0.32%	-0.30%	-0.41%
Tyres-5	Automated tyre inflation systems (ATIS) on truck	-0.20%	-0.24%	-0.19%	-0.16%	-0.22%
Tyres-6	Automated tyre inflation systems (ATIS) on truck and trailer	-0.39%	-0.52%	-0.35%	-0.34%	-0.47%
Tyres-7	Wide base single tyres	-0.42%	-0.58%	-0.38%	-0.37%	-0.52%
Mass-1	Lightweighting mild reduction rigid truck / tractor	-0.13%	-0.10%	-0.15%	-0.05%	-0.10%
Mass-2	Lightweighting strong reduction rigid truck / tractor	-1.61%	-1.24%	-1.82%	-1.69%	-1.39%
Mass-3	Lightweighting mild reduction including trailer	-0.51%	-0.43%	-0.75%	-0.59%	-0.48%
Mass-4	Lightweighting strong reduction including trailer	-4.10%	-3.23%	-4.96%	-4.39%	-3.60%
Aux-1	Electric hydraulic power steering	-0.26%	-0.19%	-0.28%	-0.15%	-0.21%
Aux-2	LED lighting	-0.06%	-0.06%	-0.07%	-0.06%	-0.06%
Aux-3	Air compressor	-1.65%	-1.28%	-1.40%	-1.09%	-1.37%
Aux-5	Engine Cooling fan	-0.50%	-0.39%	-0.59%	-0.15%	-0.41%

Tech ID	Technology	FC reduction to Baseline group 5[%]				
		LongHaul low load	LongHaul representative load	Regional Delivery low load	Regional Delivery representative load	Weighted potential
Aux-6.1	Standard electric system with best performing alternator	-0.19%	-0.14%	-0.18%	-0.08%	-0.15%
Aux-6.2	LED electric system with best performing alternator	-0.25%	-0.18%	-0.25%	-0.13%	-0.20%
Trans-1	Reduced drivetrain losses (lubricants, design)	-1.43%	-1.52%	-1.64%	-1.77%	-1.52%
ADAS-1	Engine stop-start	-0.12%	-0.09%	-1.35%	-1.07%	-0.20%
ADAS-2-1	Eco-roll (w/o PPC, w/o ESS)	-0.53%	-0.50%	-0.74%	-0.28%	-0.50%
ADAS-2-2	Eco-roll (w/o PPC, w/ ESS)	-1.06%	-1.06%	-2.79%	-1.88%	-1.17%
ADAS-3-1	PCC (w/o Eco-roll, w/o ESS)	-0.43%	-1.38%	-0.73%	-1.90%	-1.14%
ADAS-3-2	PCC (w/ Eco-roll, w/o ESS)	-0.99%	-1.94%	-1.61%	-2.42%	-1.70%
ADAS-3-3	PCC (w/ Eco-roll, w/ ESS)	-1.50%	-2.46%	-3.57%	-3.87%	-2.33%
ADAS-5	Speed limiter 80km/h	-3.36%	-2.61%	-2.06%	-1.68%	-2.73%
Engine-1	Package 1: Improved turbocharging and EGR	-4.00%	-4.00%	-4.00%	-4.00%	-4.00%
Engine-2	Package 2: improved SCR and optimised SCR heating methods	-2.00%	-2.00%	-2.00%	-2.00%	-2.00%
Engine-3	Package 3: Friction reduction + improved water and oil pumps	-1.97%	-1.46%	-1.80%	-1.40%	-1.60%
Engine-4	Package 4: Improved lubricants	-1.15%	-0.90%	-1.06%	-0.83%	-0.97%
Engine-5	Package 5: Waste heat recovery	-2.11%	-2.10%	-2.00%	-2.02%	-2.10%
Engine-6	Package 6: Downspeeding with optimised map	-1.24%	-0.37%	-1.30%	-0.83%	-0.67%
Hybrid-1	Mild Hybrid 48V (typical vehicle)	-0.44%	-0.43%	-1.24%	-1.15%	-0.51%
Hybrid-2	Full Hybrid typical vehicle 80kW electric motor continuous power/6kWh Battery capacity nominal	-0.47%	-1.98%	-5.47%	-5.87%	-1.95%
Hybrid-3	Full Hybrid best vehicle (current legislation) 80kW electric motor continuous power/6kWh Battery capacity nominal	-3.19%	-4.02%	-7.53%	-7.77%	-4.16%

3.3 Fuel consumption and CO_2 emission reduction potential with combined HDV fuel saving technologies (Task 2.2)

The mainstream technology combinations for the model year 2016 and for 2025 have been simulated based on VECTO to validate and calibrate the multiplicative approach described in the introduction to chapter 3 on page 11. The calculation of technology packages had two objectives:

a) Analyse if and where calibration factors are needed to consider interactions between technologies
b) Application of the multiplicative approach described in Task 2 to calculate possible CO_2 reduction scenarios.

Validation of the multiplicative approach
For the validation of the multiplicative approach, single technologies have been consolidated to technology packages. Each technology type (i.e. aerodynamics, engine) was subdivided into several packages with a different number of single technologies, to check the impact of the quantity of technologies considered in one package. These packages provide the input of the subsequent performed VECTO simulations. The next step was the determination of the CO_2 reduction potential for each technology package according to the multiplicative approach mentioned in the introduction to chapter 3.

The CO_2 reduction potential calculated by the multiplicative method was found on average slightly above the VECTO results. However, there are also particular technology packages, where higher reduction potentials are predicted by VECTO. In all observed cases the difference between the two variants was judged to be smaller than the uncertainty in the assessment of the single technology reduction potential. Hence, the multiplicative method was decided to be used without any further application of calibration factors.

Consolidated reduction potential of technology packages
This section shall highlight the reduction potential of various technology packages and the resulting fuel consumption levels when a vehicle is equipped with all analysed technologies.
The single technologies as shown in Table 3 have been grouped into the technology packages according to Table 4.

Table 4: Implemented technologies.

Package	**Tech_ID**[1]
Aero package "moderate"	Aero-T1-1, Aero-T1-2, Aero-T1-3, Aero-T1-4
Engine	Engine-1, Engine-2, Engine-3, Engine-4, Engine-7
Low RR "moderate"	Tyres-1
Transmission	Trans-1
ADAS	ADAS-3-3
Low RR "advanced"	Tyres-5, Tyres-7
Auxiliaries	Aux-1, Aux-3, Aux-5, Aux-6-2
Lightweighting	Mass-2
Aero package "advanced"	Aero-T2-1, Aero-T2-2
WHR	Engine-5
HEV	Hybrid-3
Aero package "trailer"	Aero-S1-1, Aero-S1-2, Aero-S1-3, Aero-S1-5
Low RR truck+trailer "moderate"	Tyres-2
Low RR truck + trailer "advanced"	Tyres-6, Tyres-7
Lightweighting truck+trailer	Mass-4
Speed limiter 80 km/h	ADAS-5

[1] Tech-ID according to Table 3

The presentation below is based on results for a group 5 vehicle (tractor and semitrailer) and for a group 4 vehicle (2 axle rigid truck, operated without trailer in the regional cycle and with trailer in long haul). Shown figures are the results for weighted potentials over both cycles and both payloads. Results for the group 5 vehicle furthermore differentiate whether measures on the semitrailer are considered in a future VECTO certification or not. The sequence of adding of technology packages to the baseline vehicle is ranked based on an estimation for costs per fuel saving potential starting with more cost efficient technologies.

Figure 2 shows the result for a group 5 vehicle without measures on the semitrailer. The fuel consumption of the typical truck and the baseline truck, which is the reference for adding the fuel saving measures, are also shown as reference. Fuel saving technologies with the highest reduction potentials are aerodynamics (in total 14%, however significant parts like roof spoiler already implemented in the 2016 typical truck); engine technologies with some 9% and low rolling resistance (RR) tyres with some 7%. Adding up all fuel saving measures except speed limiter at 80 km/h brings down the fuel consumption by some 28% from 31.1 l/100km of the typical 2016 truck down to 22.4 l/100km. This however includes also very costly technologies like waste heat recovery and hybridisation of the truck. If a speed limiter to 80 km/h would be also included, the resulting fuel consumption of the group 5 vehicle with the standard semitrailer would be down at 21.8 l/100km[5].

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[5] The real world impact of a 80 km/h speed limiter however has to be questioned as more trucks for the same transport volume and time would be needed.

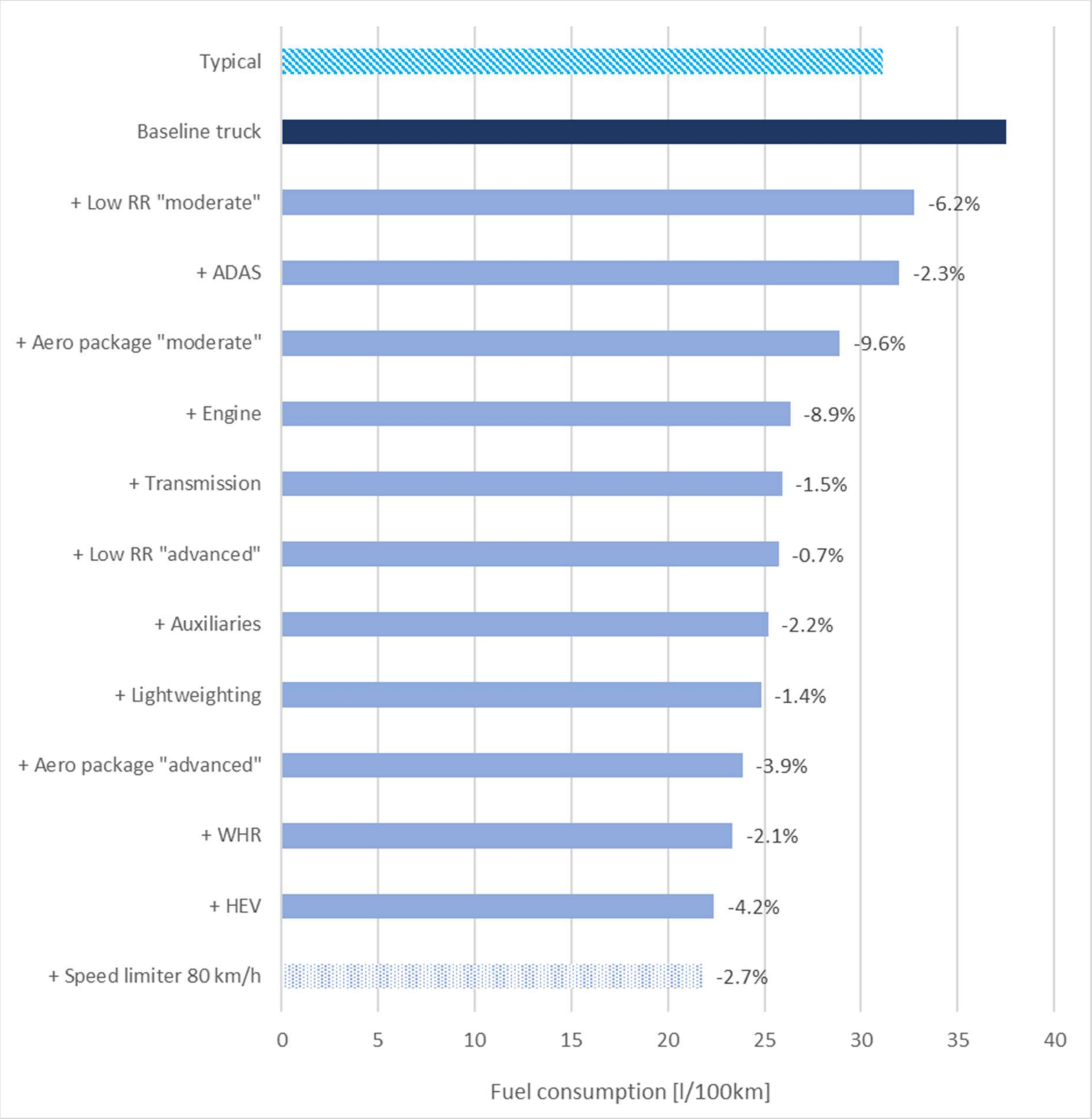

Figure 2: Fuel saving potential of technology packages for a group 5 vehicle w/o trailer measures.

Figure 3 shows the reduction potential for a group 5 tractor-semitrailer combination including optimisations on the semitrailer. Under this boundary condition a group 5 truck equipped with all analysed fuel saving technologies - except speed limiter 80km/h - has a fuel consumption of 18.6 l/100km compared to the 31.1 l/100km for the 2016 typical truck. This is a fuel consumption reduction by 40%. Compared to the results w/o semitrailer measures the further reduction in fuel consumption caused by the semitrailer technologies is at 3.8 l/100 km.

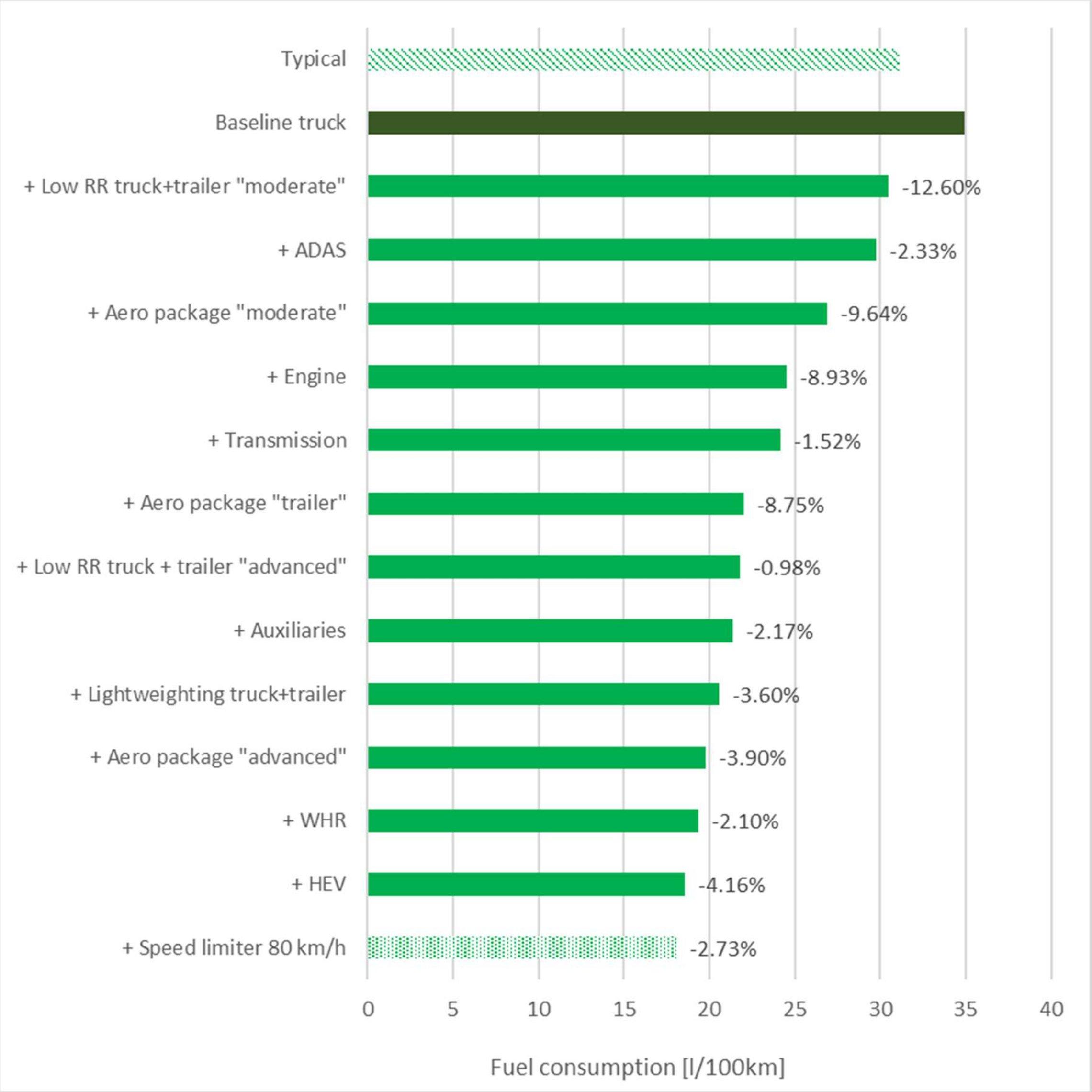

Figure 3: Fuel saving potential of technology packages for a group 5 vehicle with optimised semi-trailer.

Figure 4 shows the analogue figures for a group 4 vehicle without measures on the standard box-body and the trailer. Fuel saving technologies with the highest reduction potentials are aerodynamics (in total 16%, however significant parts like roof spoiler already implemented in the 2016 typical truck); engine technologies with 10% and low rolling resistance (RR) tyres with some 9%. Hybridisation holds another 6% reduction potential. Adding up all fuel saving measures except speed limiter brings down the fuel consumption by some 34% from 23.2 l/100km of the typical 2016 truck down to 15.3 l/100km.

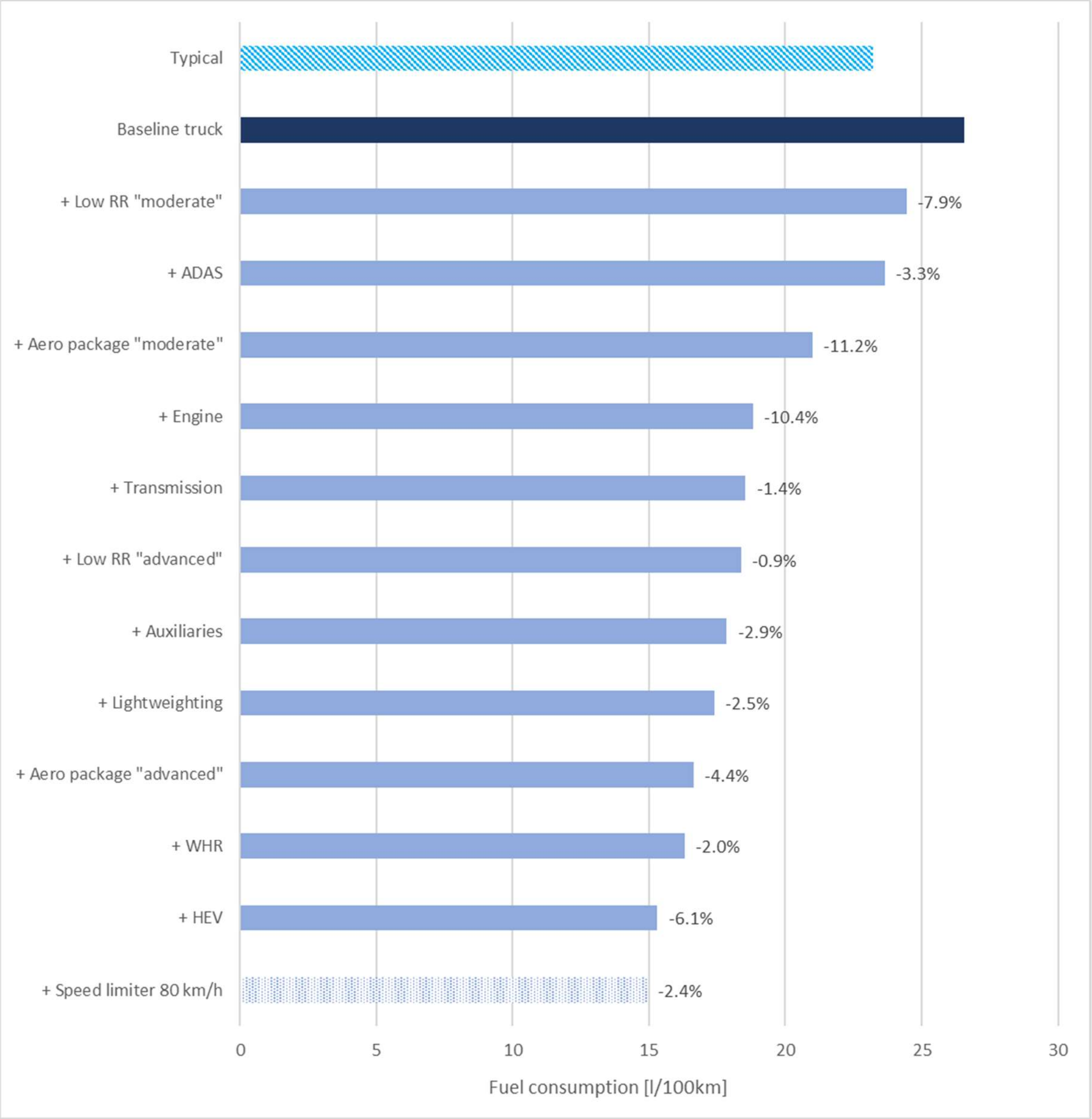

Figure 4: Fuel saving potential of technology packages for a group 4 vehicle w/o trailer measures.

Reduction potentials for additional measures on the standard-box body and the trailer have not been elaborated in detail in this study. For rigid trucks aerodynamic designs on the body of the rigid have to be optimised either for rigid (only) operation or to rigid and trailer missions. It is not clear how this could be handled in a future certification procedure.

Elaboration of shares of load factors and mission profile weightings

In the software VECTO the declaration mode automatically produces the result for fuel consumption and CO_2 emissions for following settings:

- Low payload (fixed tons in each group, representing approx. 10% payload factor)
- Reference load (fixed tons in each group, representing approx. 75% payload factor in long haul, approx. 50%payload factor in other cycles)
- For each relevant mission profile (long haul, regional delivery, other cycles)

To elaborate proposals for CO_2 limits for each of these results separately would be not meaningful due to the high number of combinations. Thus, a proposal was elaborated how a weighting of loadings and mission profiles per HDV group should look like to be representative for the average real world operation.

The weighting factors shall represent the average loading of HDVs in the group including empty trips. For the missions the weighted mission profile shall represent typical distances driven on average by vehicles designed for regional delivery and for long haul operation.

The data sources are the evaluation of fuel consumption data in Task 1.1 and a PhD thesis at TU Graz, where inter alia available sources on HDV loading factors were analysed [Kies, 2017].

The actual generic settings in VECTO are summarised in Table 5.

Table 5: Generic vehicle loading used in the VECTO declaration mode.

Payloads [kg]				Total mass [kg]	
Group	Cycle	Reference load	Low load	Reference load	Low load
4	LH	14000	1900	29700	17600
4	RD, UD	4400	900	14700	11200
5	LH	19300	2600	35029	18329
5	RD, UD	12900	2600	28629	18329
9	LH	19300	2600	36200	19500
9	RD, UD	7100	1400	18600	12900
10	LH	19300	2600	35810	19110
10	RD, UD	12900	2600	29410	19110

In [Kies, 2017] the average payloads found in literature are:

- For delivery trucks with a GCW of 12 tons: payloads from 1.9 tons excluding empty trips up to 3.7t including empty trips with an average of approx. 2.5 tons payload in high shares of urban delivery
- For long haul tractor trailer combinations with a GCW of 40 tons: payloads from 12.5t to 14.6t with an average of approx. 14.1tons

In Task 1.1 the total vehicle weights were assessed to 22.7 tons and 25.5 tons for group 4 and 5 up to 29.7 tons and 31.7 tons for groups 10 and 5, all in long haul driving (Table 6). For delivery missions no data is available from Task 1.1. The weighting factors proposed for the payload were elaborated to meet the weights found in Task 1.1 and in literature. The shares of the long haul missions were adjusted to meet the share of trips identified to be with trailers in group 4. For group 9 the same mission distribution as in group 4 was assumed. For group 5 the shares according to trop length distributions from Task 1.1 were used for differentiation between long haul and regional delivery.

Table 6: Proposed weightings of missions and payloads.

		Generic VECTO data			Weighting factors proposed			Values resulting from weighting			
Class	Mission	Reference load [kg]	Low load [kg]	veh empty weight [kg]	Ref. Load	Low load	Share cycle in class	Avg load [kg]	Max load [kg]	Load factor [%]	Weight from task 1.1 [kg]
4	long haul	14000	1900	15700	50%	50%	10%	7950	24300	33%	22712
4	reg. Delivery	4400	900	10300	50%	50%	90%	2650	7700	34%	
5	long haul	19300	2600	15730	70%	30%	90%	14290	24270	59%	26521
5	reg. Delivery	12900	2600	15730	70%	30%	10%	9810	24270	40%	
9	long haul	19300	2600	16900	70%	30%	10%	14290	23100	62%	31683
9	reg. Delivery	7100	1400	11500	70%	30%	90%	5390	14000	39%	
10	long haul	19300	2600	16510	70%	30%	90%	14290	23490	61%	29659
10	reg. Delivery	12900	2600	16510	70%	30%	10%	9810	23490	42%	

Penetration rates for fuel saving technologies

As already explained above, the baseline vehicle has none of the technologies on board, which had to be simulated for the CO_2 reduction potentials. Consequently, the CO_2 reduction potential of any scenario can be computed in a simplified way from the product of the CO_2 reduced values from each technology:

$$\mathbf{CO_{2y} = \Pi\ (1 - R_{i,\,y}\ x\ P_{i,\,y})}$$

With CO_{2y} ....[g CO_2/ton-km] and [g/km] of the new vehicle fleet in the year "y" (also separated per mission profile)

$P_{i,\,y}$ ....fleet penetration rate of a technology "i" (0 = no share, 1 = 100% share) in the newly registered vehicle fleet in the year y.

R_i ....reduction potential of a technology "i"

A similar approach can be applied to fuel consumption figures.

This approach needs an assessment of the penetration rates of each technology in the fleet.

The main scenarios described here are:

- Long haul fleet average in 2016: this scenario shall meet the average fuel consumption of the vehicles falling into the CO_2 limits (i.e. without special purpose vehicles)
- Realistic fleet penetration in 2025: this scenario shall represent penetration rates, which may be reached with reasonable efforts and without inacceptable disturbance of the market in presence of corresponding CO_2 limits. In the elaboration of penetration rates for it was furthermore assumed that VECTO still only covers technologies applied on the truck/tractor but not on trailers or vehicle bodies.

Table 7 summarises the penetration rates assessed for 2016 and 2025.

Table 7: List of penetration rates assessed for the single technologies in the average 2016 and in the engaged but realistic 2025 scenario for long haul vehicles.

Tech	Technology	Weighted penetration 2016 in groups [%]				Weighted penetration "real. 2025" in groups [%]				Explanation
		4	5	9	10	4	5	9	10	
ID	Text	% of fleet								Text
Aero- T1-1	Roof spoiler plus side flaps	80	95	80	90	90	100	90	90	Groups 4,9,10 may have more often bodies mounted not suitable for spoilers and flaps
T1-2	Side and underbody panels at truck	0	5	0	3	50	100	50	50	High damaging risk for many applications beside group 5 long haul
T1-3	Covers for rear truck wheels	0	0	0	0	75	90	75	75	Cooling of brakes is an issue but should be manageable, needs time for roll out in all models due to low effect
T1-4	Closable front grille	2	25	2	25	100	100	100	100	Technically possible but potential has uncertainties.
T2-2	Rear view cameras instead of mirrors	0	0	0	0	40	60	40	40	Actually not allowed, 2025 figures need corresponding legal framework before 2020.
T2-3	Longer and rounded vehicle front	0	0	0	0	10	70	10	20	Not all cabins can be redesigned within 6 to 7 years due to high investment costs.

Tech	Technology	Weighted penetration 2016 in groups [%]				Weighted penetration "real. 2025" in groups [%]				Explanation
		4	5	9	10	4	5	9	10	
ID	Text	% of fleet								Text
Tyres- 1	Low rolling resistance tyres on truck/tractor	29	43	27	32	90	100	90	90	Assumption: RRC values from summer tyres can be used if sold together with set of winter tyres. In groups 4, 9, 10 special applications may not allow low RRC optimised tyres.
3	Tyre pressure monitoring systems (TPMS) on truck	20	20	20	20	100	100	100	100	Not very efficient for CO2 saving. In VECTO a "bonus factor" would have to be implemented, otherwise not considered in declaration.
7	Wide base single tyres	0	2	0	2	0	2	0	2	Seems to be accepted in EU in market in niches only (difficult tyre changing, safety issues, durability).
Mass- 1	mild reduction rigid truck / tractor	2	5	2	5	100	100	100	100	No technical limitation seen.
2	strong reduction rigid truck / tractor	0	0	0	0	50	80	50	50	Not all chassis and bodies can be redesigned within 6 years due to high investment costs.
Aux 1	Electric hydraulic power steering	0	0	0	0	50	50	50	50	Slower roll out in all models due to limited CO2 saving and complexity.
2	LED lighting	36	30	30	43	100	100	100	100	No limitations seen.
3	Best air compressor	0	2	0	1	100	100	100	100	No limitations seen.
4	Best AC efficiency	0	0	0	0	100	100	100	100	No limitations seen.
5	Best Cooling fan	58	31	34	44	100	100	100	100	No limitations seen.
6.1	Best alternator	0	0	0	0	100	100	100	100	No limitations seen.
6.2	LED Electric system	0	0	0	0	100	100	100	100	No limitations seen.
Trans 1	Reduced losses (lubricants, design)	50	50	50	50	80	80	80	80	Redesigns of engine and transmission needed to be suitable for low viscosity oils.
ADAS 1	Engine stop-start	1	2	1	2	25	25	25	25	Penetration rates 2025 reflect difference to 100% from ADAS-3-3
2-1	Eco-roll (w/o PPC, w/o ESS)	12	40	32	48	0	0	0	0	Only ADAS 1+3-2 and 3-3 assumed to be relevant in 2025
2-2	Eco-roll (w/o PPC, w/ ESS)	0	0	0	0	0	0	0	0	
3-1	PCC (w/o Eco-roll, w/o ESS)	0	0	0	0	0	0	0	0	
3-2	PCC (w/ Eco-roll, w/o ESS)	2	55	19	38	25	25	25	25	Penetration rates 2025 reflect difference to 100% from ADAS-3-3
3-3	PCC (w/ Eco-roll, w/ ESS)	0	2	0	2	75	75	75	75	Due to safety issues time needed to roll out in all models (steering, braking with engine off).
5	Speed limiter 80km/h	1	1	1	1	1	1	1	1	Only accepted by operators in dangerous goods vehicles, there already limited. Lower speed would need more vehicles for same t-km.

Tech	Technology	Weighted penetration 2016 in groups [%]				Weighted penetration "real. 2025" in groups [%]				Explanation
		4	5	9	10	4	5	9	10	
ID	Text	% of fleet								Text
Engine 1	Improved turbocharging and EGR	45	45	45	45	100	100	100	100	No limitations seen.
2	Improved SCR and optimised SCR heating methods	10	10	10	10	100	100	100	100	No limitations seen.
3	Friction reduction etc.	2	5	2	5	80	80	80	80	In combination with heavy downspeeding quite demanding design.
4	Improved lubricants	2	2	2	2	80	80	80	80	In combination with heavy downspeeding quite demanding design.
5	Waste heat recovery	0	0	0	0	0	5	0	0	Due to development time and costs only in niche markets in 2025 (100% possible in 2030)
7	Package 6: Downspeeding	15	15	15	15	100	100	100	100	No limitation penetration seen
Hybrid 1	Mild Hybrid 48V	0	0	0	0	50	50	50	50	Roll out in all models need time; benefit not given in all missions.
2	Full Hybrid in "typical 2016 vehicle"	0	0	0	0	0	0	0	0	Not relevant since in case of hybridisation package 1 or 3 are expected.
3	Full Hybrid in "optimised 2025 vehicle"	0	0	0	0	10	5	10	0	Expensive technology, thus expected in special missions with potential for higher brake energy recuperation (only with ambitions CO2 limits announced in 2030)

Results for fleet average vehicles based on technology penetration rates

Figure 5 and Table 8 give the fuel consumption values calculated for the “average” vehicles in the year 2016 and the “average” vehicles in the year 2025 according to the technology penetration rates as described in the section above. Additionally the fuel consumption figures of the 2016 typical and baseline vehicles are given as reference. Displayed reduction rates shown in Figure 5 for 2016 average vehicles refer to improvement against 2016 baseline vehicles. Given reductions shown for 2025 average vehicles refer to 2016 average vehicles.

Fuel consumption of the 2016 average vehicles is very close to the figures for the 2016 typical vehicles and some 10% to 12% lower than the 2016 baseline vehicle configuration.[6] For the tractor-semitrailer configurations a further improvement of 19% (group 5) and 18% (group 10) is estimated for the time period from 2016 to 2025 according in the real technology penetration scenario. This result corresponds to an average annual improvement of 2.3% for the group 5 tractor with a standard trailer.

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[6] Theoretical considerations suggest that the fuel consumption of the average vehicle should be slightly worse than the typical (see distributions shown in Figure 22 on page 68). The main reasons why this is not the case for the assessment made in this study are: 1) only vehicles with drivelines optimised for long haul operation have been modelled in VECTO; 2) ADAS system were not considered in the VECTO models for the typical vehicles as these technology is not covered yet by VECTO

For the rigids (groups 4 and 9) the estimated reduction potential is even higher with 23% for the average 2025 vehicle compared to the 2016 vehicle. This corresponds to an average annual improvement of 2.8% per year.

The main reasons why the calculated reductions for rigids are higher than for tractors are:

- Rigids are operated in the regional delivery cycle (90% weighting) without trailer. Hence measures on the truck on aerodynamics, rolling resistance and light-weighting give more relative improvement than on tractors (semitrailer always generic).
- Due to low 2016 penetration rates for aero technology rigids have a higher improvement potential than tractors.
- ADAS gives more potential in regional delivery cycle than in long haul (e.g. higher impact of engine stop-start systems).
- Hybridisation has higher potential in regional delivery cycle than in long haul.

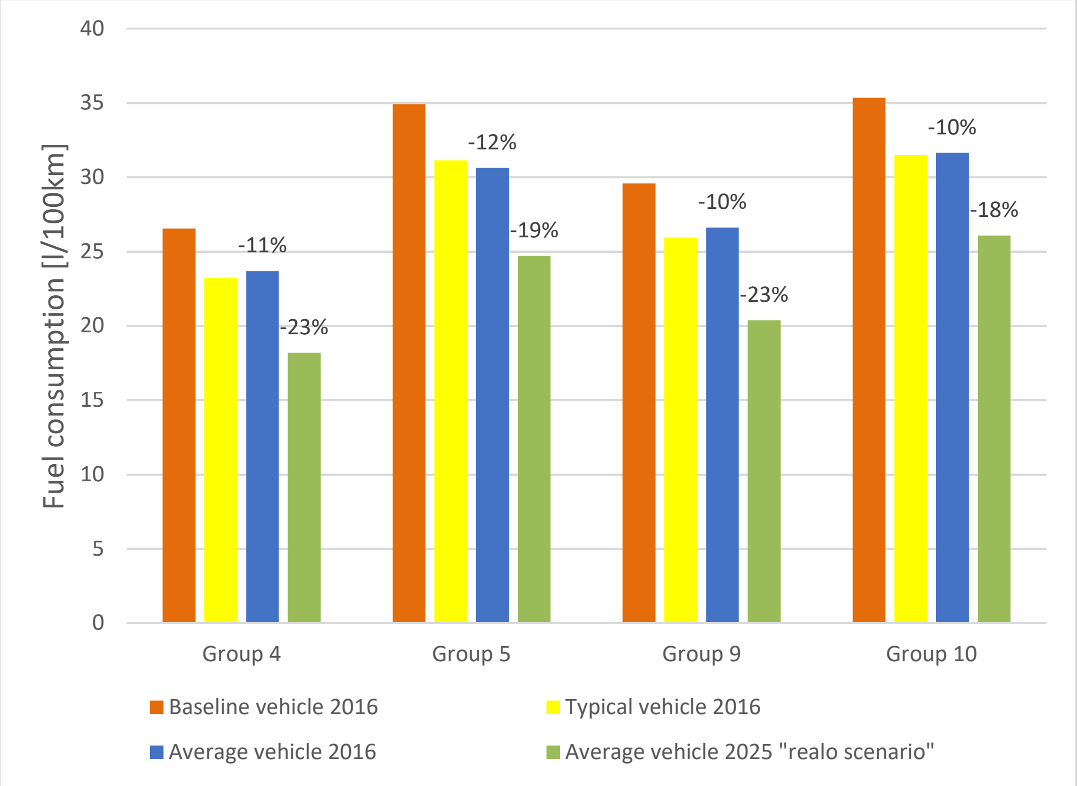

Figure 5: Weighted fuel consumption average vehicles.

Table 8: Fuel consumption of Baseline and average vehicles for each cycle.

		Fuel consumption [l/100km]				
Vehicle type	Vehicle group	LongHaul low load	LongHaul reference load	Regional Delivery - low load	Regional Delivery reference load	Weighted
Baseline	4	31.60	37.80	24.50	26.78	26.55
Average 2016	4	28.51	34.34	21.79	23.88	23.68
Average 2025	4	23.49	28.30	16.60	18.19	18.19
Baseline	5	28.77	37.52	30.01	37.16	34.91
Average 2016	5	25.06	32.97	26.42	32.96	30.62
Average 2025	5	19.88	26.82	20.89	26.70	24.72
Baseline	9	33.07	41.88	25.82	29.64	29.57
Average 2016	9	29.81	38.08	23.14	26.67	26.60
Average 2025	9	23.72	31.03	17.50	20.36	20.37
Baseline	10	29.20	37.94	30.55	37.69	35.34
Average 2016	10	25.91	34.02	27.52	34.25	31.63
Average 2025	10	21.26	28.13	22.41	28.09	26.07

3.4 References

[Rexeis, 2017]	Rexeis M., Quaritsch M., Hausberger S., Silberholz G., Steven H., Goschütz M., Vermeulen R.: VECTO tool development: Completion of methodology to simulate Heavy Duty Vehicles' fuel consumption and CO_2 emissions. Final Report By order of EUROPEAN COMMISSION DG CLIMA Report No. I 15/17/Rex EM-I 2013/08 1670 from 07.08.2017
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[Rexeis, 2009]	Rexeis M.: Ascertainment of Real World Emissions of Heavy Duty Vehicles. Dissertation, Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology. October 2009
[Hausberger, 2003]	Hausberger S.: Simulation of Real World Vehicle Exhaust Emissions; VKM-THD Mitteilungen; Heft/Volume 82; Verlag der Technischen Universität Graz; ISBN 3-901351-74-4; Graz 2003 (http://www.diglib.tugraz.at/simulation-of-real-world-vehicle-exhaust-emissions-2002)

4 Determination of the cost-effective potential for reducing HDV fuel consumption and CO_2 emissions in 2025 and 2030 (Task 3)

The objective of task 3 is to derive the costs of the CO_2 reduction technologies identified in task 2. The results of this work are described in this chapter. The cost data derived in this task were, together with the CO_2 reduction potential of technologies identified in chapter 3 (task 2), input for the cost curves developed by JRC [Krause, 2018].

4.1 Introduction

This chapter describes how cost estimates were determined for all identified CO_2 reduction technologies. Section 4.2 treats the concept of the 2025 vehicle technology costs. The harmonised methodology used to determine cost estimates based on multiple inputs is treated in Section 4.3. Section 4.4 elaborates on the studies used as input for the cost estimates, while Section 4.5 discusses the approach taken to get some expert verification. The resultant cost figures used for each technology are presented in Table 11 in Section 4.6.

4.2 Vehicle technology costs 2025

This study aims to determine cost input data for a range of truck technologies for the year 2025 for the development of cost curves, differentiated according to VECTO truck groups (4, 5, 9 and 10). To accurately inform policymakers of the costs, yet provide a comprehensible value combined with a realistic timescale it was opted to express the purchase price for the technologies for truck operators for the year 2025 in 2015 euros. These cost estimates are developed in the context of the announced legislation by the European Commission to be introduced after 2020. This implies that estimations have to be made for the development of costs over time under the assumption that technologies are applied at large scale by OEMs to comply with future CO_2 legislation. Generally, the following process improvements are taken into account to correct for future developments:

- Increased efficiency (learning by doing).
- Technological development (e.g. batteries may become cheaper).
- Size of scale effects.

4.3 Methodology

Following a literature review, the identified technologies (see Annex D) were matched with costs. In many cases, there were multiple cost estimates for each technology available, frequently spanning a substantial range. In general, the criteria to harmonise the source data are as follows:

- When possible, cost estimates from the most recent and extensive studies were used. Therefore, many of the values are based on Dünnebeil (2015) or Ricardo (2017). These data needed to be adapted in some cases to arrive at the cost definition indicated in 4.2 (see Figure 6: Illustration of 3 separate process routes to derive the costs per CO2 saving technology.).
- In certain cases where estimates spanned a particularly wide range of values or if the values were doubted, industry experts were consulted on costs for particular technologies and their

projected changes between now and 2025.
More detail on these expert consultations is provided in 4.5. In most cases the costs provided by the experts was used for verification.

- The two sources above have been complemented with own primary research on technologies currently available (e.g. LED lighting).

In Figure 6 below, the process of arriving at the 2025 costs is depicted.

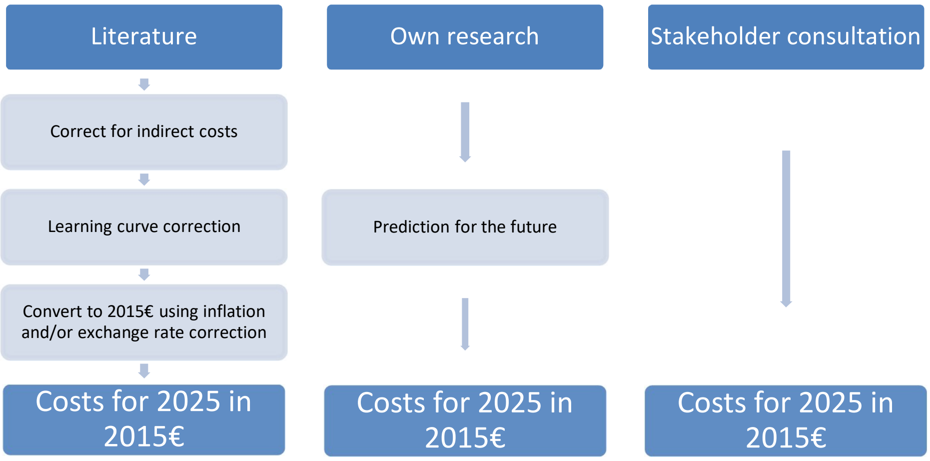

Figure 6: Illustration of 3 separate process routes to derive the costs per CO_2 saving technology. For most cases literature was used as the main source.

Figure 6 illustrates the three potential sources of input: literature, own research and stakeholder consultation.

For cost input based on literature, the following three-step adjustment approach has been used:

- Where direct manufacturing costs were reported, the prices were corrected for indirect costs (R&D, overhead, marketing, dealer support, etc.). This was done using a multiplying factor in line with the US EPA RIA's (2016) indirect cost factor for the long term for vocation vehicles, combination tractors and trailers. The indirect cost factor varies with the complexity of the technology. See Table 9.
- The next step involves accounting for potential learning effects between now and 2025. The learning rates also differ with the complexity of the technology. Low complexity technologies can be expected to have a cost of 90% of their 2015 price in 2025. High 2 complexity technologies, however, will experience a stronger learning curve. Their prices in 2025 will only be 50% of their 2015 prices. See Table 9.
- Finally, costs were harmonised to 2015 euros. This implied corrections for inflation (using OECD CPI for the US and the Euro area) and exchange rate conversions (according to the official exchange rates as reported by the ECB).

For cost inputs based on own research, a prediction for the future was made, incorporating a learning curve. For cost input based on expert stakeholder consultation, no adjustment was made as explicitly was asked for the costs in 2025 taking into account indirect costs and learning effects that might take place between now and 2025.

Table 9: Indirect cost factors (ICF) and process improvements (2025 relative to 2015) for different technology complexities.

	Low complexity technology	**Medium complexity technology**	**High 1 complexity technology**	**High 2 complexity technology**
ICF	1.14	1.23	1.27	1.37
process improvements	0.9	0.8	0.7	0.5

Source: RIA; Ricardo (2016); own analysis

As mentioned in the table above, this study classifies technologies according to their complexity. Four classes of technological complexity were identified: low complexity, medium complexity, high 1 complexity and high 2 complexity. In general, the more complex a technology, the higher the indirect costs and the steeper the learning curve.

In Ricardo EU Passenger vehicle studies (e.g. 2016) the difference between retail prices and manufacturer costs is heavily discussed. In this study, learning rates varying between 0.5 (e.g. full electric hybrid) and 0.9 (e.g. improved lubricants) are used and indirect costs multipliers range from 1.14 to 1.37. It should be noted, however, that production numbers in the passenger car market are much higher than in the truck market (typically 450,000 instead of 50,000) in (Ricardo, 2016). This implies that, in general, the potential for learning effects is smaller in the truck market than for the passenger car market, as production numbers are lower.

Taking the uncertainties of such corrections into account, it should be noted that the studies do not differ significantly. It should also be noted that production numbers are more limited in the European truck segment than in the United States truck market or the EU passenger car market (standards in place in both markets already), but the EU truck market may benefit from developments in both the passenger car market (e.g. TPMS) and the US truck market (e.g. ATIS).

Finally, costs were scaled in cases where cost data was not available for all four vehicle groups, using relevant vehicle parameters. In those cases, this is illustrated in Annex F.

4.4 List of studies used

An extensive literature review was carried out for the purpose of this study. The literature review consisted of a two-step approach:

- Firstly, an initial stocktaking was conducted, matching all costs to their technologies.
- Secondly, a selection procedure was conducted (as explained in 4.6), whereby one value was chosen per technology per truck group.

Listed below are the studies from which cost values were ultimately used (i.e. the second step sources).

- Ricardo (2017) – Heavy Duty Vehicles Technology Potential and Cost study
- Dünnebeil et al. (2015) – Zukünftige Maβnahmen zur Kraftstoffeinsparung und Treibhausgasminderung bei schweren Nutzfahrzeugen
- US EPA & NHTSA (2016) – Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2: Regulatory Impact Analysis
- Ricardo – AEA (2015) – Light weighting as a means of improving Heavy Duty Vehicles' energy efficiency and overall CO_2 emissions
- U.S. Department of Transportation National Highway Traffic Safety Administration (2015) – Commercial Medium And Heavy-Duty Truck Fuel Efficiency Technology Cost Study
- TNO (2013) – De Truck van de Toekomst: Brandstof- en CO_2-besparing anno 2013
- TNO (2013) – Study on Tyre Pressure Monitoring Systems (TPMS) as a means to reduce Light-Commercial and Heavy-Duty Vehicles fuel consumption and CO_2 emissions

- Ricardo – AEA (2011) – Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy
- ICCT (2015) – Cost effectiveness of advanced efficiency technologies for long-haul tractor-trailers in the 2020-2030 time frame

Description of the studies used
This section provides a brief summary of the studies used as regards the cost definition used in the respective study. They are directly compared in Table 10.

Ricardo (2017): The costs listed are prices to the operators expressed in 2015€. A learning curve is already incorporated in the cost values, as costs are expressed in 2015€ for the year 2025. Indirect costs are incorporated in the price mentioned. This implies that any cost value taken from Ricardo does not need any adjustment.

Dünnebeil (2015): Dünnebeil assumes that inflation over the period 2010-2015 was negligible or zero, resulting in prices being expressed in 2015€ (or 2010€). The prices were adjusted to retail price equivalents using a factor 1.5, to include indirect costs. The values we used from this study did not incorporate a learning curve for the year 2025. All technology cost estimates were relayed in conversations with experts at OEMs such as MAN and Daimler. In addition, a workshop was held with representatives from industry and prices were adjusted based on their feedback. Values taken from Dünnebeil therefore only need to be corrected for a learning curve.

US EPA & US Department of Transportation National Highway Traffic Safety Administration (2016): The Regulatory Impact Assessment expresses costs in 2013$ for the year 2025. Indirect costs and any anticipating learning effects occurring by 2025 are already taken into consideration. Values taken from US EPA & NHTSA therefore need to be corrected for inflation in the US for 2013-2015 and converted to euros.

Ricardo-AEA (2015): Costs are expressed as current estimates at 2014€. The values we have taken from this study do not incorporate learning curves or future developments in the prices of raw materials. The values are final costs, and thus have already included an indirect cost factor. Any values taken from this study have to be corrected for inflation in the Euro area for 2014-2015 and corrected with a learning curve.

US Department of Transportation National Highway Traffic Safety Administration (2015): Costs are expressed in 2011$ and incorporate a volume dependent cost curve. Based on the size of the HDV market in the EU, cumulative production numbers were calculated between now and 2025. These were then matched with the prices mentioned. Costs further represent retail prices, already having incorporated indirect costs. Values taken from this study therefore only need to be corrected for inflation in the USA and converted to euros.

TNO Truck van de Toekomst (2013): All costs are expressed as current costs, in 2013€ with current technology status. Indirect costs are already incorporated in the reported numbers from this study. Learning effects for 2025 are not yet incorporated in this study. However, this study is only used for the cost estimate of one technology (wheel alignment monitoring), which is better qualified as a service. Historically, services have not benefited from learning curve improvements resulting in lower prices, unlike manufacturing. Therefore, it was decided that costs for services should not be corrected for a learning curve by the year 2025. Cost values taken from this study therefore only need to be corrected for inflation over the years 2013-2015 in the Euro area.

TNO (2013): Costs for this study originated from responses to a questionnaire amongst TPMS suppliers and other stakeholders. Costs used from this report were expressed as 2013€ current costs, whereby it is assumed that indirect costs are incorporated. Corrections applied to cost values from this study involve an inflation correction for the Euro area for the years 2013-2015, as well as a learning curve correction.

Ricardo-AEA (2011): Costs in this study are expressed in 2010€, for the year 2010. This implies that learning curves still need to be incorporated and estimates need to be corrected for inflation in the Euro area between 2010-2015. Indirect costs are already incorporated in the estimates.

ICCT (2015): Costs in this study are expressed in 2014$, implying a correction for US inflation for 2014-2015 should be applied as well as a conversion to euros. Indirect costs are already included in these estimates, as well as a learning curve for 2025.

Table 10: Comparison of studies used for cost analysis.

Name of study	Base region	Costs expressed in which year	Costs for when	Already incorporated learning curves for 2025?	Already incorporated indirect costs?
Ricardo (2017)	Europe	2015€	2030	Yes	Yes - costs are to end users
Dünnebeil (2015)	Europe	2010-2015€ (assumed no inflation)	2015 - Current costs	No	Yes
US EPA & US Department of Transportation NHTSA (2016)	North-America	2013$	2025	Yes	Yes
Ricardo-AEA (2015)	Europe	2014€	2014 – Current costs	No	Yes
US Department of Transportation NHTSA (2015)	North-America	2011$	2011 – Current costs	Yes – volume dependent cost curves	Yes
TNO Truck van de Toekomst (2013)	Europe	2013€	2013 – current costs	No	Yes
TNO (2013)	Europe	2013€	2013 - Current costs	No	Yes
Ricardo-AEA (2011)	Europe	2010€	2010 – Current costs	No	Yes
ICCT (2015)	North-America	2014$	2025	Yes	Yes

4.5 Stakeholder consultations

For some technologies, stakeholder consultations were conducted. In these cases stakeholders were specifically asked what the technologies currently cost, and how the price would evolve by 2025, taking learning effects, economies of scale and indirect cost effects into account. Expert consultations were used for:

- Confirmation of literature values
- Refining of the costs ranges from available literature
- Getting information on the measures where no cost information

Overall, 10 experts have been consulted –sometimes multiple experts in one area. Experts have been consulted for the following areas:

- Tyres
- Aerodynamic devices
- Hybridization
- Engines related measure
- Transmission
- Driver assistance

4.6 Final 2025 cost estimates for use in developing cost curves

Table 11 shows the final cost inputs used for the calculation by JRC of cost curves for the different VECTO groups. The table shows how the cost data has been constructed, following the methodology illustrated above. In case the source data was not expressed in 2015 euro's, inflation correction was applied.

On the basis of these technology costs optimised cost curves, which were used for the further modelling work in support of determining cost effective target levels and their economic impacts, have been determined in JRC's DIONE model. This work is lined out in detail in a separate JRC report [Krause, 2018].

Table 11: Overview of studies used for cost analysis.

Technology ID	Technology Name	Main source used	Cost value used (2015€) incl. learning & indirect cost factor			
			group 4	group 5	group 9	group 10
Aerodynamics						
Aero-T1-1	Roof spoiler plus side flaps	Ricardo (2017)	€1,000	€1,000	€1,000	€1,000
Aero-T1-2	Side and underbody panel at truck chassis	US NHTSA (2015)	€3,078	€1,539	€3,078	€1,539
Aero-T1-5	Aerodynamic mud flaps	Ricardo (2011)	€54	€135	€81	€162
Aero-T2-2	Rear/side view cameras instead of mirrors	Own research	€180	€180	€180	€180
Aero-T2-3	Redesign, longer and rounded vehicle front	Own research combined with stakeholder consultation	€3,000	€3,000	€3,000	€3,000
Aero-S1-3	Side and underbody panels at trailer chassis	Stakeholder consultation	N.a.	€2,000	N.a.	€2,000
Aero-S1-4	Boat tail by variable height of trailer body	Inquiry send to consortium from EU FP7 TRANSFORMERS project				
Aero-S1-5	Boat tail short, additional	Stakeholder consultation combined with literature	€750	€750	€750	€750
Aero-S2-1	Boat tail long, additional	Stakeholder consultation combined with literature	€1,000	€1,000	€1,000	€1,000
Tyres						
Tyres-1	Low rolling resistance tyres on truck/tractor	Stakeholder consultation	€210	€210	€350	€350
Tyres-2	Low rolling resistance tyres on truck/tractor + trailer	Stakeholder consultation	€210	€420	€350	€560

Technology ID	**Technology Name**	**Main source used**	**Cost value used (2015€) incl. learning & indirect cost factor**			
			group 4	**group 5**	**group 9**	**group 10**
Tyres-3	Tyre pressure monitoring system (TPMS) on truck	TNO (2013)	€149	€149	€149	€149
Tyres-4	Tyre pressure monitoring system (TPMS) on truck and trailer	TNO (2013)	€149	€271	€149	€271
Tyres-5	Automated tyre inflation system (ATIS) on truck	Own research combined with stakeholder consultation	€1,080	€1,080	€1,080	€1,080
Tyres-6	Automated tyre inflation system (ATIS) on truck and trailer	Stakeholder consultation	€1,080	€1,350	€1,080	€1,350
Tyres-7	Wide base single tyres	Stakeholder consultation	-€35	-€35	-€70	-€70
Tyres-8	Wheel alignment monitoring	TNO Truck van de Toekomst (2013)	€351	€703	€351	€703
Mass						
Mass-1	5% Mass reduction (truck/tractor)	Ricardo – AEA (2015)	€471	€1,124	€471	€1,124
Mass-2	10% Mass reduction (truck/tractor)	Ricardo – AEA (2015)	€1,422	€3,112	€1,422	€3,112
Mass-3	5% Mass reduction tractor+trailer I	Ricardo – AEA (2015)	N.a.	€1,380	N.a.	€1,380
Mass-4	10% Mass reduction tractor+trailer II	Ricardo – AEA (2015)	N.a.	€4,234	N.a.	€4,234
Auxiliaries						
Aux-1	Electric hydraulic power steering	Ricardo (2017)	€360	€360	€360	€360
Aux-2	LED lighting	Own research	€240	€240	€240	€240
Aux-3	Air compressor	Ricardo – AEA (2011)	€135	€135	€135	€135
Aux-4	AC efficiency	Ricardo (2017)	€210	€210	€210	€210
Aux-5	Cooling fan	Ricardo (2017)	€180	€180	€180	€180
Transmission						
Trans-1	Reduced losses (lubricants, design)	Stakeholder consultation combined with same ratio between VECTO groups as Trans-2 technology	€202	€250	€202	€250
Trans-2	Transition from manual to AMT	US EPA & NHTSA (2016)	€2,661	€3,288	€2,661	€3,288
Driver Assistance						
ADAS-1	Engine stop-start	Stakeholder consultation	€280	€280	€280	€280
ADAS-2	Eco-roll	Own estimate	€150	€150	€150	€150
ADAS-3	Predictive cruise control	Stakeholder consultation	€1,500	€1,500	€1,500	€1,500

Technology ID	Technology Name	Main source used	Cost value used (2015€) incl. learning & indirect cost factor			
			group 4	group 5	group 9	group 10
ADAS-4	Adaptive cruise control	Stakeholder consultation	€275	€275	€275	€275
ADAS-5	Speed limiter 80km/h	Own estimate	€0	€0	€0	€0
Engine						
Engine-1	Improved turbocharging and EGR	Ricardo (2017)	€1,050	€1,050	€1,050	€1,050
Engine-3	Friction reduction + improved water and oil pumps	US EPA & NHTSA (2016)	€309	€309	€309	€309
Engine-4	Improved lubricants	Dünnebeil (2015)	€23	€23	€24	€24
Engine-5	Waste heat recovery	Ricardo (2017)	€5,000	€5,000	€5,000	€5,000
Engine-6	Downspeeding (combined with DCT optimization)	Stakeholder consultation	€1,250	€1,250	€1,250	€1,250
Engine-7	10% Engine downsizing	ICCT (2015)	-€353	-€353	-€353	-€353
Hybridisation						
Hybrids-1	48V system with starter/generator	Stakeholder consultation	€6,000	€6,000	€6,000	€6,000
Hybrids-2	Full electric hybrid	ICCT (2015)	€14,512	€14,512	€14,512	€14,512

4.7 Outlook for 2030 costs

Cost developments between 2025 and 2030
There is limited information available on the development of costs between 2025 and 2030. Only the American RIA concludes on the cost development between 2025 and 2030. 2027 is the final year in the RIA and the cost development has been lowered to relatively low numbers of slightly above 1% cost reduction per year.

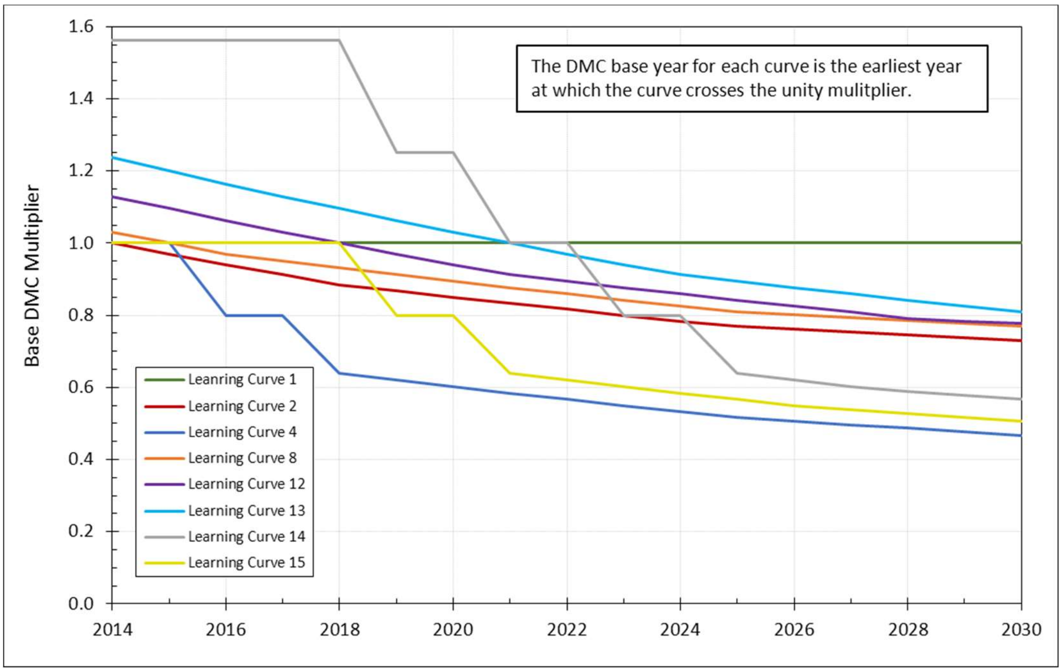

Figure 7: Direct manufacturing cost learning curves for technology cost reductions over time (from [ICCT, 2018]).

Assuming that cost reduction is already taking place since 2014, since technology suppliers and OEM are already working on all the technologies that are onboard in the study, it is fair to assume moderate cost reduction over the period 2025. All under the assumption that the massive costs reductions have taken place in the decade before 2025.

Looking on the moderate cost reductions after 2025 in the RIA and the mainly moderate cost reductions between 2025 and 2030 listed in the ICCT study[7], we propose to apply a cost reduction depending on the complexity of costs, that is somewhat lower than the cost reduction assumed in the period 2025:

Low complexity: 3.5 %	(10% cost reduction during 2015-2025)
Medium complexity: 5 %	(20% during 2015-2025)
High complexity: 10 %	(30-50% reduction 2015-2025)

4.8 Cost curve development

With the input from chapter 2 and 4, costs curves were calculated and developed by JRC [Krause, 2018], which were subsequently used as input in the PRIMES-TREMOVE model and EXIOMOD model (chapter 5) for impact assessment.

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[7] ICCT sometime assumes a steeper cost reduction between 2025 and 2030 than between 2020 and 2025

4.9 References

[Krause, 2018]	"Heavy duty vehicle CO_2 emission reduction cost curves and cost assessment – enhancement of the DIONE model", EUR 29284 EN, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/heavy-duty-vehicle-co2-emission-reduction-cost-curves-and-cost-assessment-enhancement-dione
[ICCT, 2018]	European Heavy Duty Vehicles – Cost effectiveness of fuel efficiency technologies for long haul tractor trailers in the 2025 2030 timeframe. International Council on Clean Transportation. http://theicct.org/publications/cost-effectiveness-of-fuel-efficiency-tech-tractor-trailers
[Ricardo, 2017]	Heavy Duty Vehicles Technology Potential and Cost study
[Dünnebeil et al.,2015]	Zukünftige Maβnahmen zur Kraftstoffeinsparung und Treibhausgasminderung bei schweren Nutzfahrzeugen
[US EPA & NHTSA , 2016]	Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2: Regulatory Impact Analysis
[Ricardo – AEA , 2015]	Light weighting as a means of improving Heavy Duty Vehicles' energy efficiency and overall CO_2 emissions
[ICCT, 2015]	Cost effectiveness of advanced efficiency technologies for long-haul tractor-trailers in the 2020-2030 time frame
[U.S. Department of Transportation National Highway Traffic Safety Administration, 2015]	Commercial Medium And Heavy-Duty Truck Fuel Efficiency Technology Cost Study
[TNO, 2013a]	De Truck van de Toekomst: Brandstof- en CO_2-besparing anno 2013
[TNO, 2013b]	Study on Tyre Pressure Monitoring Systems (TPMS) as a means to reduce Light-Commercial and Heavy-Duty Vehicles fuel consumption and CO_2 emissions
[Ricardo – AEA, 2011]	Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy

5 Assessment of potential impacts related to the introduction of CO_2 emission limits for lorries (Task 4)

5.1 Introduction

For the development of the scenarios, and the corresponding trajectories of fuel consumption reductions and additional automotive manufacturing costs, DG CLIMA has used PRIMES-TREMOVE, an energy and transport model that has been developed and is maintained by E3MLab/ICCS of National Technical University of Athens. The development of the scenarios and the use of PRIMES-TREMOVE was not part of the service request 9 project. In Task 4 of SR 9 output from PRIMES-TREMOVE scenarios is used as input for EXIOMOD, which is used for assessing the EU-wide impacts on economic indicators (value added by industry, production by industry, relative competitiveness and trade balance) and social indicators (employment).

This chapter is structured as follows: Section 5.2 describes the TNO model (EXIOMOD) that is used for the economic impact analysis, together with the scenarios and corresponding input data in EXIOMOD, received from PRIMES-TREMOVE. Sections 5.3 - 5.7 describe the output of EXIOMOD with respect to economic impacts of these scenarios, which is used by the Commission in their impact assessment.

5.2 Identification of options for lorries' fuel consumption and CO_2 emission standards to be assessed

The European Commission had the lead in the identification of the different policy options and the development of scenarios during the project. During the execution of task 4, the different scenarios and output from PRIMES-TREMOVE was used as input for the macro-economic analysis described in section 5.3, and for which results are presented in Section 5.4.

5.3 Modelling approach economic and social impact

Data and model description

Description of the model

EXIOMOD is an economic model able to assess the environmental and economic impacts of policies[8]. As a multisector model, it accounts for the economic dependency between sectors. It is also a global and multi-country model with consistent bilateral trade flows between countries at the detailed commodity level. Based on national account data, it can provide comprehensive scenarios regarding the evolution of key economic variables such as GDP, value-added, turn-over, (intermediary and final) consumption, investment, employment, trade (exports and imports), public spending or taxes. Thanks to its environmental extensions, it makes the link between the economic activities of various agents (sectors, consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases, wastes).
A more extensive description is given in Annex G. The full description of EXIOMOD 2.0 is given by Bulavskaya et al. (2016).[9]

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[8] For a full description and examples of applications of EXIOMOD see Bulavskaya, Hu, Moghayer, & Reynès (2016).

[9] Tatyana Bulavskaya, Jinxue Hu, Saeed Moghayer and Frédéric Reynès (2016). EXIOMOD 2.0: EXtended Input-Output MODel: A full description and applications. TNO Working Paper Series 2016-02

For the purposes of the present impact assessment, EXIOMOD is used to quantify the macro-economic impacts of different CO_2 targets for HDVs on the wider economy. That is, GDP, output and employment by sector, and net-export. The modeled scenarios use input from PRIMES-TREMOVE. Modeled scenarios are described further on in this section.

Description of the data

The current version of EXIOMOD uses the detailed Multi-regional Environmentally Extended Supply and Use (SU) / Input Output (IO) database EXIOBASE 3.3. with base year 2011[10] (www.exiobase.eu). This database has been developed by harmonizing and increasing the sectorial disaggregation of national SU and IO tables for a large number of countries, estimating emissions and resource extractions by industry, harmonizing trade flows between countries per type of commodity. Moreover, it includes a physical (in addition to the monetary) representation for each material and resource use per sector and country.

The EXIOBASE database has one of the most detailed products and environmental extensions that are currently available from input-output tables. The database covers 49 regions (44 countries representing around 90% of the world GDP and five rest of the world regions), 200 products and various environmental indicators. All 28 countries from EU28 are present in this database.

Products sold in the following sectors will be directly impacted by the policies scenarios proposed in this WP:

- Manufacturing of motor vehicles, trailers and semi-trailers;
- Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts and accessories; retail trade of motor fuel;
- Other land transport services.
- Mining and manufacturing of petroleum products.

Scenarios

Description of the scenarios

Cost curves, in relation to the CO_2 abatement potential are derived by the JRC. These cost curves allowed the European Commission to define a range of scenarios. The names of the scenarios assessed below are defined by the CO_2 reduction at vehicle level in 2025 and 2030. That is, Scenario 1020 indicates 10% reduction of CO_2 emissions in 2025, and 20% reduction of CO_2 emissions in 2030, relative to 2019. Scenario 12h30 indicates 12,5% reduction of CO_2 emissions in 2025, and 30% in 2030, relative to 2019.

Each scenario comes with a corresponding increase in cost for the automotive sector, and a potential decrease in fuel use for heavy duty vehicle trucks, i.e. transport over land. These effects are calculated by PRIMES-TREMOVE and function as scenario input for EXIOMOD 2.0.

The following six scenarios have been defined:

- Reference scenario
- Scenario 1020
- Scenario 12h30
- Scenario 1530
- Scenario 17h32
- Scenario 2035

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[10] Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J. M., … Bouwmeester, M. (2009). Towards a global multi-regional environmentally extended input-output database. Ecological Economics, 68(7), 1928–1937. http://doi.org/http://dx.doi.org/10.1016/j.ecolecon.2008.11.010

Visualization of scenarios

For the integration of model results from partial equilibrium model PRIMES in TNO's computational equilibrium model EXIOMOD, the following input parameters where received from PRIMES for each of the described scenarios:

	Description
GDP	Gross domestic product (in M€ 2013)
Population	Population (in Millions)
Fuel consumption	Fuel consumption from total road transport (in ktoe)
Production costs	Annuity payment for capital costs for total road transport vehicles (in M€ 2013)
Registered road transport	New registrations for total road transport (in thousand vehicles)
Road transport activity	Activity of road freight transport (incl. heavy duty trucks and freight light duty trucks) (in Gtkm)

These input values have different units than monetary units used in EXIOMOD. For the use in EXIOMOD, indices are calculated. An index of 1.10 in 2020 indicates a 10% increase with respect to the level in 2010. These indices are illustrated in Figure 8 - Figure 12.

Growth paths of GDP and population are part of each scenario. Input data from PRIMES shows that GDP is expected to grow with 80% between 2010 and 2050, with a relatively steep slope. Population shows a decreasing increasing path, with a 4% growth in 2050 with respect to 2050.

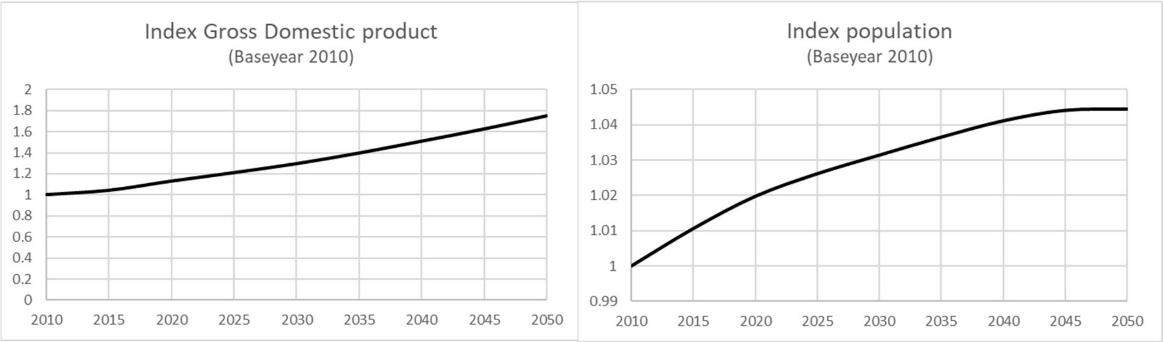

Figure 8: Indices for Gross Domestic Product and Population, based on input data from PRIMES-TREMOVE

One of the most important input data from PRIMES is the decrease in fuel use in Heavy duty vehicles in land transport. Figure 9 shows that in the reference scenario, total use of fuel is expected to increase with more than 16%. Also in the reference scenario, already some technological changes are taken into account. However, due to expected improvement of the economy, demand for transport increases, hence fuel use used in the freight road transport sector increases.

The policy scenarios fan out in a decreasing and logical order. That is, scenario 1020 - where 10% emissions reduction in the freight land transport sector should be achieved by 2025 and 20% in 2030 - shows less fuel reduction than scenario 1530. This scenario assumes a reduction of 15% emissions by 2025 and 30% by 2030.

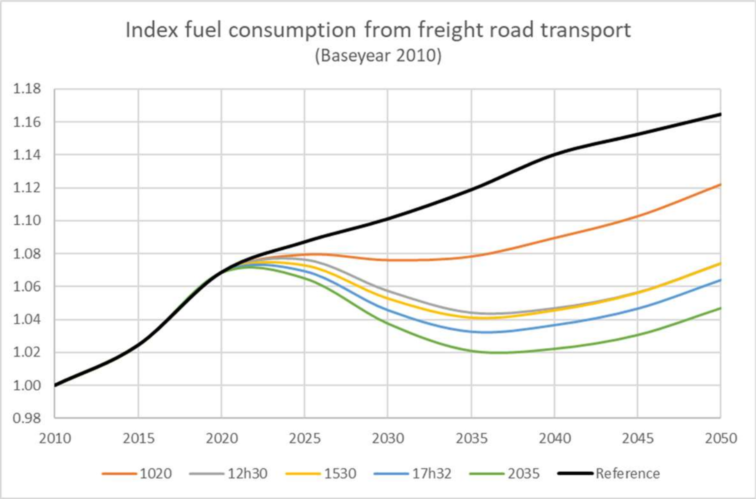

Figure 9: Indices for fuel consumption from freight road transport based on input data from PRIMES-TREMOVE.

These fuel use reductions require upfront investments that increase the price of trucks. Because the database (EXIOBASE 3.3) used for CGE EXIOMOD only has an aggregated industry for the automotive manufacturing industry, we used the impact on the price for the full industry. This includes both production for passenger transport as for freight transport. By taking the index of the annuity payments for the total road transport vehicles, higher freight transport costs are weighted in the total annuity costs. Hence, this index can safely be used to impact the aggregated automotive manufacturing industry.

Figure 10 shows that impact on the costs of manufacturing land transport vehicles. Again, the thick black line represents the reference scenario. This PRIMES input data shows that the difference in costs in the automotive industry is quite small between the policy scenarios and the reference scenario. This could be because it is a weighted price index that also includes other automotive vehicles that are not impacted by the policies.

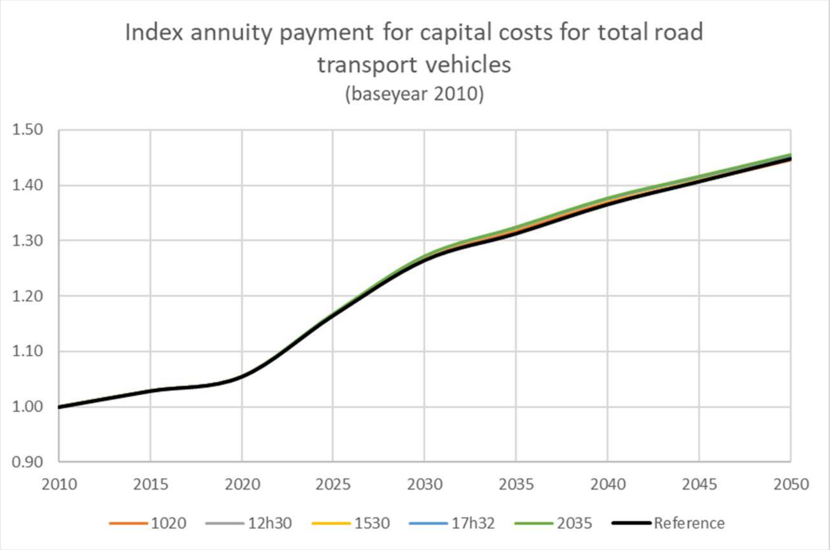

Figure 10: Indices for annuity payment for capital costs for total road transport vehicles, based on input data from PRIMES-TREMOVE.

The transport sector is known as a highly competitive sector. We assume that cost savings are unlikely to be passed on to better wage conditions for the truckers or increases in profit. Instead, these cost savings are assumed to be passed on to the market. Those industries that have demand for (land) transport shall face lower prices, hence, demand for land transport increases. In order to prevent that these costs savings are passed on to the value added elements 'labour' and 'profit', the expected growth in demand for freight transport is taken from PRIMES-TREMOVE. Labor and profit shall not increase by more than the index presented Figure 11. Similar assumptions are taken for the automotive manufacturing sector, where the labor and profit increase proportionally with respect to the number of new registered road vehicles (see Figure 12). The number of registered road vehicles is expected to decreases under the policy scenarios compared to the reference scenario.

In Figure 10, Figure 11 and Figure 12, scenario deviations from the reference scenario are barely visible. For example, in the figure for 'new registrations for total road transport', only scenario 2035 shows a deviation from the reference scenario. However, all other scenarios are right underneath this line. Therefore, for Figure 10, Figure 11 and Figure 12, we also present a table with the development with respect to the reference scenario, for 2040 and 2050 (Table 12).

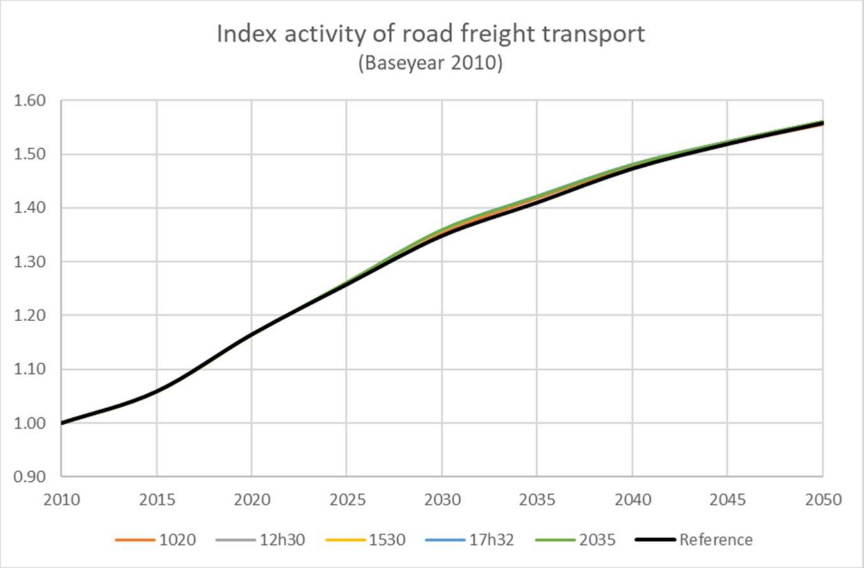

Figure 11: Indices for activity of road freight transport, based on input data from PRIMES-TREMOVE.

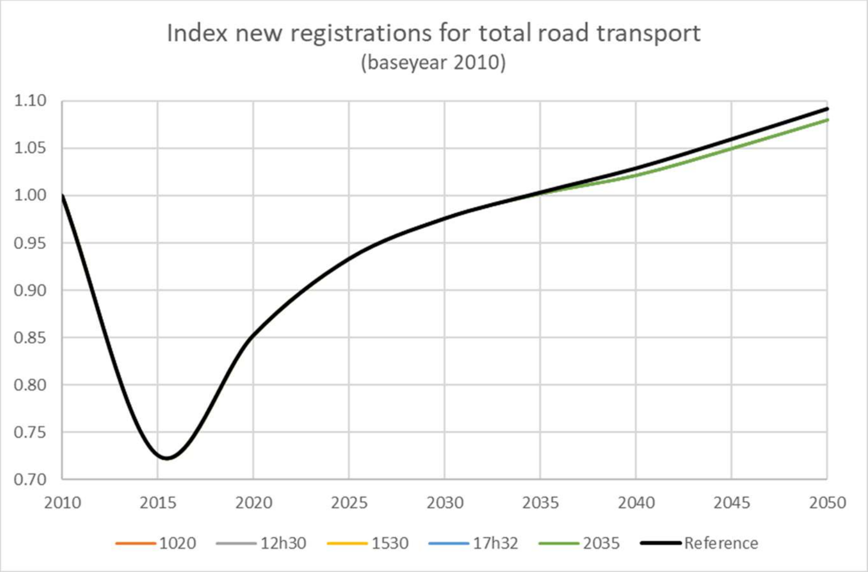

Figure 12: Indices for new registered vehicles for total road transport, based on input data from PRIMES-TREMOVE.

Table 12: Relative change in "annuity payment for capital costs for total road transport vehicles" (Figure 10), "activity of road freight transport" (Figure 11), and "new registered vehicles for total road transport" (Figure 12), with respect to the reference scenario in 2040 and 2050.

	Figure 10		**Figure 11**		**Figure 12**	
	2040	2050	2040	2050	2040	2050
1020	0.1%	-0.2%	0.4%	-0.1%	-0.7%	-1.1%
12h30	0.5%	0.2%	0.6%	0.2%	-0.7%	-1.1%
1530	0.5%	0.2%	0.6%	0.2%	-0.7%	-1.1%
17h32	0.6%	0.3%	0.6%	0.2%	-0.7%	-1.1%
2035	0.8%	0.5%	0.5%	0.2%	-0.7%	-1.1%

Model assumptions EXIOMOD

Assumptions with respect to policy scenarios

Assumptions with respect to policy scenarios refer to implementation of input of the PRIMES-TREMOVE indices in EXIOMOD. That is, shocks are placed on those parameters that impact the endogenously determined variable that it should directly influence. A shock refers for example to an increase in GDP or a decrease in fuel use. Which parameters are used is explained for each of the shocks below.

Increase in GDP
The GDP trajectory of the reference scenario is implemented by calibrating capital and labor productivity such that GDP follows that pathway from PRIMES-TREMOVE in the reference scenario. These values for capital and labor productivity are also used for the policy scenarios. This allows us to evaluate the changes in GDP due to the policy scenario.

Decrease in fuel costs
The input data from PRIMES-TREMOVE on 'Fuel consumption from freight road transport', has been transformed into a trajectory of indices. These indices are used to decrease the share of fuel consumption from total expenditures in the transport sector. For example, for each euro worth of production in the 'other land transport' industry, 25% of total expenditures in this industry comes from demand for fuel. Using the mentioned indices, calculated from the PRIMES-TREMOVE input data, this share is decreased every year to follow the same pathway as the pathway of 'fuel consumption from freight road transport'.

Proportional increase in capital and labor
Decreases in fuel use result in higher turnover values in the 'other land transport' industry. If we would not pose any restrictions to the model, also labor and capital (profit) increases proportionally from this boost to the sector. However, transport is a highly competitive sector, were efficiencies in the market are likely to be forwarded to the consumers of transport.
Trajectories 'activity of road freight transport' and 'new registrations for total road transport' were received by primes for all scenarios. These trajectories give an indication of the demand for transport and transport equipment in volumes (not monetary values). Labor and capital in the respective sectors that deliver those products, are bounded to increase to volume increases in 'activity of road freight transport' and 'new registrations for total road transport'.

Increases in costs manufacturing automotive vehicles
Trucks produced for the European market have to meet the new European standards. This implies that retail price of trucks for the European market are expected to increase. The increase in price is given by the trajectory 'index annuity payment for capital costs for total road transport vehicles', input from PRIMES-TREMOVE into EXIOMOD.
Note that it does not matter whether these trucks are produced in countries outside the European union. Also trucks produced elsewhere should satisfy the new standards, and thereby face higher production costs.

Additional assumptions

Besides external impacts on the model that come from the policy scenarios defined by PRIMES-TREMOVE, there are some additional impacts to the model.

Transfers from government to household
Assume that transfers from government to households grow at the rate of population. Population growth is taken from PRIMES-TREMOVE.

Endogenous labor growth
EXIOMOD has the option to include an extra model with a labor equation. In the base model of EXIOMOD 2.0, labor growth is exogenous. Without the extra labor equation, labor grows the rate of population. With the extra labor equation, labor grows with the price of labor, and is corrected for inflation.

5.4 Economic impact of scenarios (Results)

This section shows the economic impact results of scenarios that were considered by DG CLIMA, and that results from input parameters received from PRIMES-TREMOVE. An overview of the different results with reference to the specific tables is given in the overview below. All results are shown on the aggregated level of EU28.

Economic indicators	***Table***
Impact on value added by industry (e.g. automotive manufacturers and oil sector)	Table 13
Production by industry (e.g. of the manufacturers and oil sector)	Table 14
Trade balance	Table 17
Social indicators	***Table***
Employment (impact on EU job creation/ deletion)	Table 15 and Table 16

Gross Domestic product

Overall, we can say that the impact of technological changes in Heavy Duty Vehicles in EU28 has limited impact on the rest of the economy. This is highlighted by the effect on Gross Domestic Product (GDP), illustrated in Table 13. Under the prespecified baseline, i.e. the reference scenario, GDP in EU28 is expected to add up to more than 19 trillion euro. The scenarios have a positive impact on the value of the economy, however, never more than 0.02%.

Table 13: GDP impacts in the baseline (million euros) and percentage change from the baseline under the policy options.

Option	2025	2030
Baseline (M EUR)	14,447,916	15,397,847
1020	0.00%	0.03%
12h30	0.01%	0.08%
1530	0.02%	0.09%
17h32	0.02%	0.11%
2035	0.03%	0.14%

Production by industry

Also impacts on different sectors have been quantified, where the impact on all other sectors, besides the ‘other land transport’ sector, is relatively small. Due to decreases in production costs in ‘other land transport’, caused by the fuel reductions, prices for a product from this sector decrease. This leads to increase in demand, which has a positive impact on demand for land transportation. Sectors, like the construction sector, that have relatively large demand for land transport also benefit from the lower transport prices. Table 14 also shows that sectors related to petroleum products (manufacturing or mining of petroleum) are in a disadvantaged position compared to the baseline situation.

Table 14 : Impacts on the turnover of the most affected sectors as a percentage change from the baseline

Sector	Option	2025	2030
Manufacturing of refined petroleum products	1020	-0.1%	-0.2%
	12h30	-0.1%	-0.4%
	1530	-0.1%	-0.4%
	17h32	-0.2%	-0.5%
	2035	-0.2%	-0.5%
Manufacturing of motor vehicles	1020	0.0%	0.0%
	12h30	0.0%	0.0%
	1530	0.0%	0.0%
	17h32	0.0%	0.0%
	2035	0.0%	0.0%
Transportation services	1020	0.0%	0.1%
	12h30	0.0%	0.2%
	1530	0.1%	0.3%
	17h32	0.1%	0.3%
	2035	0.0%	0.0%
Other land transportation services	1020	0.1%	0.6%
	12h30	0.2%	1.4%
	1530	0.3%	1.6%
	17h32	0.4%	1.9%
	2035	0.6%	2.4%
Mining fossil fuel (no petroleum)	1020	0.0%	-0.1%
	12h30	0.0%	-0.1%
	1530	0.0%	-0.1%
	17h32	0.0%	-0.2%
	2035	-0.1%	-0.2%
Extraction crude petroleum	1020	-0.1%	-0.2%
	12h30	-0.1%	-0.5%
	1530	-0.1%	-0.6%

Sector	Option	2025	2030
	17h32	-0.2%	-0.6%
	2035	-0.3%	-0.8%
Construction	1020	0.0%	0.0%
	12h30	0.0%	0.1%
	1530	0.0%	0.1%
	17h32	0.0%	0.1%
	2035	0.0%	0.2%
Sale and maintenance of motor vehicles	1020	0.0%	-0.1%
	12h30	0.0%	-0.1%
	1530	0.0%	-0.1%
	17h32	0.0%	-0.1%
	2035	0.0%	0.0%
Manufacturing industry (no motor vehicles)	1020	0.0%	0.0%
	12h30	0.0%	0.0%
	1530	0.0%	0.0%
	17h32	0.0%	0.0%
	2035	0.0%	0.0%

Employment

Table 15 and Table 16 give the impact on employment under the different policy scenarios. Where Table 15 shows the impact on the economy as a whole, Table 16 looks at employment effects within specific sectors. Most sectors that observe an increase (decrease) in output, also observe an increase (decrease) in population. As mentioned, the increase in economic output (monetary values) does not directly lead to higher employment. Employment increase in this sector is bounded by the ‘activity of road freight transport’ (in volumes) received by PRIMES-TREMOVE.

The ‘sale and maintenance of motor vehicles’ sector is the sector from which ‘other land transport’ receives its trucks. Output prices in this sector determine how much the ‘other land transport sector pays for the trucks. Therefore, output prices in ‘sale and maintenance of motor vehicles’ received a positive shock. At the same time, employment in ‘sale and maintenance of motor vehicles’ has been bounded by the increase in volumes within this sector, reported by PRIMES-TREMOVE under ‘new registrations for total road transport’.

Table 15: Total number of jobs (000s) under the baseline and percentage changes to the baseline under different policy options.

Option	2025	2030
Baseline (000s)	236,339	242,102
1020	0.0%	0.0%
12h30	0.01%	0.04%
1530	0.01%	0.05%
17h32	0.02%	0.06%
2035	0.02%	0.08%

Table 16: Total employment impacts in terms of percentage changes to the baseline.

Sector	Option	2025	2030
Manufacturing of refined petroleum products	1020	-0,1%	-0,2%
	12.5-30	-0,1%	-0,4%
	1530	-0,1%	-0,4%
	17.5-32	-0,2%	-0,5%
	2035	-0,2%	-0,5%
Manufacturing of motor vehicles	1020	0,0%	0,0%
	12.5-30	0,0%	0,0%
	1530	0,0%	0,0%
	17.5-32	0,0%	0,1%
	2035	0,0%	0,1%
Transportation services	1020	0,0%	0,1%
	12.5-30	0,0%	0,2%
	1530	0,1%	0,3%
	17.5-32	0,1%	0,3%
	2035	0,1%	0,4%
Other land transportation services	1020	0,1%	0,4%
	12.5-30	0,2%	0,8%
	1530	0,3%	0,8%
	17.5-32	0,3%	0,9%
	2035	0,4%	0,9%
Mining fossil fuel (no petroleum)	1020	0,0%	-0,1%
	12.5-30	0,0%	-0,1%
	1530	0,0%	-0,1%
	17.5-32	0,0%	-0,1%
	2035	0,0%	-0,1%
Extraction crude petroleum	1020	-0,1%	-0,2%
	12.5-30	-0,1%	-0,5%
	1530	-0,1%	-0,5%
	17.5-32	-0,2%	-0,6%
	2035	-0,2%	-0,7%
Construction	1020	0,0%	0,0%
	12.5-30	0,0%	0,1%
	1530	0,0%	0,1%
	17.5-32	0,0%	0,2%
	2035	0,1%	0,2%
Sale and maintenance of motor vehicles	1020	0,0%	0,0%
	12.5-30	0,0%	0,0%
	1530	0,0%	0,0%
	17.5-32	0,0%	0,0%
	2035	0,0%	0,0%
Manufacturing industry (no motor vehicles)	1020	0,0%	0,0%
	12.5-30	0,0%	0,0%
	1530	0,0%	0,0%
	17.5-32	0,0%	0,0%
	2035	0,0%	0,0%

Trade balance

Net exports are presented in Table 17. The automotive sector in EU28 requires quite some input from other automotive sectors outside EU28. (For example, a semi-finished automotive product from China is input in the automotive industry in EU28.) Therefore, we observe an increase in import from automotive products. Export from automotive products decreases slightly, despite that total output in this sector in the EU increases. Reason of slightly decreasing export could be that trucks produced in the EU are necessary in EU28, due to the increase in demand for transportation over land.

Also, notice that changes with respect to the baseline are larger than in the case of other parameters. Where GDP, output, and employment increased with percental changes around 0-0.7%, we find changes in net export up to nearly 6%.

Table 17: Net exports (million euros) and percentage change from baseline under the policy options.

Product from industry	Scenario	2025	2030
Manufacturing of refined petroleum products	BL	2,542	11,141
	1020	0.3%	0.2%
	1530	0.6%	0.4%
	2035	0.9%	0.5%
	12h30	0.4%	0.3%
	17h32	0.7%	0.4%
Manufacturing of motor vehicles	BL	192,695	214,746
	1020	0.0%	-0.1%
	1530	-0.1%	-0.3%
	2035	-0.1%	-0.5%
	12h30	0.0%	-0.3%
	17h32	-0.1%	-0.4%
Transportation services	BL	-38,575	-51,902
	1020	-0.1%	-0.4%
	1530	-0.2%	-0.9%
	2035	-0.4%	-1.4%
	12h30	-0.2%	-0.8%
	17h32	-0.3%	-1.1%
Mining fossil fuel (no petroleum)	BL	-57,565	-62,009
	1020	0.0%	0.1%
	1530	0.0%	0.2%
	2035	0.1%	0.3%
	12h30	0.0%	0.2%
	17h32	0.1%	0.2%
Extraction crude petroleum	BL	-113,923	-122,181
	1020	0.0%	-0.1%
	1530	-0.1%	-0.3%
	2035	-0.1%	-0.3%
	12h30	-0.1%	-0.2%
	17h32	-0.1%	-0.3%
Construction	BL	10,475	9,924
	1020	-0.1%	-0.9%
	1530	-0.4%	-2.3%
	2035	-0.8%	-3.4%
	12h30	-0.3%	-2.0%
	17h32	-0.6%	-2.7%
Sale and maintenance of motor vehicles	BL	-292	-5,863
	1020	14.3%	2.8%
	1530	25.7%	5.1%
	2035	38.9%	6.7%
	12h30	19.9%	4.6%
	17h32	32.0%	5.8%
Manufacturing industry (no motor vehicles)	BL	104,254	98,719
	1020	-0.2%	-1.8%
	1530	-0.8%	-4.5%
	2035	-1.5%	-6.5%
	12h30	-0.5%	-3.9%
	17h32	-1.1%	-5.3%

Annex A Determination of the EU baseline fuel consumption and CO_2 emissions (Task 1)

A.1 General

Initially the main purpose of Task 1 was to determine the baseline fuel consumption and the best performer fuel consumption for all 10 VECTO vehicle groups, split up in the relevant mission profiles as indicated in Table 2 as far as possible.

However, after discussions with the European Commission and in the light of preparing the impact assessment it was decided to focus on the four vehicle groups 4, 5, 9, 10, which are responsible for the largest share of all HDV CO_2 emissions.

In the end the results from Task 1 have not been used for the impact assessment and the regulatory proposal of the European Commission. Instead the Commission's proposal and the associated impact assessment are based on actual monitoring data collected for the year 2019, as described in a report by the JRC [Fontaras, 2018].

The sequence and interaction between the subtasks in Task 1 are presented schematically in Figure 13. To be able to compare the fuel consumption calculated with VECTO with the fuel consumption in the real world, monitoring data was collected for fleets and individual trucks, and subsequently analysed (1.1). Real world vehicle specifications were derived from these data as well, to be used in VECTO calculations (1.3). Next, for several vehicle categories baseline fuel consumption averages were calculated using these monitoring data (1.2). In the same time the fuel consumption was estimated for these vehicle categories using VECTO model calculations (1.3). The real-world and VECTO results were compared and analysed (1.4). As a conclusive task, the baseline was determined (1.7).

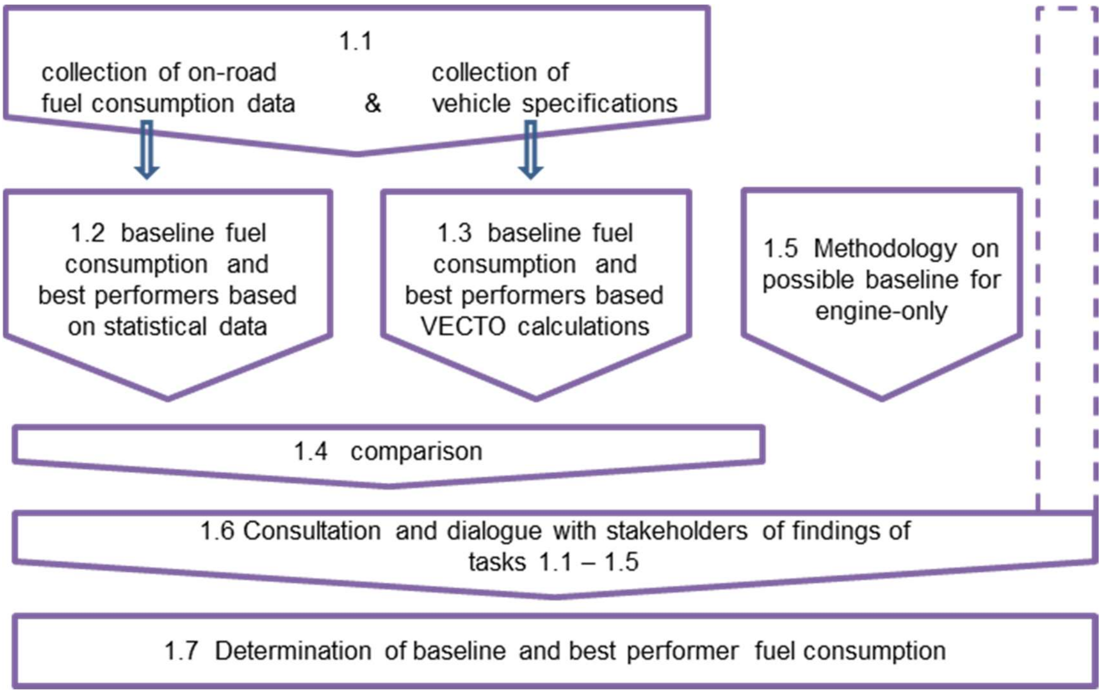

Figure 13: Schematic of Task 1.

A.2 1.1: Survey of truck fleet characteristics and analysis of on-road records of fuel consumption

Approach
In order to gather data about fuel consumption and the characteristics of the European truck fleet and the on-road use of vehicles, a diverse strategy was developed to gather real world data from diverse sources. The consortium reached out to truck operators, truck importers and dealers, truck manufacturers and their industry representatives.

Approximately 60 companies and a number of industry groups have been approached with the purpose of catalysation in early 2017. 25 individual companies have finally agreed to co-operate and have shared detailed fuel consumption data (individual truck data) of vehicles in their fleet. In total, data was collected for 1353 vehicles. Additionally, the Dutch Association for Transport and Logistics (TLN) provided fleet data for >2500 vehicles.

In addition, the consortium reached out to OEMs (through ACEA) for gathering of vehicle characteristics. Also, Dutch importers and dealers were contacted and asked to provide characteristics of the truck fleet. Data formats have been developed to gather the data, a ‘static’ format for gathering information about the layout of vehicles and an ‘operational’ data format for gathering of day-to-day operational data.

Most of the vehicles in the collected data sets belong to group 5 and 10, the tractor-semitrailer combinations. This is a good representation of the on-road situation. Four vehicle groups were selected to proceed with the analysis, see Table 18.

Table 18: Vehicle groups selected for analysis.

Group	Chassis configuration	Axle configuration	Gross vehicle weight
Group 4	Rigid truck	2 axles, 4x2	>16 ton
Group 5	Tractor-semitrailer	2 axles, 4x2	7.5-16 ton
Group 9	Rigid truck	3 axles, 6x2	All weights
Group 10	Tractor-semitrailer	3 axles, 6x2	All weights

The collected data sets contain fuel consumption data for trucks in each of the four groups, on either individual truck level or aggregated fleet level. Table 19 provides an overview of the data collected, in terms of vehicle count and total distance driven. Data for pre-Euro VI trucks was not taken into consideration.

Table 19: Number of Euro VI trucks for which fuel consumption data was received.

	Number of vehicles		Total distance x1000 km	
Vehicle group	Individual truck data	Fleet data (TLN*)	Individual truck data	Fleet data (TLN*)
4	13	136	690	11,339
4 + trailer	5	125	20	10,341
5	146	1,322	8,395	156,821
9	58	88	4,448	6,900
9 + trailer	-	113		12,438
10	102	514	8,119	54,348
Total	324	2,298		252,187
	Euro VI	Euro VI	Euro VI	Euro VI

*) TLN: the Dutch Association for Transport and Logistics

The data received were analysed and summarized in the next sections:
In the section below ‘truck fleet characteristics’ a baseline truck configuration is derived from the penetration of fuel saving features in the current truck fleet described in the section below. The fuel consumption data on an individual truck level and on fleet level are described in respectively the sections (A 2.1) and (A 2.2) below.

Truck fleet characteristics
The static data format has been used to gather information from Dutch truck importers and dealers about the typical vehicles that are sold on the Dutch market, during interviews. Details over specific fuel-efficient technologies, such as used in VECTO, could not be recovered. Also, OEMs did not provide such details. It was therefore not possible to link the best performers in the fleet to forerunners with best technologies.

One of the key points made in the answers is that truck performance can be defined from various perspectives, where fuel consumption is not the only perspective. The truck’s mission is also important for its design. Consequently, the truck with most fuel consumption reduction options installed are used for international transport, but have the largest cabin and engine at the same time. Although the following characteristics could be allocated to a basic or fuel efficient truck, in reality these better correlate with the specific mission profile:

- Empty weight: 6.2 (national transport) - 7.5 tonnes (international transport)
- Cabin height: day cabin (national transport) or sleeper cabin (international transport)
- Engine power 265 (national transport); – 370 kW (international transport)
- Engine displacement 10 (national transport)-12 litres (international transport)

For other characteristics that correlate with basic performance and best performance from a fuel consumption point of view, the following information for long haul trucks has been derived from various interviews with truck importers in the Netherlands, see Table 20.

Table 20: Overview of basic and best in class characteristics for a long haul truck-semitrailer (40 ton GVW) used by Dutch operators.

Body	**Basic**	**Best in class**
Roof spoiler	standard	standard
Cabin side flaps	standard	standard
Side-skirts truck/tractor	-	optional
Active grill shutter	-	standard
Tyres	C/D label	B label
Engine/transmission		
Transmission type	(A)MT 12 speed	AMT 12 speed
Axle ratio	2.6	2.6
Final gear ratio	1	1
Fuel saving technologies		
Engine Start/Stop	optional	optional
Eco-Roll	optional	standard
Predictive Cruise Control - PCC	-	optional / standard
Adaptive Cruise Control - ACC	-	optional
Driver assistance software (FleetBoard, Dynafleet, Transics, etc.)	standard	standard
Tyre pressure management system (TPMS)	optional	standard
Max speed setting Speed limiter	legal maximum (89+1)	legal maximum (89+1)
Retarder type	exhaust brake	hydraulic brake

Moreover, there are publications that describe truck technologies that influence the fuel consumption, and their penetration grade. Based on European sales data acquired from KGP[11], ICCT (2017) provides generic data on the penetration of some key technologies in new vehicles in the year 2015, as illustrated in Table 21.

Table 21: Technology penetration in newly sold vehicles – 2015.

Technology	Penetration rate rigid truck	Penetration rate tractor trailer
Turbo-compounding	--	--
Automated manual transmission	50%	70%
Automatic transmission	--	2%
Dual clutch transmission	--	2%
Active grille shutter	N/A	25%
Side skirts	N/A	15%
Single wide tyres	--	2%
Tyre pressure monitoring	--	5%
High efficiency SCR	10%	10%
Variable speed fan	--	--
On demand pumps	--	5%
Adaptive cruise control	N/A	50%
Predictive cruise control	N/A	20%

Source: [ICCT, 2017]

As part of a consultation amongst operators in the Netherlands, penetration rates of various technologies amongst 87 operators have been gathered, by [CE Delft, 2014]. The results are listed in Table 22.

Table 22: Technology penetration amongst Dutch operators (2013).

Technology	Purchased	Fleet coverage within company
Tyre pressure management system (TPMS)	18%	40%
Low rolling resistance tyres (LRRT)	24%	47%
Aerodynamic mud flaps	4%	51%
Trailer side skirts	10%	33%

(Average) vehicle configuration
The average and best-in-class truck have been characterised on the basis of information available, being the information gathered and presented in this section and other studies performed in this area [Ricardo, 2017; Dünnebeil, 2016, ICCT, 2017]. The results are displayed in Table 23.

The best-in-class truck has been designed as such, that features are fitted that are already applied in >10% of the current fleet. Engine power is correlated with mission profile rather than with fuel consumption performance. The range in engine power is rather large, 300-375 kW for group 5 or 10 with a median value of 338 kW.

Data largely overlap for group 5/10 and 4/9. In case the data differs, this is indicated by a slash symbol in the table (e.g. 225/325 kW).

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[11] A U.K.-based consulting firm specializing in the international automotive industry. KGP obtains its data from a variety of sources including government
registrations, published databases, automotive suppliers, expert consultations, and inhouse experts.

Table 23: Vehicle characteristics for basic and best in class vehicles.

	Long haul (group 5/10)		Rigid (group 4/9)	
	Basic	**Best in class**	**Basic**	**Best in class**
GVW (tonnes)	18/25	18/25	18/26	18/26
Body				
Roof spoiler	yes	yes	yes	Yes
Cabin side flaps	yes	yes	--	Yes
Side-skirts truck/tractor	--	yes	--	--
Active grill shutter	--	yes	--	--
Tyres	single tyre C/D label	single tyre B label	single tyre C/D label	single tyre B label
Empty mass (tonnes)	7.5	6.5	Not available	Not available
Engine/transmission				
Engine power	335 kW	335 kW	225/325 kW	225/325 kW
Engine displacement	12.8 liter	12.8 liter	8 liter	12 liter
High efficiency SCR	no	yes	no	No
Transmission type	AMT 12 speed	AMT 12 speed	MT 12 speed	AMT 12 speed
Axle ratio	2.6	2.6	Not available	Not available
Final gear ratio	1	1	0.8	0.8
Fuel saving technologies				
Engine Start/Stop	--	--	--	--
Eco-Roll	yes	yes	--	--
Predictive Cruise Control	-	--	--	--
Adaptive Cruise Control	-	yes	--	--
Driver assistance software (FleetBoard, Dynafleet, Transics, etc.)	yes	yes	yes	Yes
Tyre pressure management system (TPMS)	--	yes	--	--
Max speed setting Speed limiter	legal maximum (89+1)	legal maximum (89+1)	legal maximum (89+1)	legal maximum (89+1)
Retarder type	exhaust brake	hydraulic brake	exhaust brake	hydraulic brake
On-demand pumps	--	yes	--	--
Variable speed fan	--	yes	--	--

A.2.1 Individual truck data

Approach
An Excel-based questionnaire was designed to help companies in collecting relevant trip fuel consumption data and vehicle characteristics information. The requested data consisted of static data (truck fleet characteristics) and dynamic data (periodical fuel consumption data and operational data).

The vehicle characteristics requested encompassed the vehicle group, manufacturer, type, truck dimensions, GVW, axles, year built, engine power, Euro class, data on the powertrain (engine and transmission), tyres, body type and aerodynamics, fuel saving technologies applied, and trailer information (if applicable).

The dynamic data requested included fuel consumption data per trip, tank or period, distances, payload, speed, driver behaviour (such as stops, braking, cruise control, idling, speeding) and location.

Dataset
For most transport companies, it was difficult to collect vehicle characteristics (e.g. vehicle configuration details), as it required too much effort. For only 17 vehicles (distributed over 6 companies) a complete dataset was returned. Most of the vehicle characteristics information was therefore derived from a licence plate lookup in the type approval authority's database. Many of the details relevant for VECTO were absent in this static data.

Because of the diverse systems used by fleet managers, the dynamic (fuel consumption) data was provided in different formats. The data were logged manually by the transport company or provided through printouts from, or electronic access to, fleet management system (FMS) data. Considerable effort has been made to make the information accessible, to harmonise its format and to check its validity. Fuel consumption data was not always available at a trip level. Hence, to be able to utilise all data in our analyses, the validated data has been sorted into three levels of detail: data per trip, data per tank event and data per period (mostly monthly averages).

The full dataset includes Euro VI and Euro V vehicles. Only Euro VI vehicles were used in the present analysis. In Table 24 an overview is given of the number of vehicles with trip data including the total distance for which fuel consumption data was collected. It can be seen that the total distance for group 4 vehicles, a little over 700,000 km, is rather limited. For groups
5, 9 and 10 the distance ranges from 4 to 8 million km (all Euro VI).

Table 24: Number of Euro VI trucks for which fuel consumption trip data was received.

Vehicle group	Number of vehicles	Total distance x1000 km
4	13	690
4 + trailer	5	20
5	146	8,395
9	58	4,448
9 + trailer	-	
10	102	8,119
Total	324	
	Euro VI	Euro VI

Table 25 gives the data recording system (fleet management system) per transport company, as well as the number of vehicles per vehicle group for Euro V plus Euro VI vehicles together. The transport companies are not named as the collected data was provided under confidentiality.

Table 25: Overview of data recording systems and number of vehicles per vehicle group (Euro V + Euro VI).

Company	Vehicle data	Fleet management system	Vehicle group			
			Group 4	**Group 5**	**Group 9**	**Group 10**
A	Number plate	Transics		2		32
B	Number plate	Transics	68	7	1	
C	Number plate	Transics		106		19
D	Number plate	Fleetmanagement Mercedes	16	1	33	
E	Number plate	Trimble		13	5	
F	Number plate	No	2			
G	Number plate	Groeneveld Board computers	2	23	14	
H	Number plate	Yes, but unknown	12	35		
I	Number plate	Dynafleet		6		
J	Number plate	Trimble			1	7
K	Number plate	Transics		3	6	99
L	Number plate	Yes, but unknown	29	53	7	
M	Class, euroclass, GVW, brand, type	Yes, but unknown		61		
N	Brand, type, euroclass, configuration	Unknown		137		7
O	Full dataset	Yes, but unknown	5			
P	Full dataset	Scania Fleet Management				4
Q	Manufacturer, type, dimensions, GVW, axles, registration year, engine power, euroclass	Yes, but unknown	10	9	13	9
R	No data	Scania Fleet Management				
S	Full dataset	Yes, but unknown	1		2	
T	Full dataset	Unknown				1
U	Full dataset	Unknown		1		
V	Full dataset	Yes, but unknown				3
W	Brand, type, configuration, number plate	Unknown		15	136	6
X	Brand, type, axles, number plate	Fleetboard		72		4
Y	Number plate	Scania Fleet Management		6		13

From the dynamic data, besides the fuel consumption itself especially payload data is considered to be important, as it is expected to have a high impact on the fuel consumption rate (a fully loaded truck will have a much higher fuel consumption than the same truck in empty state). Payload data is often absent, or with limited details.

Table 26 shows the type of information that was available per vehicle group. In total for 505 Euro VI vehicles fuel consumption data on an individual truck basis was available from which 161 vehicles information over payload was available (13 out of 25 companies).

Table 26: Overview of number of vehicles per vehicle group with fuel consumption data and additional information (Euro VI).

Vehicle group	**Fuel consumption**	**Payload**	**Speed**	**Driver behaviour**
4	31	31	29	22
5	296	88	90	89
9	72	34	42	42
10	106	8	85	81
Total	**505**	**161**	**246**	**234**

Table 27 shows the time period and the information included in the dataset for each company. During the data collection, the following challenges were encountered:

- The systems for fuel consumption data (vehicle fleet) and payload data (logistics) are often separated within the company
- Different people were responsible for these systems, and the logistics department was too busy to help with the data request
- Sometimes it was unknown to the company what exactly was shipped (the vehicles were rented out)
- The burden for collection of payload data was considered to be too high by most transport companies

Table 27: Detailed overview of operational data for datasets collected from transport companies.

Company	Period	# Vehicles	Fuel consumpt.	Payload	Average speed	Driver behaviour	Main type of transport	Type of cargo
A	12 months - 2016	34	x		x	x	Long haul	Convenience food, pharmaceuticals, high-tech
B	average 2016	107	x		x	x	Regional delivery	Healthcare, media (books) and fashion
C	day-by-day - 2016	125	x				Long haul	Deep sea containers (general cargo, dry bulk, containers and flexitanks)
D	day-by-day - 2016	53	x	x	x	x	Municipal utility	Waste trucks
E	12 months - 2016	20	x				Long haul	Groupage (e.g. food, animal food, chemicals, electronics)
F	average 2016	2	x	x	x		Regional delivery	Specialised in distribution of clothes
G	14 months - 2016	39	x	x	x	x	Long haul	Both bulk and volume transport (construction, eventing, machines, retail distribution, pallets, garden products)
H	69 days 2017, average 2016	47	x	x	x	x	Long haul and regional delivery	Very different as they offer their service to any client
I	13 months - 2016	6	x		x	x	Long haul and regional delivery	Specialised in particular in automotive parcels - and pallet distribution
J	day-by-day - 2016	8	x		x	x	Long haul and regional delivery	Flowers, trees, refrigerated transport
K	30 days 2016	108	x		x	x	Long haul	Refrigerated transport
L	day-by-day - 2015-2016	118	x	x			Long haul and regional delivery	Any type of cargo, national distribution to international groupage
M	30 days 2017	61	x	x	x	x	Long haul	Any type
N	12 months - 2016	148	x				Long haul	General cargo
O	14 days 2017	5	x	x	x		Long haul and regional delivery	Distribute packed goods in Full Truck Loads
P	12 months - 2016	4	x	x	x		Long haul	Unknown
Q	average one month	41	x				Long haul and regional delivery	Refrigerated goods for supermarkets e.g. dairy products
R	one week average - 2017	14	x		x	x	Long haul	Vehicles
S	21 days - 2017	3	x	x	x	x	Long haul	Unknown regional delivery
T	five month average - 2017	1	x	x			Long haul	Unknown
U	14 days - 2017	1	x	x	x		Long haul	Unknown
V	30 days - 2017	3	x	x	x	x	Long haul	Food and drink logistics
W	year - 2015, six-month average - first half of 2016, 6 months - last half of 2016	160	x				Long haul	
X	trip-by-trip - March 2016 until March 2017	89	x	x		x	Long haul	
Y	tank-by-tank - 2016	20	x				Long haul	

Figure 14 shows the total distance coverage for each of the three levels of detail:

- Period data: average fuel consumption per vehicle during a certain period (usually per month)
- Tank data: fuel volume and odometer reading per re-fuelling
- Trip data: detailed reporting by OEM or third party fuel monitoring systems based on engine management system output.

From the trip data, outliers were removed outside two times the standard deviation. This was done on the basis of a fuel consumption prediction model, which is described in Annex B.

Note that the scale of the graph is logarithmic.

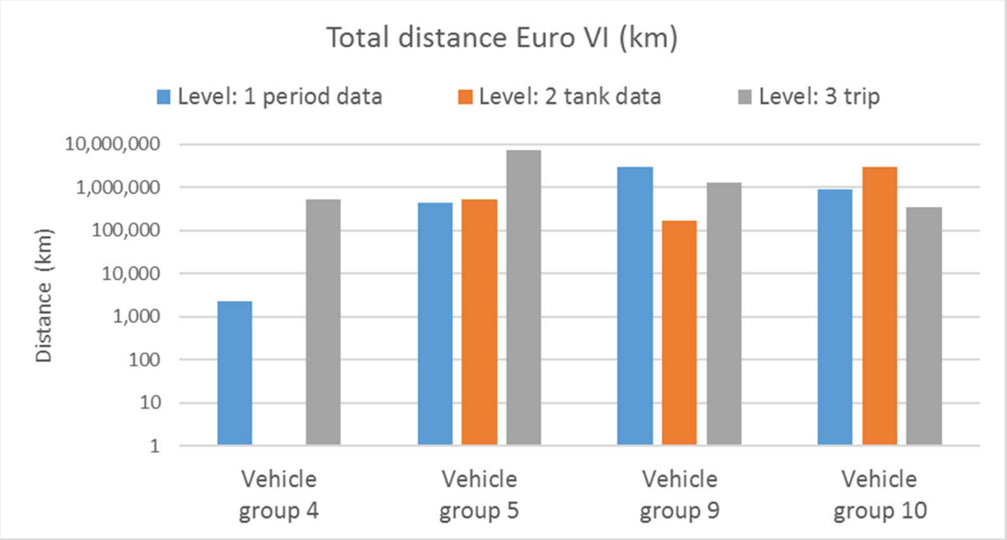

Figure 14: Total distance per type of data, Euro VI vehicles.

Analysis of vehicle data

For a comprehensive comparison with VECTO simulations, all data (period, tank and trip data) is split in two mission profiles: ‘regional delivery’ and ‘long haul’. This can be done based on several parameters such as average speed, trip distance or annual distance (per vehicle).
The unique parameter that was available or could be calculated for each vehicle in the data set, is the annual distance. Hence, the split between regional delivery and long haul was made on the basis of annual distance: in the case of an annual distance of below 80,000 km the vehicle is considered a regional delivery truck. (A typical daily mileage of 300 kilometre.) Above 80,000 km a vehicle is considered to be used for long haul. From the group of regional delivery trucks, municipal utility trucks have been removed on the basis of the type of truck (indicated in the type approval data). This is done because municipal utility is significantly different from regional delivery, leading to skewed results if left in the set.

Table 28, which shows the data coverage per mission profile type, leads to the following conclusions:

- Vehicle group 4: consists solely of municipal utility vehicles.
- Vehicle group 5: almost exclusively long haul.
- Vehicle group 9: this group contains some regional delivery, but is mostly municipal utility and long haul
- Vehicle group 10: almost exclusively long haul.

Table 28: Data split per mission profile.

Vehicle group	Total distance x 1000 km	Municipal utility (not further investigated)	Regional delivery	Long haul
4	544	100%	0%	0%
5	8,414	0%	1%	99%
9	4,374	30%	12%	59%
10	4,153	0%	2%	98%

The data coverage per mission profile is displayed in Figure 15.

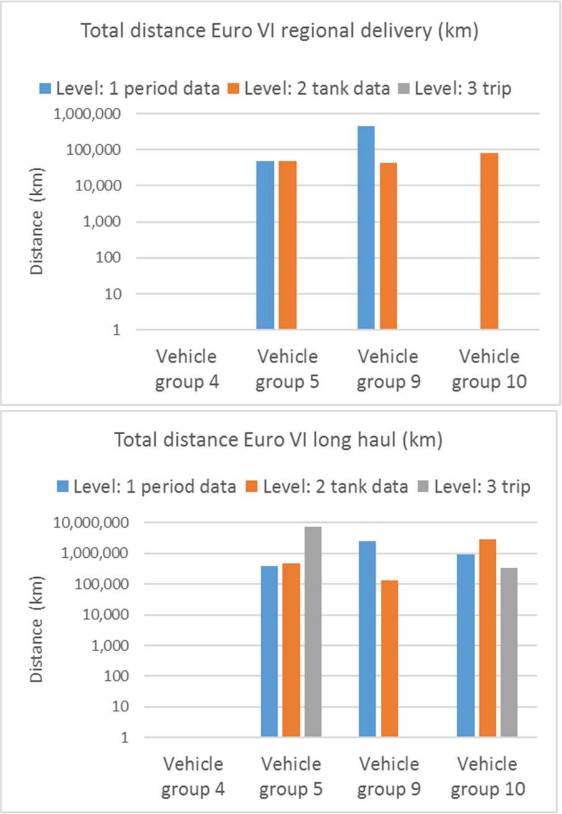

Figure 15: Data coverage per level of detail (period/tank/trip data), Euro VI vehicles, split in regional delivery (left) and long haul (right).

Fuel consumption results

For each truck the average fuel consumption has been calculated. In the following four graphs (Figure 16 till Figure 19) the trucks are grouped per vehicle category. Each graph shows the average fuel consumption against the annually mileage for each individual truck (regional delivery and long haul trucks in the same graph).

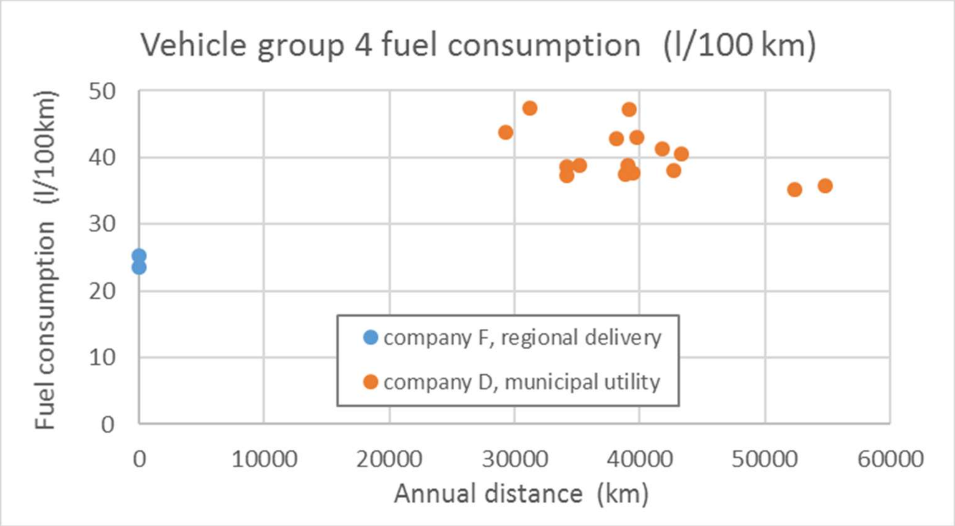

Figure 16: Average fuel consumption per vehicle in group 4.

Note that for company F no annual distance could be calculated, due to a lack of data.

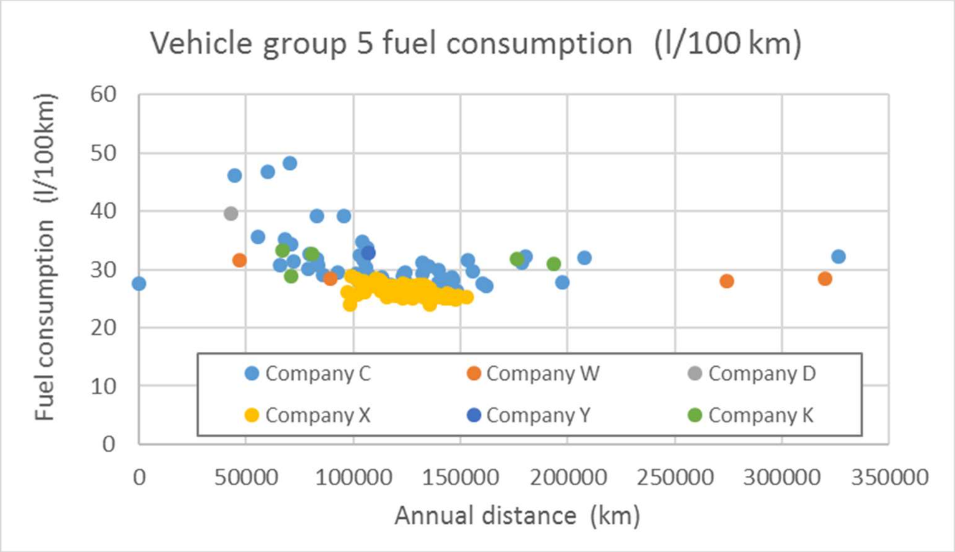

Figure 17: Average fuel consumption per vehicle in group 5.

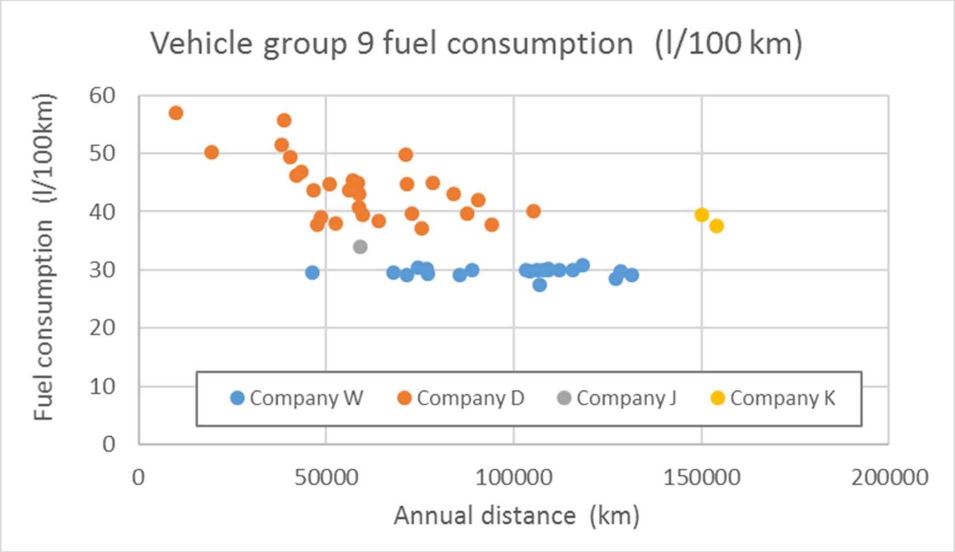

Figure 18: Average fuel consumption per vehicle in group 9.

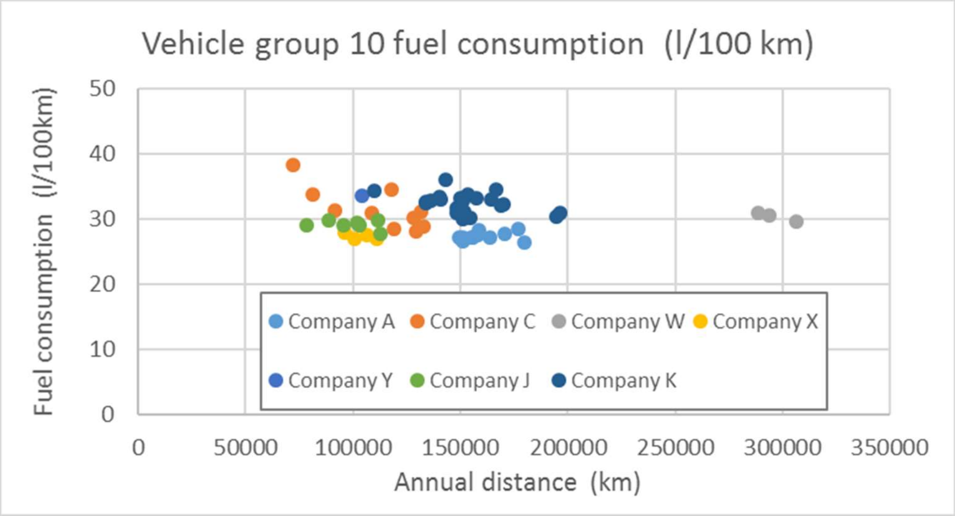

Figure 19: Average fuel consumption per vehicle in group 10.

It can be observed that trucks that have a lower annual mileage generally have a higher specific fuel consumption. Also, the spread increases towards the lower annual mileage end of the graphs. This can be partially due to the larger uncertainty (lower mileage is less data for the same monitoring period), but can also related to the more diverse use of these vehicles.

Average fuel consumption per group (individual truck data)
Figure 20 shows the average fuel consumption per vehicle group per mission profile. The fuel consumption levels were calculated in the following way: for each vehicle group – mission profile combination, the fuel consumption in litres of all trucks together was divided by the sum of their driven distance in km. This way, vehicles for which more data was available (longer period or higher annual mileage) have a higher weight in the average.

The fuel consumption in municipal utility is clearly higher than for regional distribution and long haul. Interesting is the similar fuel consumption of the use of regional trucks and long haul trucks for groups 9 and 10.

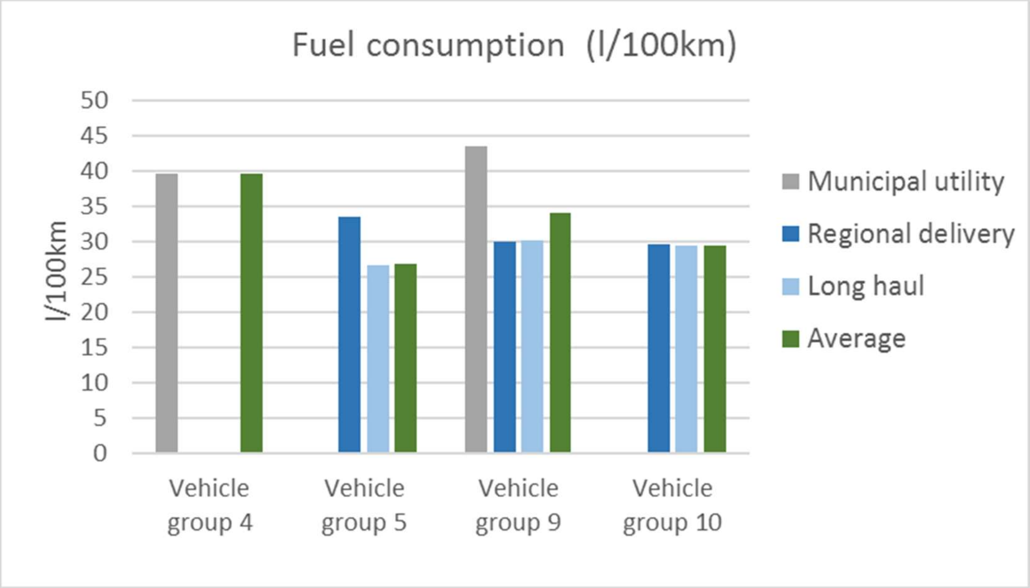

Figure 20: Average fuel consumption based on Euro VI individual truck data, split in municipal utility, regional delivery and long haul mission profiles.

In the light of VECTO relevance, municipal utility trucks were not further investigated in this task.

Comparison between trip, period and tank data
Some analyses as shown for Task 1.2 (Section A.3) can only be performed on trip data. In order to assess if trip data are a good representation of the total data set, Figure 21 shows the average fuel consumption per vehicle group for the three levels of detail, and the average fuel consumption for all levels together (green bars). The averages are distance weighted (total fuel consumption divided by total distance of all trucks in a category).
The different mission profiles and trucks with and without trailer are not distinguished, and are all included in the average values.

It can be observed that trip data averages are within ten percent from the averages of all data, except for vehicle group 9, for which the trip data fuel consumption is 25% higher. This might be related to the frequent use of trailers.

The average trip weight of group 9 trucks for which trip data is available, exceeds the maximum permittable weight for group 9 rigid trucks, suggesting that trailers are used in many cases.
For period data and tank data this seems not the case.

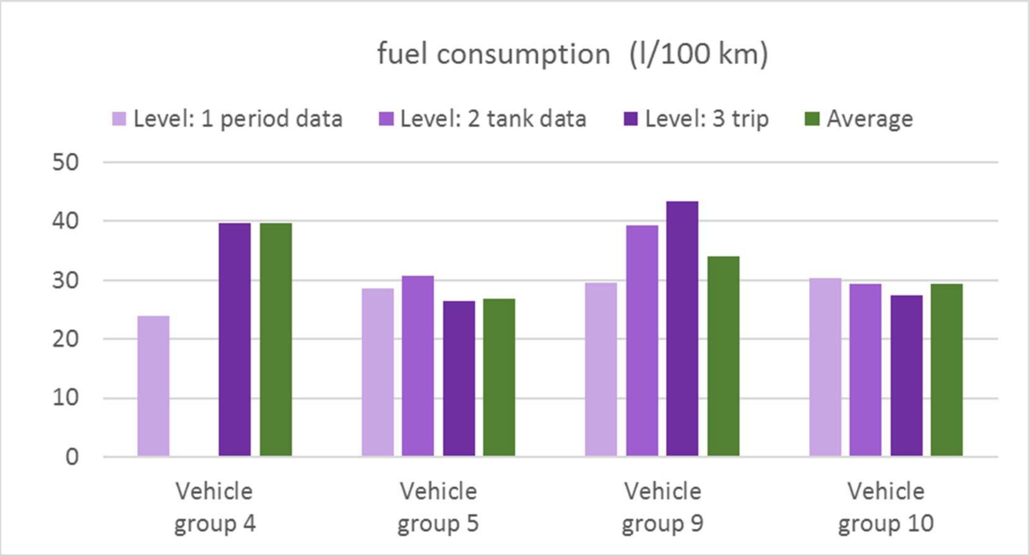

Figure 21: Comparison period, tank and trip data for all vehicles.

A.2.2 Fleet data

The Dutch Association for Transport and Logistics TLN has collected fuel consumption data among its members. From these data the average fuel consumption was calculated for a total of almost 2,300 trucks that fall into the four vehicle categories investigated (4, 5, 9 and 10). This included group 4 and 9 with trailer as well.

In the dataset, the average fuel consumption is given per group of vehicles per company, distributed over the vehicle groups 4, 5, 9 and 10, and 4 with trailer and 9 with trailer. On the basis of the annual mileage, two different use types have been distinguished. In case of an annual distance below 80,000 km the vehicle is considered a regional delivery truck, above this value it is considered to be used for long haul. Only 179 vehicles fell in the category of regional delivery, distributed over the four groups, which is not enough for statistical analysis. Therefore, fleet data of regional delivery trucks have not been further analysed. Also, a part of the set of trucks had a special use profile or an unknown or invalid mileage. Finally, the group of long haul trucks in group 9 without trailer was considered too small and was left out of the analysis. The remaining data set of 1697 long haul trucks was used for further analysis.

Table 29 shows an overview of the number of vehicles per vehicle group, the average distance and the average fuel consumption.

Table 29: Overview of fleet data; all vehicles.

Vehicle group	**Number of vehicles (long haul)**	**Average fuel consumption Litre/100km**	**Average annual distance (km)**
4	83	20.7	87,000
4 + T	72	28.6	107,000
5	1136	28.4	120,000
9 + T	85	29.7	113,000
10	321	29.6	113,000
Total	1697		

A.3 1.2: Determination of baseline vehicles and fuel consumption and CO_2 emission data

The individual truck data (324 trucks) and the fleet data (1697) trucks are compared in Table 30. As described in Task 1.1, the data is split in several mission profiles using the total distance per year: trucks that cover over 80,000 km per year are considered to be in long haul use. Trucks that drive less than 80,000 km are considered to be in either regional delivery or municipal utility use. The municipal trucks are distinguished on the basis of type approval information on the type of vehicle. Municipal trucks, which generally have a big variation in driving patterns, are not included in this baseline.

The individual truck data are weighted averages of period data, tank data and trip data (see Table 30). The average fuel consumption per vehicle category is distance weighted. This means that vehicles for which data is available over a large driven distance, have a higher weight in the average. The fleet data is based on an annual fuel consumption, so vehicles with a higher annual mileage have a larger share in the average fuel consumption numbers than vehicles with a lower annual mileage.

Table 30: Average fuel consumption for different types of HD transport (based on both individual truck data and fleet data sets).

		Individual truck data		Fleet data (TLN)	
Vehicle group	Mission profile	Average fuel consumption (l/100 km)	Data coverage (mkm)	Average fuel consumption (l/100 km)	Data coverage (mkm)
Group 4	Long haul			20.7	7.2
Group 4+ trailer	Long haul			28.6	7.7
Group 5+ trailer	Long haul	26.7	8.3	28.4	136.3
Group 5+ trailer	Regional delivery	33.5	0.1		
Group 9+ trailer	Long haul	30.2	2.6	29.7	9.6
Group 9	Regional delivery	30.0	0.5		
Group 10+ trailer	Long haul	29.4	4.1	29.6	35.4
Group 10+ trailer	Regional delivery	29.6	0.1		

Sufficient data coverage is necessary to produce reliable fuel consumption figures.
From Table 30, only the values with a data coverage over 2 million km were selected (green fields in the table). These numbers were averaged per vehicle group where two sources are available.

The resulting average fuel consumption values are presented in Table 31. The standard deviation was calculated from the fuel consumptions per vehicle, whereby each vehicle's deviation was weighted with its data coverage in km (similar to how the average fuel consumptions were calculated).

Table 31 also shows the estimated average total mass per vehicle group. These data have been derived from information published in a 2015 TNO report[12] on so-called Weigh-in-Motion data: data from measurements of axle weights on Dutch motorways. The standard deviations on the average total mass were estimated from graphs in the Weigh-in-Motion report of 2013[13].

Table 31: Expected range for average fuel consumption for different types of HD transport (based on both individual truck data and fleet data sets).

Vehicle group	**Mission profile**	**Average fuel consumption (l/100 km)**	**Standard deviation +/-)**	**Average total mass (ton)**	**Standard deviation +/-)**
Group 4	Long haul	20.7	2.8	cannot be determined	
Group 4+ trailer	Long haul	28.6	1.8	22.7	6.4
Group 5+ trailer	Long haul	27.5	2.4	26.3	2.3
Group 9+ trailer	Long haul	30.0	2.7	31.7	12.5
Group 10+ trailer	Long haul	29.5	2.1	31.5	6.5

The large standard deviations on the average mass of group 9 and 10 with trailer are a result of transportation of goods with different density. Volume limited transport and mass limited transport cannot be distinguished in the dataset. With the lack of detailed vehicle technology data and this large variation caused by vehicle use, it is not possible to determine the best performer, or technological forerunners, from this data.

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[12] Ligterink, N.E., Composition and payload distribution of the on-road heavy-duty fleet in the Netherlands, TNO, december 2015, report number TNO 2016 R10040.

[13] Kuijper, E. and N.E. Ligterink, Voertuigcategorieën en gewichten van voertuigcombinaties op de Nederlandse snelweg op basis van assen-combinaties en as-lasten, TNO, december 2013, report number TNO 2013 R12138.

A.4 1.3: VECTO based calculation of the baseline fuel consumption and CO_2 emissions

Since future CO_2 limits will be based on VECTO results, the assessment of the actual fleet CO_2 level as well as the assessment of CO_2 reduction potentials have to be based on VECTO calculation results or on methods delivering directly comparable CO_2 emission figures. Main tasks for the VECTO based assessment in this study were:

a) Define VECTO input data reflecting the actual vehicle fleet properties

b) Define input data reflecting possible future technology levels in a way, which allows the assessment of the CO_2 reduction due to single technologies as well as of technology combinations.

The work in the current contract was focused on the HDV groups 4, 5, 9 and 10. Boundary conditions for the assessment of fuel consumption and CO_2 emission figures as well as technology reduction potentials were the generic data as defined in the final VECTO software version from the LOT4/SR7 contract (VECTO 3.2.0.940 from July 2017). These boundary conditions are defined by the mission profiles (driving cycles), driver model settings, vehicle payloads and generic data on power consumption from auxiliary units. VECTO results for EMS vehicle configurations[14] were decided not to be analysed in this study. The model VECTO is described in more detail in section 3.1 related to Task 2.1.

To cover the real distribution of CO_2 figures in the fleet, for each of the four considered HDV groups four sets of VECTO input data have been elaborated representing four different technology levels:

- Typical 2016 vehicle
- Baseline 2016 vehicle
- Best (in class) 2016 vehicle
- Worst (in class) 2016 vehicle

Typical vehicle:

The “typical vehicle” represents the most common vehicle technology in the fleet. This vehicle configuration is the main point of reference for comparison of VECTO results with fuel consumption figures as elaborated in Task 1.2.

Baseline vehicle:

The baseline vehicle represents a truck without any of the technologies which have to be assessed later (see Task 2) but with a basic design for long haul or regional delivery operation since this mission profiles are most relevant in the groups 4, 5, 9 and 10. Such a vehicle has a worse fuel efficiency than the “average case” truck in the long haulage fleet since such a baseline vehicle has e.g.no roof spoiler, high tyre rolling resistance levels etc.

The VECTO models for the baseline vehicles play also an important role in Task 2. They are used to implement separately each fuel saving technology (except for hybrids and ADAS; for these technologies the VECTO models for “typical” are the reference) to calculate the associated CO_2 reduction potential. This approach is described in detail in the documentation of Task 2.

Best and worst (in class) vehicle:

For depicting the full range of uncertainty of VECTO results when comparing with the fuel consumption figures from Task 1.2 also VECTO models for a “best” and a “worst” case vehicle

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[14] The segmentation matrix as defined in Annex I, Table I also includes vehicle configurations with a gross combination mass of more than 40.000 kg according to the “European Modular System” (EMS) European concept as permitted in Directive 96/53 EC, Article 4, § 4 (b). The proposed vehicle configurations have a gross combination mass of 60.000 kg and a maximum length of 25.25 m and can be configured from vehicles of the groups 5, 9, 10, 11 and 12.

have been elaborated. These sets of vehicle input data do not only differ from the typical vehicle in the level of implementation of fuel saving technologies (e.g. best- or worst case tyres) but also cover variations in fuel consumption relevant boundary conditions, which were not possible to be corrected for in the elaboration of Task 1.2 results (e.g. influence of tyre wear conditions).

Figure 22 shows a schematic picture of the distribution of CO_2 figures in the fleet and indicates the location of the four different VECTO models.

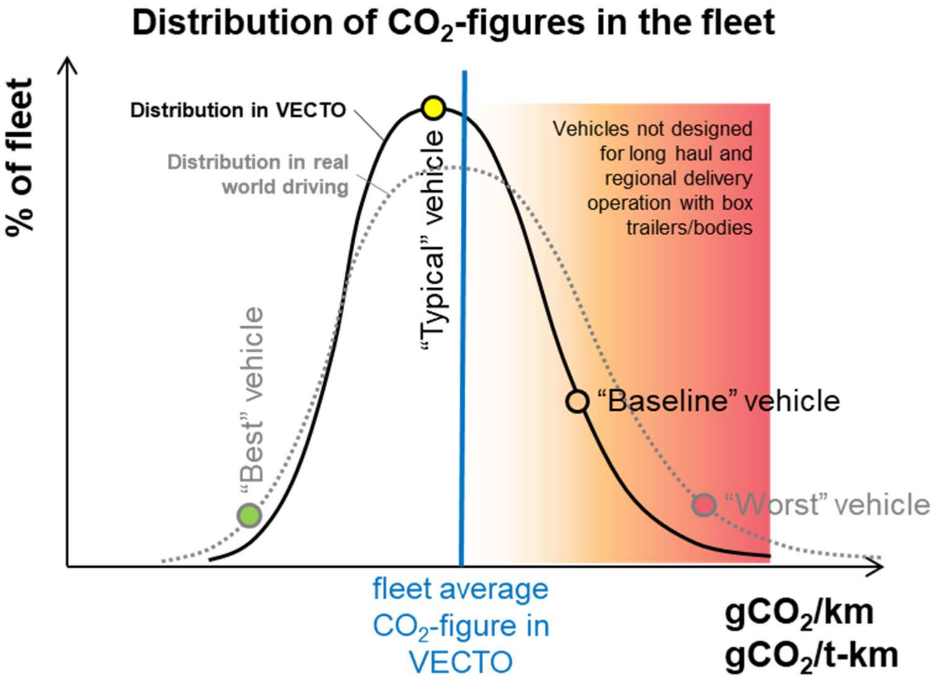

Figure 22: Schematic picture of the distribution of CO_2 figures in the fleet.

Elaboration of VECTO input data for 2016 "typical" vehicles

The VECTO input datasets for the 2016 typical vehicles of each considered HDV group have been consolidated based on the followings sets of information:

- Data on average vehicle configurations as collected in Task 1.1
- Data on engine fuel efficiencies in the type approval cycles WHTC and WHSC from the European Type Approval Exchange Server (ETAES)
- Sets of VECTO input data for all HDV groups elaborated for a project for the German Federal Ministry of Transport and Digital Infrastructure [Rexeis, 2016]
- Data on distributions of rolling resistance coefficients for 22.5'' tyres per tyre type (steer, driven, trailer) as provided by ETRMA (baseline year 2014, corrected to 2016 sales levels assuming an improvement of 1% per year)
- Data collected from magazines (e.g. Lastauto&Omnibus) or other sources of literature

The elaboration of VECTO input data took place in the period from July to September 2017, so it was not possible to consider any information as delivered by ACEA for the 2016 fleet to DG JRC.

Table 32 shows the main relevant specifications of the resulting VECTO input datasets. Single vehicle parameters (e.g. final gear ratios for group 9 and 10) deviate from the data as presented in Task 1.1 to get a well aligned vehicle setup for the complete vehicle. In the elaboration of vehicle models it was especially taken under consideration, that vehicles not designed for predominant operation in long haul or regional delivery missions are planned to be exempted from the future CO_2 limit legislation. This results in quite homogenous vehicle specifications (e.g. rated power, axle ratio) for the four HDV groups under consideration.

ADAS systems have not been considered in the 2016 vehicle models as these fuel saving technologies are not yet available in the VECTO software[15] and the total influence on the 2016 fuel consumption levels is considered to be small.

Table 32: Main relevant vehicle specifications of the VECTO 2016 "typical" vehicles.

	Group 4	**Group 5**	**Group 9**	**Group 10**
GVW (tonnes)	18	18	26	25
Curb Mass (kg)	8200	8229	9300	9010
CdxA (m²)	5.40	5.57	5.50	5.67
Rolling resistance coefficient (RRC, steer / driven axle) (kg/t)	5.21/6.12	5.21/6.12	5.21/6.12	5.21/6.12
Tyre dimension (driven vehicle)	315/70 R22.5	315/70 R22.5	315/70 R22.5	315/70 R22.5
Engine rated power (kW)	325	325	325	325
Engine displacement (lit.)	12.7	12.7	12.7	12.7
Transmission type and number of gears	AMT 12 speed	AMT 12 speed	AMT 12 speed	AMT 12 speed
Transmission final gear ratio	1.0	1.0	1.0	1.0
Axle ratio	2.64	2.64	2.64	2.64
Retarder type	secondary	secondary	secondary	secondary
Engine cooling fan technology	Belt driven or driven via transm. - Electronically controlled visco clutch	Belt driven or driven via transm. - Electronically controlled visco clutch	Belt driven or driven via transm. - Electronically controlled visco clutch	Belt driven or driven via transm. - Electronically controlled visco clutch
Steering pump technology	Fixed displacement with elec. control	Fixed displacement with elec. control	Fixed displacement with elec. control	Fixed displacement with elec. control
HVAC technology	Default	Default	Default	Default
Electric System technology	Standard technology	Standard technology	Standard technology	Standard technology
Pneumatic System technology	Medium Supply 1-stage + ESS + AMS	Medium Supply 1-stage + ESS + AMS	Medium Supply 1-stage + ESS + AMS	Medium Supply 1-stage + ESS + AMS
Advanced Driver Assistant Systems (ADAS)	none	none	none	none
Max speed setting Speed limiter	legal maximum (89+1)	legal maximum (89+1)	legal maximum (89+1)	legal maximum (89+1)

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[15] The reduction potential of ADAS technologies has been modelled in Task 2 based on post-processing of VECTO modal results and is considered in the scenarios for the future HDV fleet.

Elaboration of VECTO input data for 2016 vehicles “baseline”, “best” and “worst”
On the basis of the VECTO input data for the 2016 typical vehicles, the input data for “baseline”, “best” and “worst” vehicles have been elaborated. Modified parameters are tyre rolling resistance, air drag, engine fuel map and auxiliary technology. Other specifications (like drivetrain layout) have been kept constant due to the boundary condition that only vehicles for long haul and regional delivery operation shall be considered. Table 33 gives a comparison of the relevant vehicle specifications and the background for the modifications compared to the typical vehicle.

Table 33: Comparison of vehicle specifications of the different 2016 vehicle configurations.

	Best vehicle	**Typical vehicle**	**Baseline vehicle**	**Worst vehicle**
Rolling resistance coefficient RRC (Steer/Drive/Trailer) [N/kN]	3.6 / 3.6 / 3.6 *this correlates with tyre labels B/B/B and minus 20% tyre and road conditions influence*	5.21 / 6.12 / 5.5 *this correlates with 50% value from RRC distribution as provided by ETRMA*	6.22 / 7.21 / 5.5 *this correlates with 90% value from RRC distribution as provided by ETRMA*	6.6 / 7.8 / 7.8 *this correlates to tyre labels C / D / D +20% tyre and road conditions influence*
Air drag CdxA [m^2] (group 4 / 5 / 9 / 10)	5 / 5.2 / 5 / 5.2 *expert guess*	5.4 / 5.565 / 5.5 / 5.67	6.46 / 6.625 / 6.56 / 6.725 *Corresponding to a typical vehicle w/o roof spoiler and side flaps*	7 / 7.25 / 7.10 / 7.35 *expert guess*
Engine fuel consumption map	-5% compared to "typical" *expert guess*	engine fuel map from [Rexeis, 2016]	+2% compared to "typical" *Corresponding to a typical w/o 50% of the engine technology “package 1” (see Task 2)*	+5% compared to "typical" *expert guess*
Engine cooling fan technology	Crankshaft mounted - Electronically controlled viscous clutch	Belt driven or driven via transm. - Electronically controlled viscous clutch	Belt driven or driven via transm. - Bimetallic controlled viscous clutch	Belt driven or driven via transmission - Bimetallic controlled viscous clutch
Steering pump technology	Variable displacement elec. Controlled	Fixed displacement with elec. control	Fixed displacement	Fixed displacement
HVAC technology	Default	Default	Default	Default
Electric system technology	Standard technology	Standard technology	Standard technology	Standard technology
Pneumatic system technology	Medium supply 2-stage + ESS + AMS	Medium Supply 1-stage + ESS + AMS	Medium Supply 2-stage	Medium supply 2-stage

Uncertainties
As the elaboration of VECTO models for the 2016 reference vehicles had to be performed without any monitoring data for complete vehicles, the resulting vehicle specifications and resulting CO_2 figures are affected with significant uncertainties. These affect the properties of the “typical” vehicles of the groups 4, 9, and 10 (the properties of the typical vehicle for group 5 are judged to be quite reliable) as well as the broadness of the distribution of CO_2 figures (best, baseline, worst) for all four considered vehicle groups.

The main sources of uncertainties can be allocated to the following factors:

1) Air drag data
   Only very few measurement data (which are fully conform with the latest provisions of 2017/2400) on group 4 and 5 vehicles are available. Additional uncertainties arise from the strategy, how the OEMs handle the air drag family concept (how many specific vehicles are measured, how many vehicles get a CdxA from a worse parent vehicle).

2) Vehicle configurations of trucks not primarily designed for long haul operation
   Trucks are designed for various purposes. It is not clear how sharp the cut between “special purpose vehicles” (which will be presumably exempted from the CO_2 limit regulation and shall not be covered by the analysis in this study) and “classical long haul vehicles” is. It might be the case that especially in groups 4, 9, and 10 a certain percentage of vehicles falls in between the above mentioned categories.

3) Engine fuel efficiency data
   All VECTO models were configured with a “typical” engine with 325 kW rated power and 12.7 litres capacity. In reality there is distribution of engine sizes (capacities) and ratings, which both affect the driving behaviour (vehicles with higher engine ratings have higher average speeds and consume more energy for propulsion per kilometer) and engine efficiencies (larger engines have typically higher efficiencies). Making a further differentiation between engine sizes would have increased the complexity of the VECTO calculations excessively. Furthermore, the ETAES system (from which the engine fuel efficiency data was extracted) predominately includes data on parent engines (i.e. highest rating for a certain engine hardware configuration): So deriving reliable data especially on small engines from different OEMs would not have been possible.

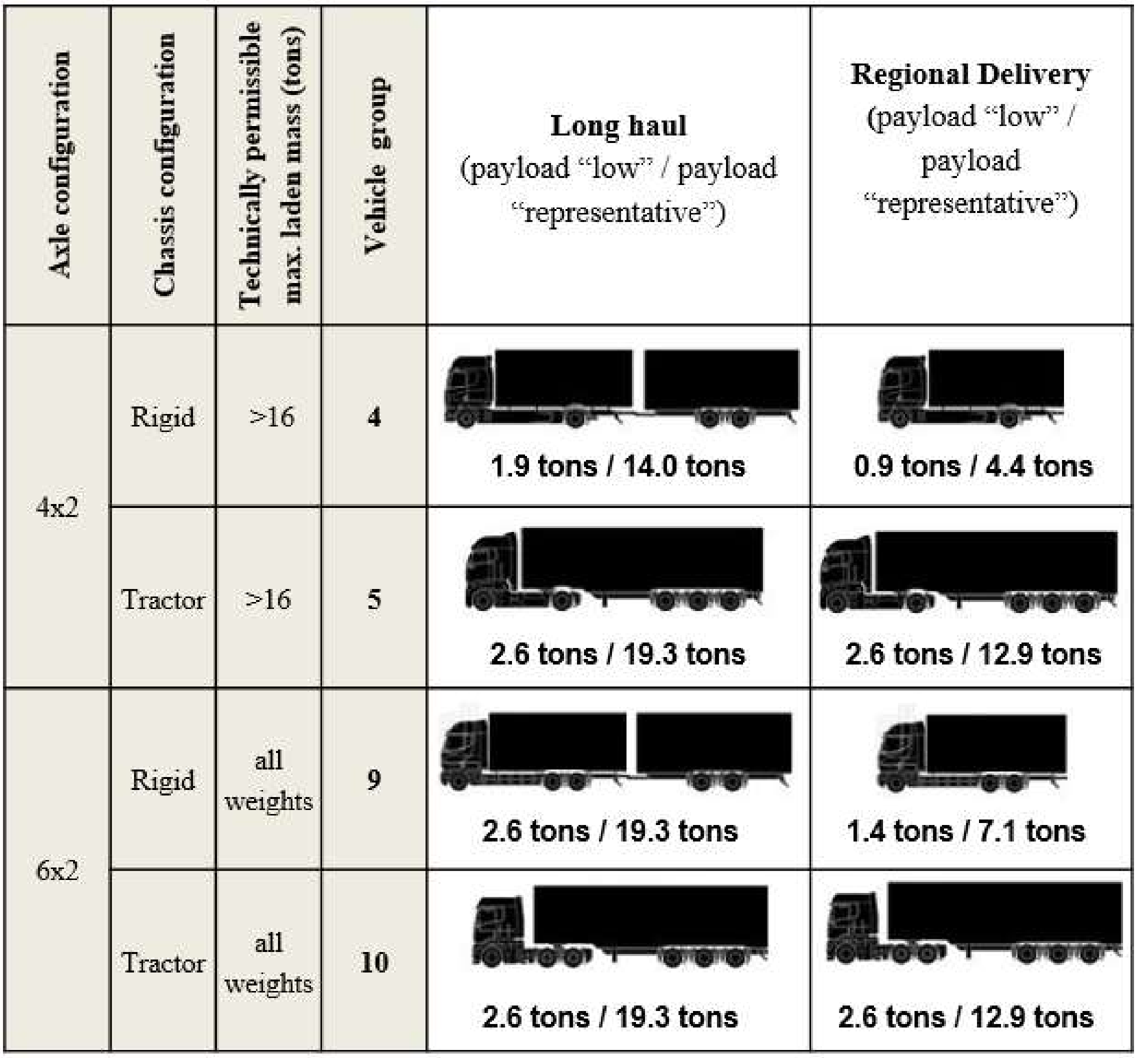
Uncertainties regarding VECTO inputs for rolling resistance are estimated to be quite low as data from ETRMA was available. Also assumptions made on drivetrain losses (transmission, retarder, axles) and auxiliaries are judged to have secondary importance on overall CO_2 levels as well as reduction potential of different vehicle technologies.

Results

In total 64 simulation runs have been performed with VECTO for the assessment of the “baseline” fuel consumption and CO_2 emissions of the 2016 vehicles. These results consist of

- 4 vehicle groups (4, 5, 9, 10)
- 4 technology levels (best, typical, baseline, worst)
- 2 mission profiles (long haul, regional delivery)
- 2 payloads (“low” and “representative”)

Figure 23 gives example pictures for all simulated vehicle configurations and specifies the payloads as currently defined in VECTO.



Axle configuration	Chassis configuration	Technically permissible max. laden mass (tons)	Vehicle group	**Long haul** (payload "low" / payload "representative")	**Regional Delivery** (payload "low" / payload "representative")
4x2	Rigid	>16	**4**	**1.9 tons / 14.0 tons**	**0.9 tons / 4.4 tons**
	Tractor	>16	**5**	**2.6 tons / 19.3 tons**	**2.6 tons / 12.9 tons**
6x2	Rigid	all weights	**9**	**2.6 tons / 19.3 tons**	**1.4 tons / 7.1 tons**
	Tractor	all weights	**10**	**2.6 tons / 19.3 tons**	**2.6 tons / 12.9 tons**

Figure 23: HDV configurations, mission profiles and payloads.

Figure 24 shows the results for CO_2 emissions in the unit grams per kilometre for all 64 calculated combinations. In the long haul cycle the lowest figure is calculated with 554 g CO_2/km for the group 5 "best" vehicle (low payload), the highest figure was simulated with 1220 g CO_2/km for the "worst" group 9 vehicle (high payload). In the regional delivery cycle the lowest figure is calculated with 478 g CO_2/km for the group 4 "best" vehicle (low payload), the highest figure was simulated with 1103 g CO_2/km for the group 10 "worst vehicle" (high payload). Certainly results in g/km cannot directly be compared between different groups, loadings and payloads.

The calculated CO_2 emissions for the "best" vehicles are some 15% lower than for the "typical vehicles". The CO_2 performance of the "worst" vehicles are some 25% higher in the regional cycle and some 30% higher in the long haul cycle compared to "typical". A part of these differences between "typical" and "best" or "worst" respectively is allocated to influences which will not be reflected in the certified VECTO results as real world tyre condition influence was considered in the calculations for the "best" and "worst" for purpose of comparison with fuel data from Task 1.2.

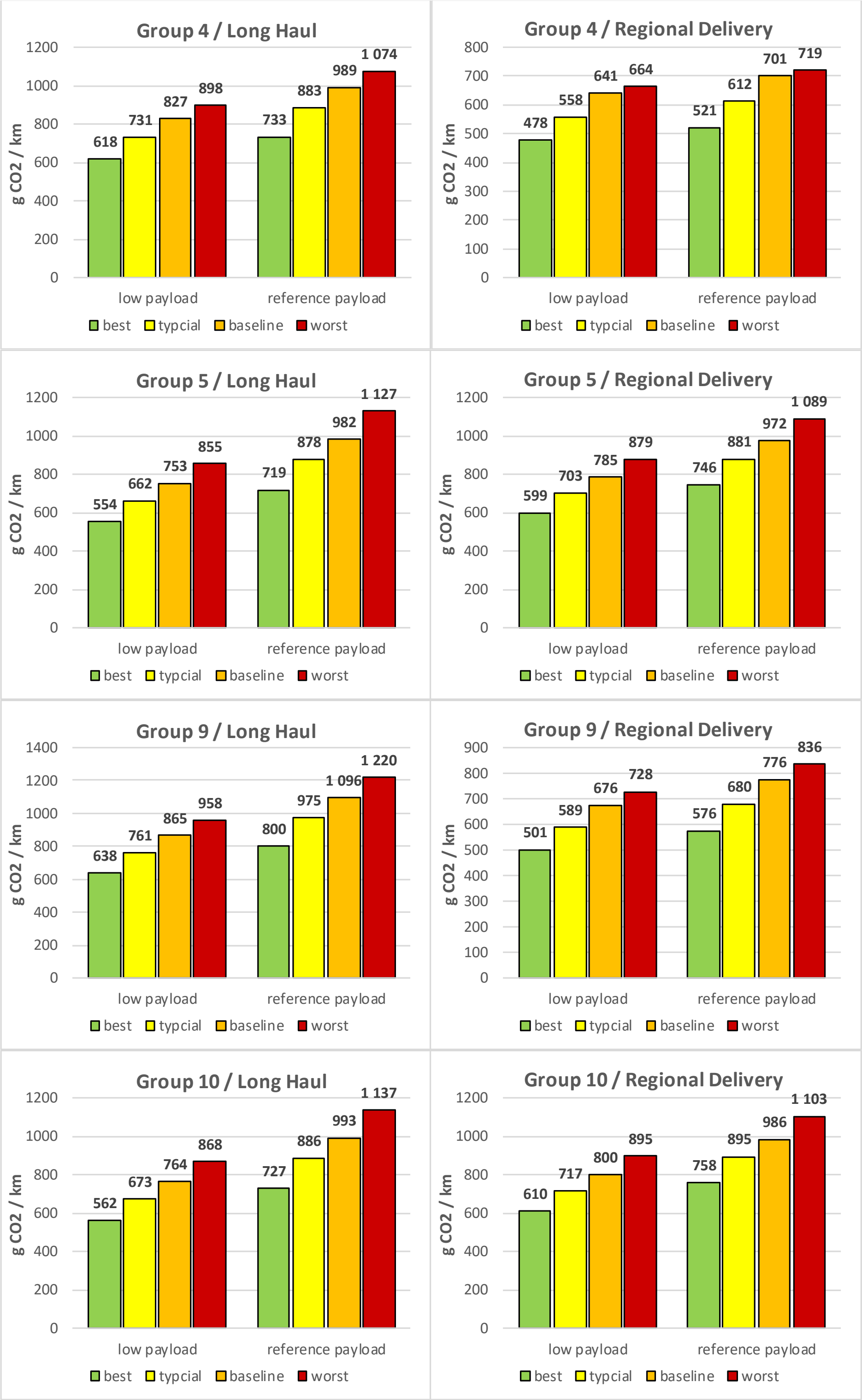


Figure 24: Results CO_2 emissions in gram per kilometre for the VECTO 2016 vehicles.

Figure 25 gives the results for payload specific CO_2 values. As a matter of principle g/t-km figures decrease with increasing payload. The lowest CO_2 figures are calculated for the group 5 vehicles in long haul cycle and reference payload (19.3t) with a range of 37 to 58 g CO_2/t-km from “best” to “worst”.

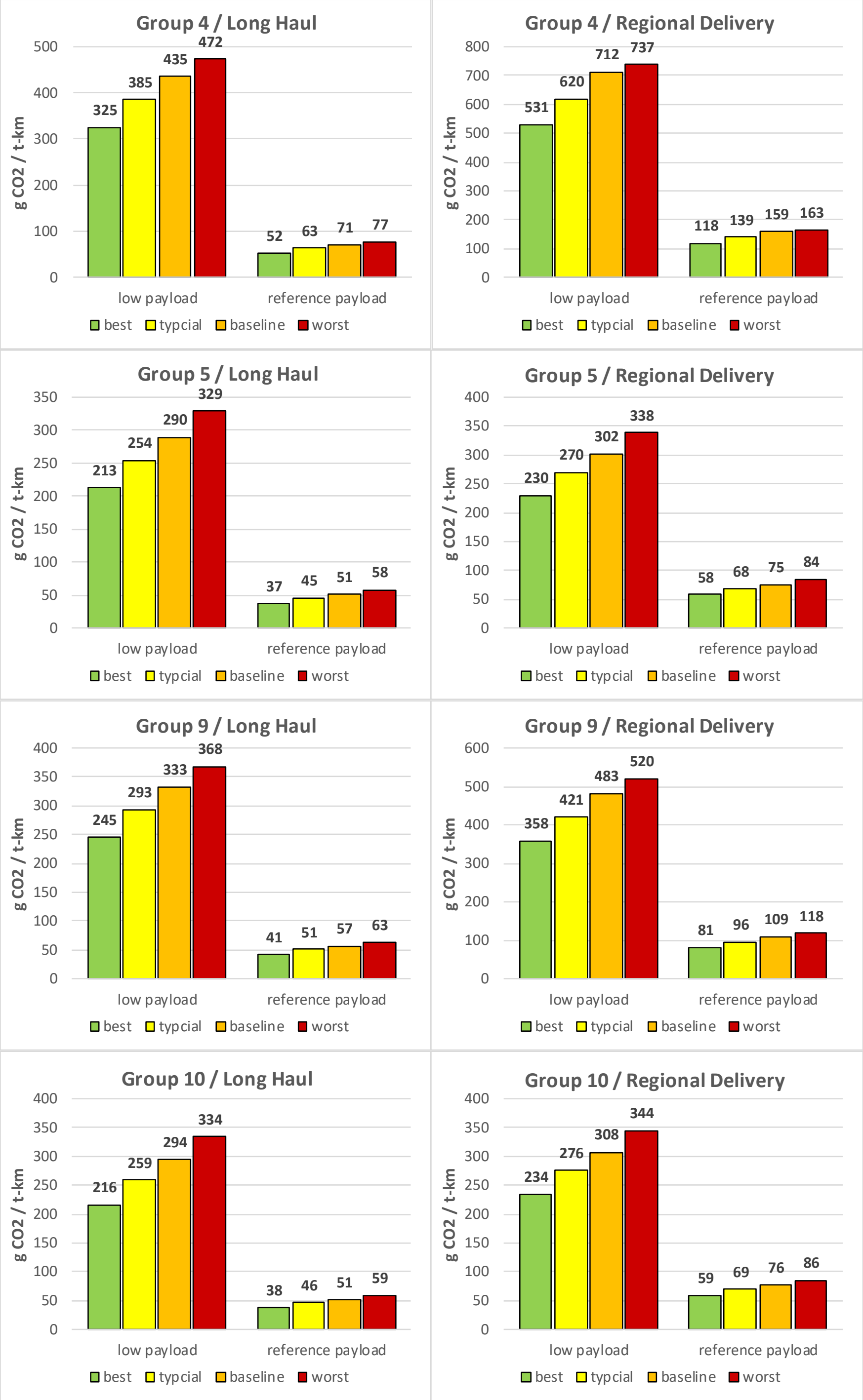


Figure 25: Results CO_2 emissions in gram per ton-kilometre for the VECTO 2016 vehicles.

Results for CO_2 figures for the 2016 “average” vehicles are presented in Section 3.2

References

[Rexeis, 2016]	Rexeis M., Kies A.: Ertüchtigung von VECTO zur Berechnung des Energieverbrauches von Schweren Nutzfahrzeugen vor Erstzulassung 2018. Erstellt im Auftrag des Bundesministerium für Verkehr und digitale Infrastruktur, Bericht FVT-097/16 Rex Em 15/25-1/6790 vom 30.11.2016

A.5 1.4: Comparison fuel consumption VECTO and on-road

Approach
To validate the VECTO elaborated in Task 1.3 the VECTO fuel consumption as presented in Section A.4 is compared to the on-road fuel consumption data presented in Section A.3.

However, a simple comparison of average values cannot be made without adjusting a number of conditions. Once the vehicle group and its mission profile is known, the average fuel consumption is further dependent on the vehicle (technology), the mass of the vehicle plus cargo, and the ambient conditions (ambient temperature and pressure, ambient wind conditions). Also the driving cycle related to a “mission profile” adds uncertainty to the comparison as e.g. long haul operation may include significant road gradients or regional delivery can be operated in more or less dense traffic conditions.

The average temperature for the on-road data should be close to the average temperature at the latitude of the Netherlands. For the Netherlands the average annual temperature is 10.1°C. Regression analysis (see Annex B) of seasonal variation in fuel consumption suggests a dependence of 0.12 l/100 km per degree Celcius of difference in average temperature. VECTO calculations take 12°C as a set average, so the deviation would be limited to 0.2 liter per 100 km, which is not significant.

For investigating the influence of the driving cycle, the VECTO long haul cycle was simulated in two versions:

- “Total cycle” including a section with an altitude difference of approx. 200m in its first part
- “Flat part” where the first part has been eliminated. This “flat part” is assumed to be more representative for fuel consumption in long haul operation in the Netherlands region

The average mass conditions and other variations such as vehicle technology are covered in a sensitivity analysis:

- Multiple VECTO runs have been done with varying total vehicle mass and for best, typical, baseline and worst case conditions according to the descriptions in Section A.4.
- Standard deviations have been established for on-road data in terms of vehicle weight and fuel consumption

Due to a lack of on-road fuel consumption data for regional delivery, comparisons between VECTO and on-road could be made only for long haul applications.

Results

Figure 26 to Figure 29 give the comparison of VECTO results and the on-road data. Results for fuel consumption in litre per kilometre are plotted over total vehicle mass. The standard deviation in on-road fuel consumption and in on-road average total vehicle weight is shown as a blue box.

VECTO vehicle models have been elaborated in a way that in the ideal case the fleet data should meet the VECTO results for the “typical” vehicle (line in light yellow). This is nearly perfectly the case for groups 4, 5 and 10 when considering the “flat part” of the long haul cycle as representative driving cycle. Comparison of VECTO typical and fleet data for group 9 is slightly off from the typical, but considering the uncertainty in fleet data indicated by the blue box, there is still a big overlap between real world numbers and VECTO results.

As conclusion it can be stated that on-road fuel consumption as collected in this study and VECTO results match very well.

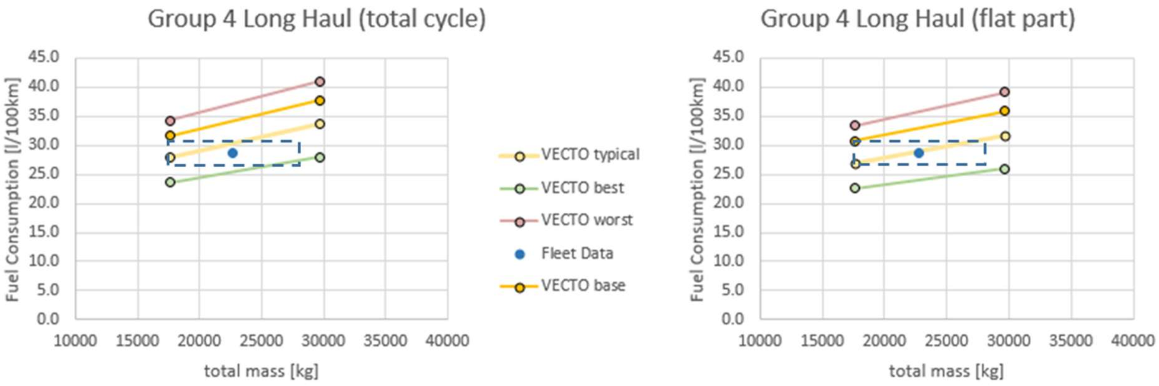


Figure 26: Comparison of VECTO and on-road fuel consumption for long haul use of group 4 trucks (rigid truck, 2 axles).

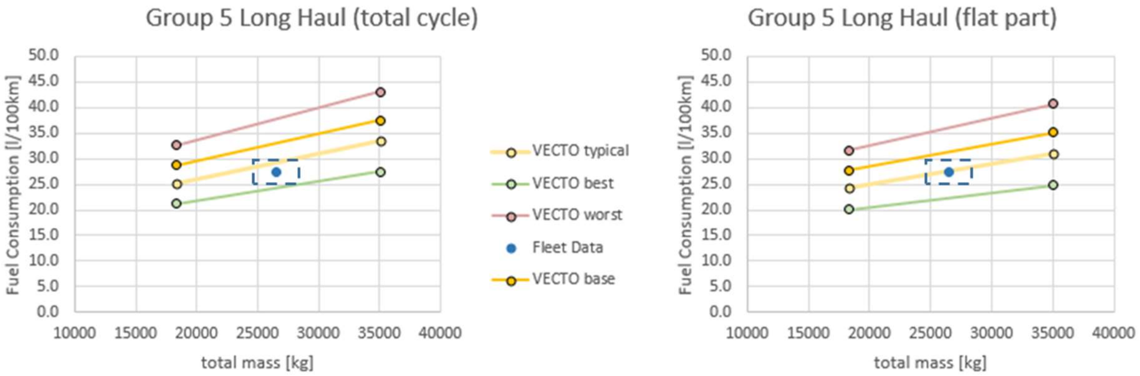


Figure 27: Comparison of VECTO and on-road fuel consumption for long haul use of group 5 trucks (tractor, 2 axles, semitrailer).

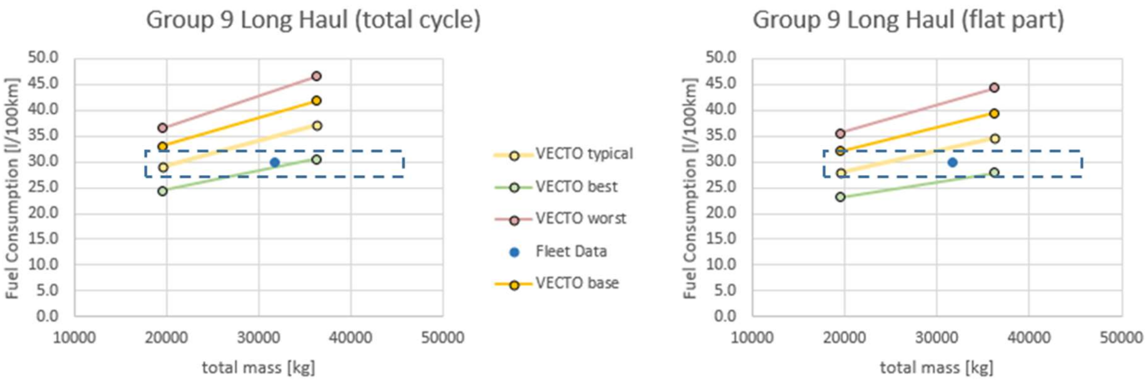


Figure 28: Comparison of VECTO and on-road fuel consumption for long haul use of group 9 trucks (rigid truck, 3 axles).

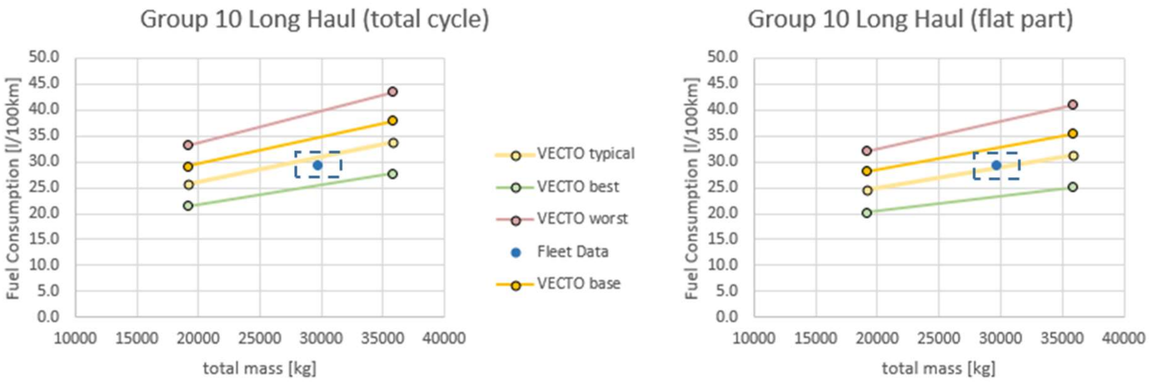


Figure 29: Comparison of VECTO and on-road fuel consumption for long haul use of group 10 trucks (tractor, 3 axles, semitrailer).

A.6 1.6: Consultation and dialogue with stakeholders

For the execution of task 1, there was frequent contact with the main stakeholders namely transportation companies, transport organisations, truck dealers and importers and the manufacturers organisation ACEA through the Commission Services.

Twenty five transport companies made detailed fuel consumption data available from their truck fleet (about 1350 trucks in total). This consisted of different types of transport companies with mostly box type trucks with a wide range of normal transportation goods such as food, healthcare, cloth, but also some companies with cooled or refrigerated products and container transport. For details refer to section Annex A.2. Additionally, the Dutch Association for Transport and Logistics (TLN) provided fleet fuel consumption data for >2500 vehicles.

Dealers and Importers were interviewed on the configuration of the trucks and the market shares of fuel saving devices such as aerodynamic measures, low rolling resistance tyres, automatic transmission and driver assistance systems.

There was continuous contact with ACEA, primarily through the Commission Services.
This was on a number of aspects such as:
- the metrics to be used and standard payload and share of different road/mission cycles.
- Current and future fuel saving technology shares (also for task 2).
- VECTO input and output

There was also interaction with road authorities in order to get market information on truck specifications for the different vehicle groups.

Specific input from ACEA was requested by the Commission Services in terms of data collection for VECTO results for the vehicles produced in 2016. This data collection was executed by the JRC outside of the SR9 project. A few pieces of information from this data collection (e.g. technology penetrations for auxiliaries in the 2016 fleet) have been shared by DG JRC and were incorporated into this study.

A.7 1.7: Determination of baseline and best performer fuel consumption and CO_2 emissions

The project plan was laid out to have at least one loop of adjustments of VECTO models as elaborated in Task 1.3 to consider feedback from stakeholders and potential deviations in the comparison with fleet operator data. During the project several loops of adjustments were made based on the available information from the data gathering in task 1 and from the consultation and dialogue with stakeholders and the Commission. At the end, the baseline and best performer on CO2 emissions are based on VECTO modelling. The results of this work are described in detail in a report of the JRC [Fontaras, 2018].

Annex B Regression analysis on trip data

Due to the large set of real-world fuel consumption trip data that was received (Annex A), a regression analysis was performed to identify how well the fuel consumption (in litres per trip) can be predicted by the characteristics present in the data set: laden mass, trip duration and trip distance. This is done to be able to remove outliers in the data set, e.g. those due to incorrect registration of the odometer, or anomalies due to the division of very small values. This obviously only as far as these differences are a result of differences in these trip characteristics such as weight, distance and duration.

The results of the regression analysis are summarized in Table 34. The regression coefficient is the value that the parameter needs to be multiplied with to best predict the trip fuel consumption. The regression analysis must be considered as a whole: isolated terms may yield different effects.

Table 34: Results of regression analysis.

Parameter	Multiplication factor	Notes
Total weight x distance (ton.km)	0.00449	
Trip duration (h)	5.872	
Trip distance (km)	0.0548	
Ambient temperature (°C)	0.12 / -0.12	Negative for temperatures higher than 10°C, positive for lower temperatures

The numbers in Table 34 should be interpreted as follows: to predict the fuel consumption of a trip with a truck with total weight of 19 tons instead of 18 tons, the fuel consumption should be increased by 0.0049 times the number of ton.km (ton laden vehicle mass).

Details

In total, 198,347 trips were considered, driven by 124 trucks. No distinction was made among mission profiles, because in principle the variation should be covered by the parameters in the analysis.

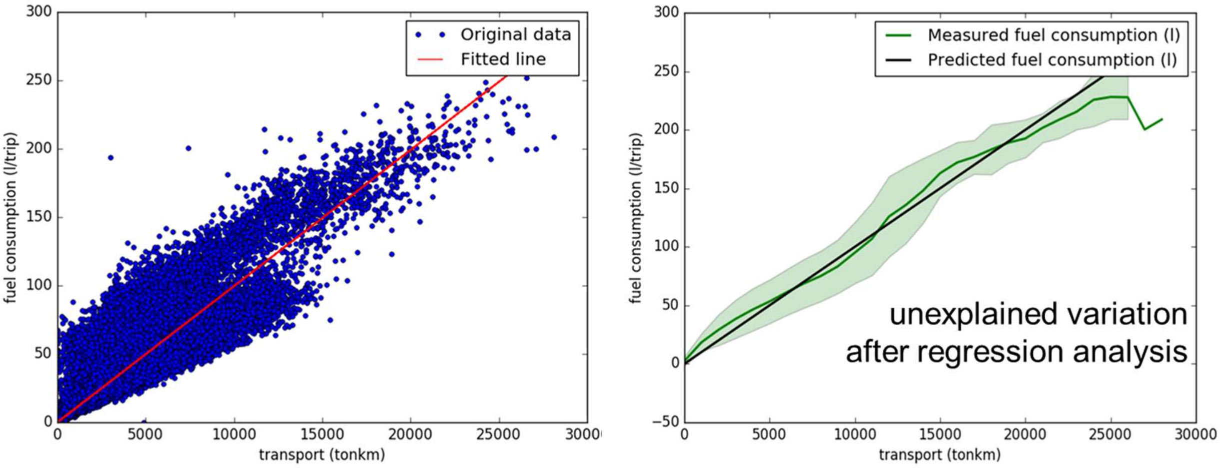
The available parameters in the data set were:
- Total weight (ton)
- Trip duration (h)
- Trip distance (km)
- Date

These parameters have been converted into inputs for the regression analysis:
  - Transport performance in ton.km (note: this is based on total weight, not on cargo)
  - Trip duration (h)
  - Trip distance (km)
  - Season / month of year

The ratio between trip duration and distance determines the average speed of a trip.
The two parameters were included separately to take into account cold start and idle effects.
For ton.km, duration and distance, only linear regression was analysed. The seasonal influence was estimated on the basis of the remaining unexplained variance in the results.

To see which parameters are of influence, first each one of them is separately analysed.

The regression of fuel consumption in litres per trip with transport performance in ton.km is given in Figure 30. The chart on the left hand side represents data points of individual trips. In the chart on the right hand side, the fuel consumption is averaged for each interval of transport performance (e.g. 0-10 ton.km, 10-20 ton.km and so on). This results in the dark green line. The light green band represents two times the standard deviation. The difference between the green and black line is the unexplained variation by this parameter (other parameters are trip duration – and indirectly the amount of idle time, trip distance, month (ambient conditions), vehicle efficiency (engine, transmission, fuel saving measures, etc.).
Figure 31 and Figure 32 show similar graphs for the regression of fuel consumption with trip duration and with trip distance.



unexplained variation
after regression analysis

Figure 30: Linear regression of total truck weight in ton.km and trip fuel consumption in litres.

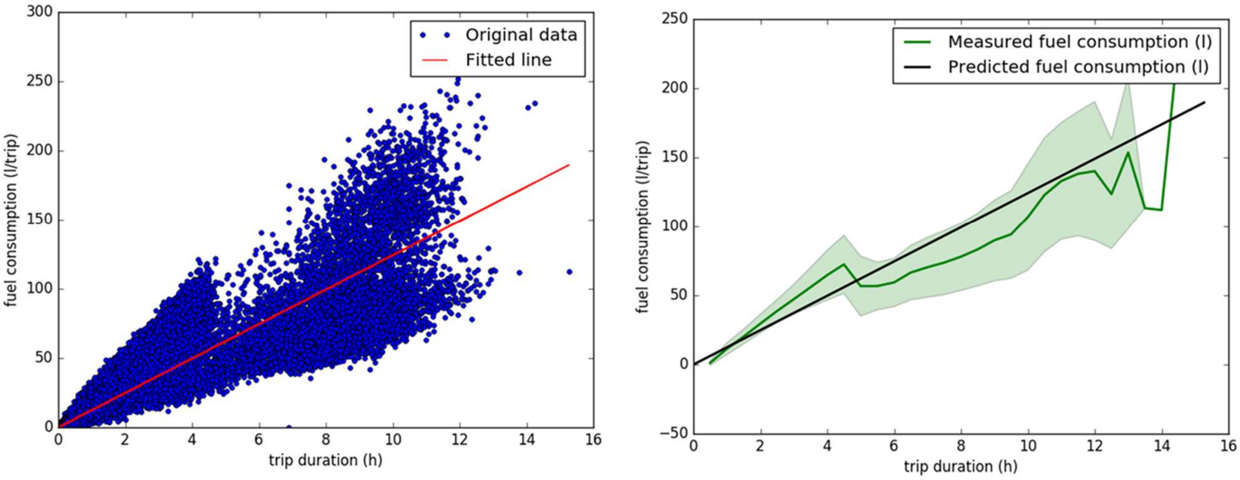


Figure 31: Linear regression of trip duration in hours with trip fuel consumption in litres.

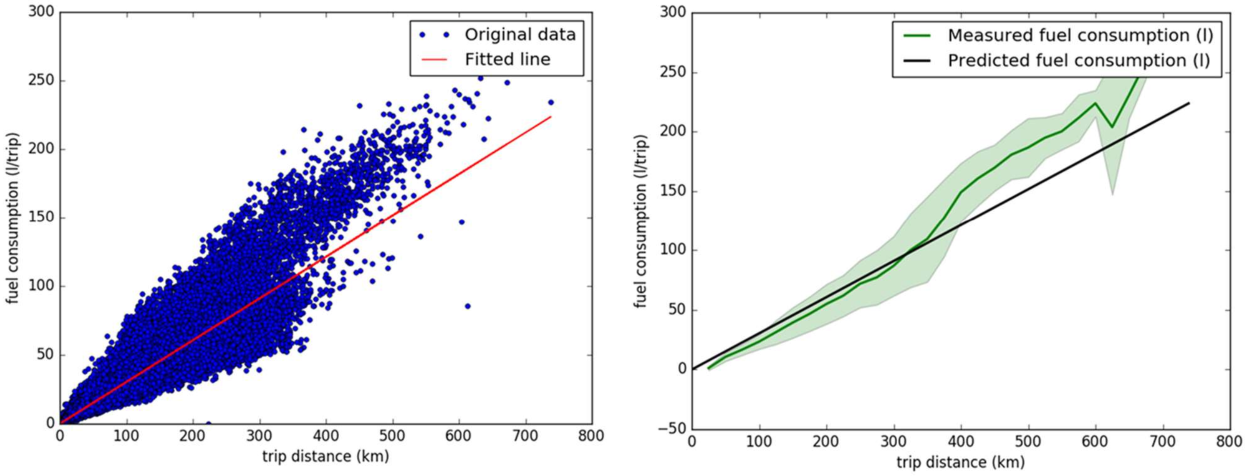
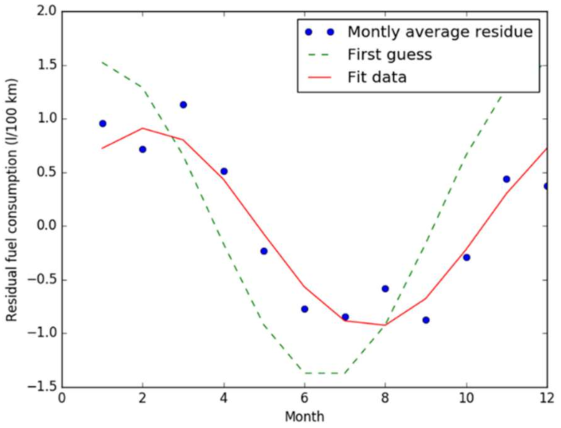


Figure 32: Linear regression of trip distance in km with trip fuel consumption in litres.

All three parameters described above have a more or less linear relationship with the trip fuel consumption. From the combination of the three parameters in a multi-variable regression analysis one can expect a more accurate prediction of the fuel consumption. Indeed, the resulting function has a regression coefficient of 0.977 which means it is accurate. To improve the result, the residue was plotted against the month of the year. This resulted in the next graph. The blue dots indicate the average residue for each month of the year. A sinus-like function was drawn from it (red line), which was used to correct the fuel consumption prediction. The correction is around +/- 1 liter per 100 km, which in practice means approximately +/-3%. Combining this information with the average temperature in the Netherlands, approximately 10°C, and the seasonal variation of the monthly average of 18°C, the sinus represents approximately -0.12 l/100 km per degree above 10 degrees, and +0.12 l/100 km per degree below 10 degrees.



After the correction, the multi-variable regression analysis is run again. The result is shown in Figure 33. The predicted fuel consumption is on the horizontal axis, the measured fuel consumption on the vertical axis.

It can be observed that over the entire range of trips, from low to high fuel consumption, the prediction is fairly accurate (around 10% or less for +/-1 standard deviation; light green area in the graph).

The regression coefficient R^2 is only marginally better than without season correction, 0.978. The prediction is somewhat underestimated for trips with high fuel consumption, and somewhat overestimated for trips with low fuel consumption (i.e. the shorter trips).

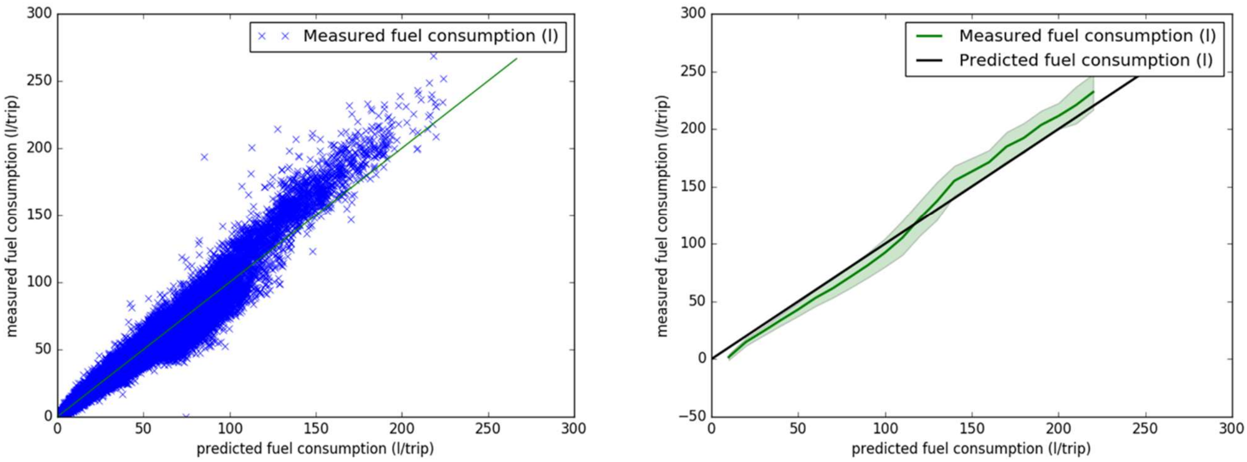


Figure 33: Multi-variable regression: prediction of fuel consumption by a combination of trip length, trip duration and laden vehicle weight.

The coefficients for the three variables are:

Transport performance (tkm): 0.00449
Duration (h): 5.872
Distance (km): 0.0548

The formula to predict a trip's fuel consumption is as follows:

F.C. = 0.00449 * transport performance in tkm + 5.872 * duration in h + 0.0548 * distance in km

Using this formula, the average fuel consumption for the trip data set can be calculated to verify the representativeness; see Figure 34.
The predicted values correspond reasonably well for the tractor-trailers (group 5 and 10, long haul use), and more substantial for groups 4 and 9 (municipal utility). Note that the regression analysis could be performed only on individual truck data, not on fleet data, which means that insufficient data was available for regional use of tractor-trailers and long haul use of rigid trucks.

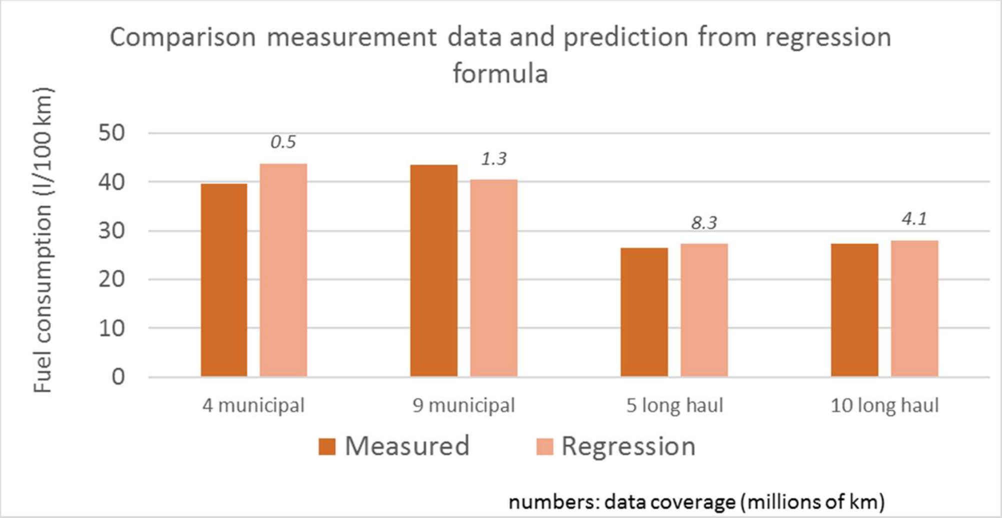


Figure 34: Comparison of fuel consumption: as measured and as predicted by regression formula.

The residue, which is the difference between prediction and actual fuel consumption value, is subsequently expressed as liters per ton.km, and plotted in Figure 35.

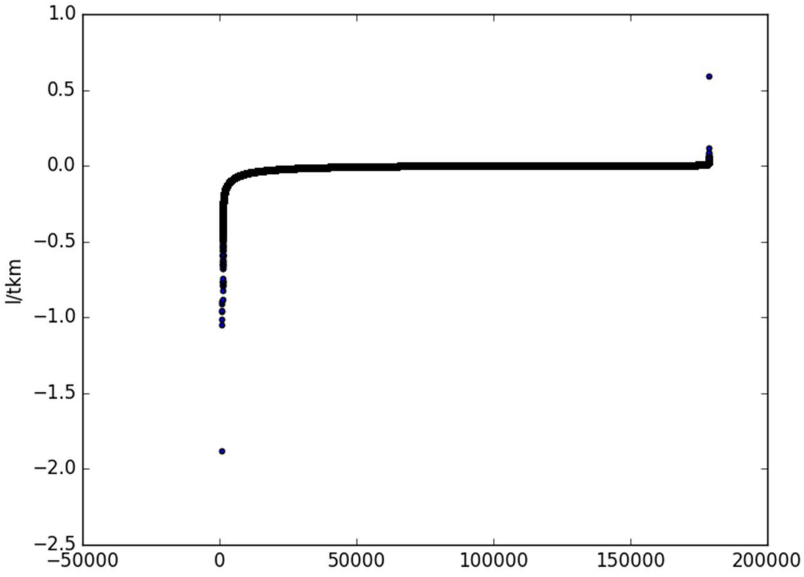


Figure 35: Residue of fuel consumption, expressed in liters per ton.km.

All trips for which the residue lies outside 2 times the standard deviation of the residues (~95% confidence interval) were left out of further analysis.

Annex C Analysis of an engine-only CO_2 standard (Task 1.5)

The goal of Task 1.5 was to analyse potential methods for engine-only based CO_2 limits. The documentation below covers the following content:

- Overview on engine-only CO_2 standards in other regions of the world
- Arguments pro and against engine-only based standards
- A draft method for engine-only standards compatible with the existing European HD CO_2 legislation
- Outline of the necessary steps for the elaboration of engine-only standards and first results from analysis based on available engine type approval CO_2 data
- Conclusions and recommendations

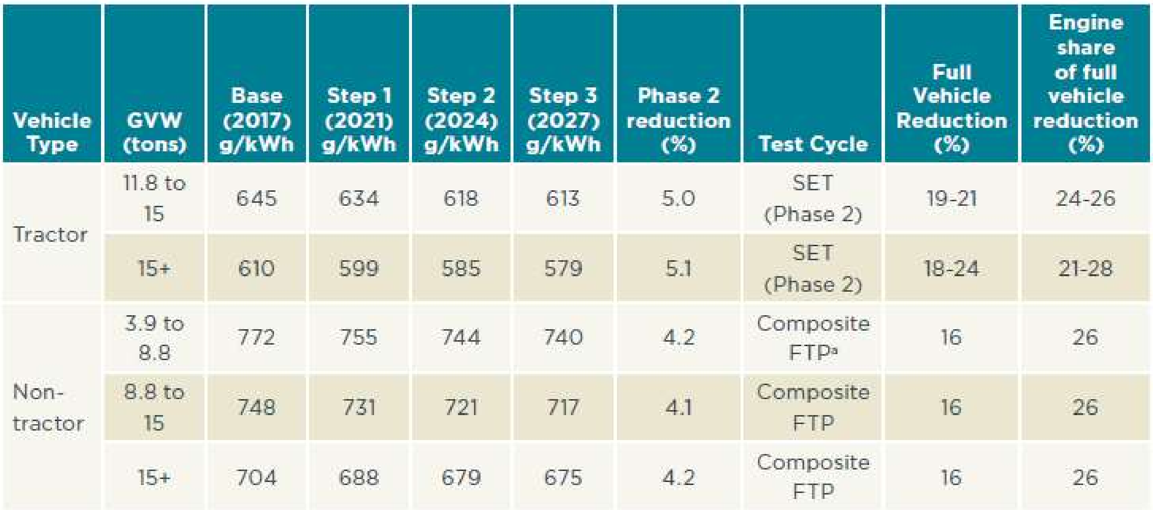
C.1 Engine-only standard in other regions of the world

Engine-only CO_2 standards exist already in other regions of the world with the most important market being the US (and associated Canada). Japan also has a CO_2 regulation in place, which is in fact a mixture of a full vehicle and an engine-only related standard.

In the Japanese standard, the vehicle cycle is converted into an actual engine cycle by means of simple longitudinal vehicle dynamic equations. This engine cycle is then measured on the engine test bed for evaluation of fuel consumption and CO_2 emissions. The power demand in the test cycle is fixed within a single vehicle segment and defined by the respective vehicle class the engine is allocated to. Only the engine load points (i.e. engine speed and torque) over the cycle can vary based on the gear ratios of the actual vehicle used for conversion of the given power to speed and torque. Since individual vehicle characteristics have no influence on the propulsion power demand over the test cycle, the Japanese standard can be seen as an engine-only approach, which does not incentivize improvements on vehicle level but only for the engine itself. In Japan, up to now the same test cycle is used for evaluating pollutant emissions and fuel consumption (except for generic gear ratios used for pollutant emissions). Since Japan is currently working on introducing the WHTC as new emission test cycle also the CO_2 standard will most likely have to be updated in order to keep the link between emissions and fuel consumption.

The US GHG standard, on the other hand, includes also CO_2 limits to be met in an engine-only test in addition to the imposed limits on vehicle level. The CO_2 limits are segmented based on the type and class of vehicle in which the engine will be installed (“primary intended service class”). The vehicle type can be either tractor or non-tractor, the three vehicle classes are light, medium or heavy heavy-duty which are characterised by the gross vehicle weight. The segmentation by mass can also be seen as an implicit differentiation in engine power rating, since heavier vehicles require more powerful engines. As engine efficiency tends to increase with higher power, lower CO_2 limits are to be met by engines installed in heavier vehicles. Tractor engines are tested in a steady-state cycle (SET) since they are considered to be operated without a lot of transient operation on the highway. Non-tractor engines are tested in a transient cycle (FTP) since transient engine operation is considered more likely for this type of vehicles. The FTP cycle is run as a combination of cold- and hot-start test where the final results are obtained by applying a weighting factor of 1/7 for the cold-start and 6/7 for the hot-start values. In the current Phase 2 of the US standard, the CO_2 emissions of diesel engines need to be reduced around 4% for non-tractor and 5% for tractor engines from the 2017 baseline until 2027. The applicable standards have to be met for each manufacturer based on the sales-weighted average for each segment. Table 35 gives an overview on the US Phase 2 heavy-duty diesel engine standard CO_2 limits.

Table 35: Overview US Phase 2 heavy-duty diesel engine-only CO_2standards [Muncrief, 2017].



Vehicle Type	GVW (tons)	Base (2017) g/kWh	Step 1 (2021) g/kWh	Step 2 (2024) g/kWh	Step 3 (2027) g/kWh	Phase 2 reduction (%)	Test Cycle	Full Vehicle Reduction (%)	Engine share of full vehicle reduction (%)
Tractor	11.8 to 15	645	634	618	613	5.0	SET (Phase 2)	19-21	24-26
	15+	610	599	585	579	5.1	SET (Phase 2)	18-24	21-28
Non-tractor	3.9 to 8.8	772	755	744	740	4.2	Composite FTP[a]	16	26
	8.8 to 15	748	731	721	717	4.1	Composite FTP	16	26
	15+	704	688	679	675	4.2	Composite FTP	16	26

C.2 Arguments pro and against engine-only based CO_2-limits

Potential arguments pro and against engine-only based CO_2-limits are listed in Table 36.

Table 36: Potential arguments pro and against engine-only based CO_2-limits.

Pro's	Con's
Forces engine R&D and implementation of new engine technologies independently which strategy OEMs chose for CO_2 reduction on vehicle level.	An engine-only based cycle may be very different from the real world application of the engine in the complete vehicle. This could be especially the case for special purpose vehicles, which are not covered by the VECTO full vehicle CO_2 certification approach. This might result in a conflict of targets for OEMs in the optimisation of the engine (engine cycle vs. real world) and increases the effort in engine development.
Putting pressure on CO_2 performance of engines installed in vehicles that are not covered by the full vehicle CO_2 standards.	Additional efforts in testing and administration generated for OEMs.
Ensuring CO_2 reductions over entire vehicle life-time as some vehicle related technologies might be not effective over the full vehicle life-time (e.g. replacement of tyres, removal of aero parts).	With applicable engine-only standards OEMs have less flexibility in development and application of most cost efficient CO_2 reduction strategies on a full vehicle level.
Total GHG potential could be assessed by incorporating measurement results for CH_4 and N_2O in addition to CO_2.	

C.3 Possible approach for engine-only standards compatible with VECTO

Due to the current structure of the heavy-duty vehicle market allowing a single engine model to be installed in a range of different vehicles, defining an engine test cycle is a challenging task. Engine operation differs quite a lot from one vehicle group to another and even for the same vehicle type there can be significant differences in real world operation. For a long-haul tractor model for example the engine speed at 80 km/h can vary by ±12% (this equals around ±200 rpm) due to the different final drive ratios available for that specific vehicle.
These arguments underline that there is no engine cycle fitting for all types of applications. Thus, an engine cycle for evaluating CO_2 emissions would always need to be some kind of compromise covering the most common operation profiles of engines in heavy-duty applications. The WHTC was developed with exactly this requirement, namely to cover the most frequent operation patterns of heavy-duty engines.
Therefore, using this well-established engine cycle offers several advantages:

- Highly representative for typical average operation of heavy-duty engines
- No need of developing a completely new test cycle and corresponding methods
- No additional testing effort for OEMs by using existing test procedures
- Measurement methods already well established in industry generate less methodical errors and lead to more accurate results from the beginning
- Only a single test cycle independent from vehicle type in which the engine is installed facilitates evaluation of limits at the end of one business year (Missing upfront information at engine OEMs in which vehicle the engines will be installed later on requires additional flexibility for CO_2 limits.)

Furthermore, the WHTC represents the most important link between the three columns of the European certification framework:

1. Pollutant emissions are addressed by the WHTC (lab) and in-service conformity testing (real-world)
2. FC and CO_2 emissions in vehicle certification through Vecto simulations are determined from a steady-state fuel map in combination with correction factors which are all derived from the WHTC
3. A plausibility check of the official CO_2 data reported in vehicle certification is done in the VTP test where the measured FC is compared to the simulated counterpart derived again from the fuel-map in combination with the WHTC

Thus, the WHTC is already an element of significant importance linking pollutant emissions with FC in the existing European framework. Therefore, the test cycle as well as the necessary methods for an engine-only standard could be taken over straightforward from the existing engine test procedure of the European CO_2 regulation 2017/2400 without any need for modification. The approach as indicated below correlates to the method how CO_2 emissions are determined by VECTO for the complete vehicle:

The relevant results for determining the CO_2 emissions of an engine would be:

- Fuel consumption measured in the cold-start WHTC
- Fuel consumption measured in the hot-start WHTC
- Correction factor for periodically regenerating DPF systems CF_{RegPer}
- Net calorific value (NCV) of the test fuel used

The determination of the CO_2 emissions of an engine could be carried out with the following steps in accordance with the methods defined in Annex V of regulation 2017/2400:

1. Evaluation of the specific fuel consumption figures in g/kWh for both the cold-start and hot-start WHTC
2. Conversion of actual measured fuel consumption from point 1. above to fuel consumption for fuel with standard NCV
3. Calculation of weighted test result from the cold-start and hot-start WHTC corrected in accordance with point 2 above. The weightings are applied in accordance with the cold-hot-balancing factor defined in the regulation.
4. Multiplication of the weighted result from point 3 above by the CF_{RegPer}
5. Multiplication of the outcome of point 4 above by the CO_2 content of the generic fuels used in VECTO

The final value is the relevant parameter to be considered for e.g. meeting fleet average CO_2 limits.

Further thoughts should be spend how the GHG impact of CH_4 and N_2O emissions shall be handled in a future legislation. The current European provisions only cover CH_4 emissions from NG natural gas engines by setting NTE pollutant limits. Commission Regulation (EU) 2017/2400 dealing with VECTO certification of HDV only covers emissions of CO_2. In the US GHG legislation both CH_4 and N_2O are handled as separate engine emission standards, however not consolidated with figures for CO_2.

The potential contribution of CH_4 and N_2O on the total GHG impact was checked by adding tailpipe emission levels corresponding to the CH_4 limit as defined in the European legislation for NG engines (0.5g/kWh) and corresponding to the N_2O limit in the US legislation (0.134g/kWh) to the tailpipe CO_2 emissions as simulated with VECTO. Based on these assumptions, CH_4 emissions can add up to 3% in CO_2 equivalent (tailpipe CO_2 emissions of a CNG vehicle as baseline). The N_2O contribution can be up to 6% CO_2 equivalent (tailpipe CO_2 emissions of a Diesel vehicle as baseline).

Identified options for covering CH_4 and N_2O emissions are:

1) Combined approach, engine CO2 standards:
   Measurement results for CH_4 and N_2O could be added to CO_2 emissions and the combined CO_2-equivalent could be the basis for a future engine-only GHG standard. In the elaboration of standards, a certain amount of CO_2-equivalent needs to be considered for the impact of the two additional emission components.

2) Combined approach, full vehicle CO2 standards:
   CH4 and N2O could be measured on the WHTC at TA as ratios of CO2 emissions and then the CO2 emissions simulated in Vecto would be corrected by multiplicative factors to get the total greenhouse gas emissions.

3) Separate approach, engine pollutant standards:
   CH_4 and N_2O are handled as separate NTE emission standards which could be covered in the provisions on pollutant emissions.

If only a part of the HD engines are applicable to engine-only CO_2/GHG standards, option 3 would be more reasonable as similar pressure on reducing CH_4 and N_2O would apply for all engines.

C.4 Elaboration of engine-only standards

In the elaboration of an engine-only CO_2 or GHG standard, the following main tasks have to be covered:

1. Analysis of recent engine CO_2 type approval data with the purpose to elaborate the baseline level
2. Determination of a method for engine segmentation
3. Defining limits and timing

The Section below gives a few first analyses on these items based on the limited data and resources available in this study.

In this analysis only data on Diesel engines (certified either to B7 or B10) were considered. In a later elaboration of engine-only standards, other fuel types (e.g. natural gas engines) need to be considered as well, as allocated market shares are expected to increase in future.[16]

C.5 Analysis of recent engine CO_2 type approval data

For the analysis of CO_2 data from recent engine models, two sources of data were available:

- ETAES (European Type Approval Exchange System)
  Engine type approval data from the year 2015 and later have been extracted. Data cover 18 "parent" and 18 "child" engines with measured CO_2 figures in the WHTC and WHSC according to the EURO VI regulations. Data cover engines from 5 different OEMs.
- Data provided by a single OEM on recent type approval results
  This dataset comprises 4 parents and 8 child engines.

As both sources of data have been derived from measurements performed under the provisions of the current EURO VI legislation, significant deficiencies have to be taken into consideration when using as baseline for the elaboration of engine-only CO_2 limits:

- Low measurement accuracy demands for engine torque and engine speed
- Low accuracy demands for measurement of fuel flow
- No precise provisions available how to calculate engine work from the raw measured engine torque and speed signals

It is estimated, that the resulting range of uncertainty can be up to +/-7% for CO_2 in g/kWh.[17]

Figure 36 and Figure 37 give the work specific CO_2 emissions in the weighted WHTC for both data sources plotted over engine rated power and over engine displacement.[18] Also the CO_2 levels of the 2016 "baseline" and 2016 "typical" engine as modelled in VECTO in this study are included in the picture. The CO_2 levels are very widespread, covering the range from 617 g/kWh to 778 g/kWh. If these figures are converted using fuel properties as defined in VECTO, this gives a range from 33.9% to 42.8% average engine efficiency. A major part of this observed spread may however result from the uncertainties of the test data described above and not to the "real" spread in engine efficiencies. If the CO_2 emissions are determined in future according to the methods of Annex V in Commission Regulation (EU) 2017/2400, much lower uncertainties are expected.

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[16] In the US GHG legislation the standards apply to the average engine of a manufacturer, independent of the fuel type.

[17] For the measurement of fuel consumption and CO2 according to Commission Regulation (EU) 2017/2400 much more stringed and precise provisions were elaborated. It is recommended that for any further analysis data measured under the provisions of Commission Regulation (EU) 2017/2400 shall be used.

[18] To keep the data as anonymous as possible, the scaling of the x-axes was removed by intention.

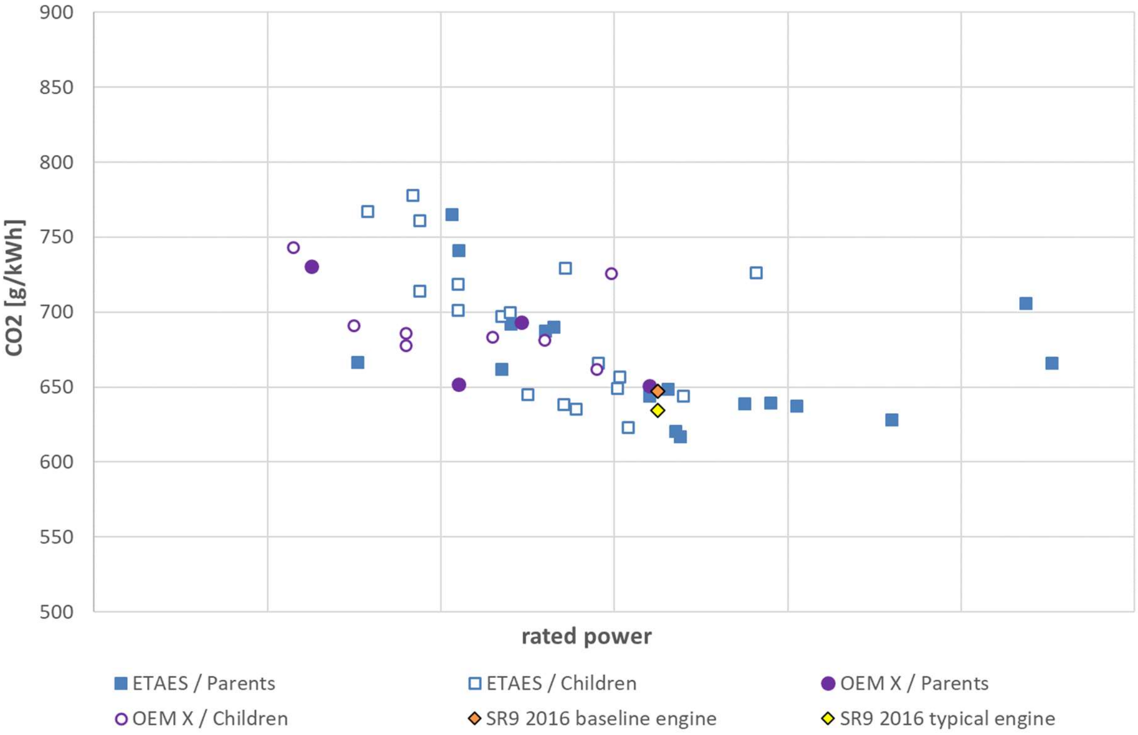

Figure 36: Brake specific CO_2 emissions [g/kWh] over engine rated power of current engine generation in the cold/hot weighted WHTC

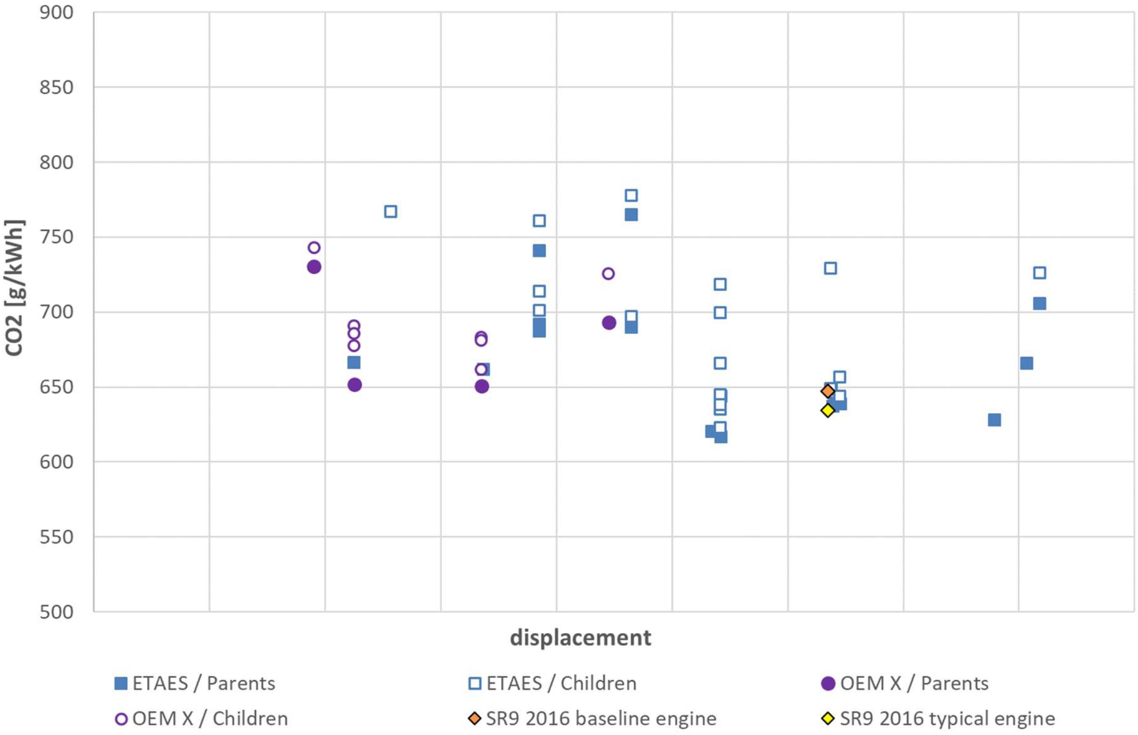

Figure 37: Brake specific CO_2 emissions [g/kWh] over engine displacement of current engine generation in the cold/hot weighted WHTC

C.6 Determination of a method for engine segmentation

Differentiating engine standards into segments with separate limit values makes sense due to two arguments:

i. Dependency of specific CO_2 figures with engine size or rating

For a given cycle and a given engine technology level, engine efficiencies and correlated specific CO_2 figures show general trends with engine size and rating. For a given engine type (hardware), the engine with the highest rating typically has the lowest specific CO_2 emissions amongst all ratings. This can be explained by a lower ratio of engine internal losses (which do not change significantly between the ratings) compared to the engine effective work (effective work at the crankshaft approximately scales linear with engine rating in type approval cycles).

An additional influencing factor is the engine displacement. Typically an engine with a higher displacement has slightly higher CO_2 emissions compared to an engine rating with similar rating but lower displacement.

ii. Dependency of specific CO_2 figures with engine cycle

As a matter of course CO_2 figures if measured in different engine cycles (e.g. like in the US the SET cycle for tractors and the FTP cycle for non-tractors) cannot directly be compared.

Not considering effects from i. in a standard properly, may cause negative impacts on CO_2 in real world as it might enforce a shift to engines with higher rated power. Such engines have lower brake specific CO_2 emissions in the engine test but in real world operation in a given vehicle application would cause higher CO_2 levels due to higher energy consumption per kilometre (cause by better driving performance and thus higher average speeds) and/or due to lower relative engine loads and higher engine weights.

The segmentation as implemented in the US legislation (“primary intended service class”) covers both arguments. The definition of different segments for “tractors” and “non-tractors” is caused by allocation of different engine cycles (steady state test “SET” to tractors, transient “FTP” test to non-tractors). Subdivisions for vehicle GVW implicitly cover engine size dependency.

For a potential engine-only limit approach based on the WHTC cycle as test procedure applied to all vehicle applications a segmentation on a solely engine related size parameter is suggested. Whether engine rated power or engine displacement is the main relevant parameter was analysed by statistics based on several subsets of the available engine data. As expected from theory, rated power was identified to be of significantly higher correlation with specific CO_2 levels than engine displacement. Furthermore, the engine power is the more future proved parameter if in future downsizing or upsizing trends may change the specific power output of HD engines.

Figure 38 gives the dependency of CO_2 in g/kWh with rated power. Linear trends have been calculated for each OEM separately to eliminate the influence of different engine size ranges between the OEMs. Brake specific CO_2 emissions are observed to decrease by some 0.15 g/kWh to 0.47 g/kWh by kW rated power.

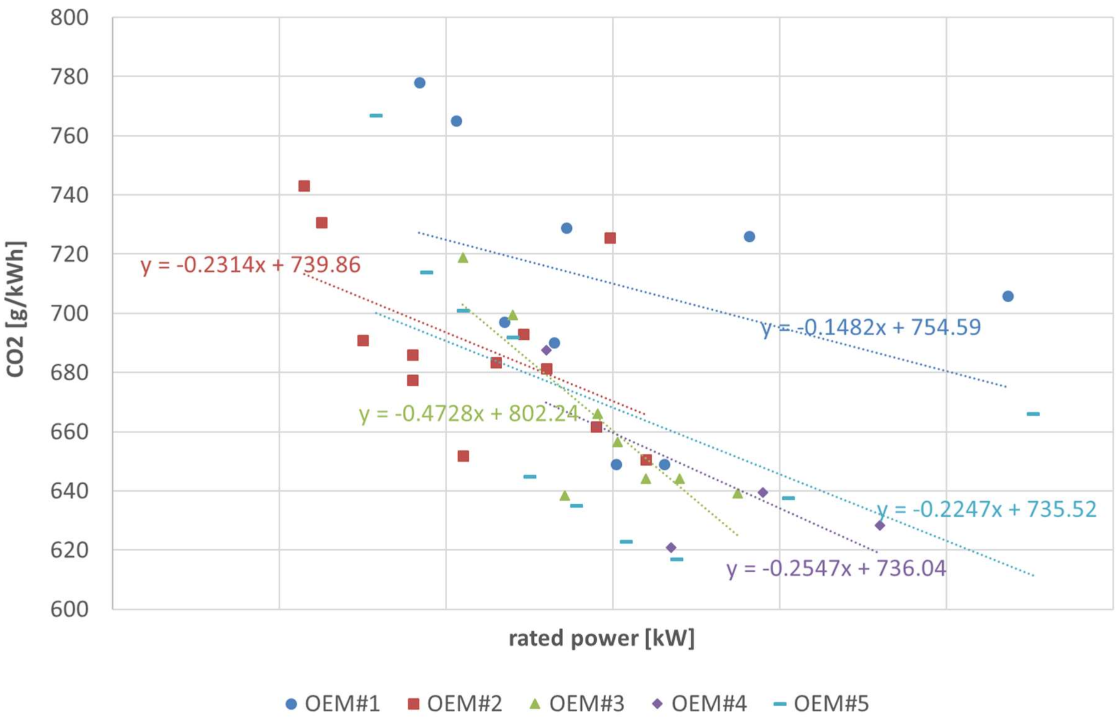

Figure 38: Dependency of brake specific CO_2 emissions [g/kWh] over engine rated power for different OEMs

The size dependency of an applicable CO_2 or GHG limit with engine rated power could be applied in the legislation by an analogue approach as used for mass dependency of CO_2 limits for passenger cars.

C.7 Indications for potential CO_2 limits

As already mentioned above due to insufficient significance of available type approval data no clear baseline for brake specific CO_2 emissions of actual engines as certified in the EU can be given. To get a first idea on possible CO_2 limits and correlated reductions over the years, data for the typical 2016 engine and certain engine technology packages have been compared with the US phase 2 standards. The comparison was performed for the service class “tractors 15+ tons GVW” by simulating the applicable SET phase 2 cycle with VECTO in the “engine only mode”.

The result of this comparison is given in Figure 39. The SET result for the EU 2016 typical engine is with 606 g/kWh very close to the US 2017 base engine as determined with 610 g/kWh by US EPA. Based on the 2017 level the US provisions demand for an annual reduction in CO_2 figures by 0.52% until the year 2027. The corresponding SET limit for 2027 is at 579 g/kWh. In comparison the VECTO result for the engine with the 2025 “realo scenario” gives a CO_2 figure of 566 g/kWh, which would be an annual reduction compared to 2016 typical by 0.76%.[19] If all fuel saving technologies – including costly measures like waste heat recovery - are considered in the VECTO simulations, the CO_2 emissions in the SET cycle are at 552 g/kWh.

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[19] In this regard is has to be considered, that the US limit applies to all engines in this vehicle segment, whereas the “realo scenario” as elaborated in this study assumes that some percentage of low technology vehicles are not included in the comparison with the EU full-vehicle CO2-limit.

Compared to the EU 2016 typical engine this means a reduction in CO_2 levels of 9%. Since the VECTO engine data for the vehicle limits represent engines for long haul operation, fleet average limits may be higher and thus be in line with the US-Standards if these are converted to the WHTC.

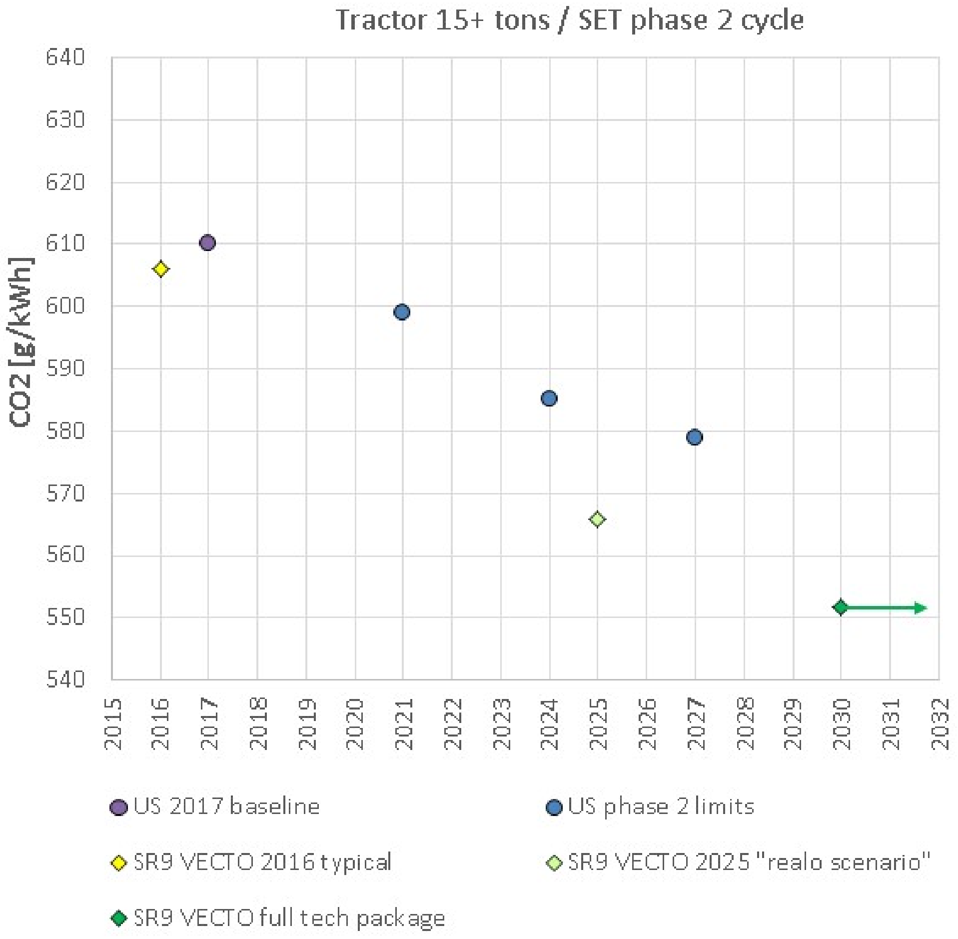

Figure 39: Comparison of US phase 2 standards with results from this study

C.8 Conclusions and recommendations

From the analyses as performed above the following conclusions and recommendations have been derived:

- The application of engine-only standards in addition to full vehicle standards has several pro’s and con’s which need to be thoroughly discussed with stakeholders. A straight forward decision “for” or “against” cannot be judged from the actual point of view. If the future vehicle based CO_2 emission limits are rather stringent and cover a high share of the HDV fleet, additional engine limits will bring rather small additional benefits.
- For the elaboration of well-grounded engine-only standards, type approval data measured according to the provisions of Commission Regulation (EU) 2017/2400 needs to be available. Existing CO_2 data measured under the provisions of the EURO VI pollutants Regulation (EC) 582/2011 have significant deficiencies in delivering reliable brake specific CO_2 numbers.

- While whole vehicle emission data calculated with Vecto are not available yet, the availability of historical CO_2 emission data for "engines-only" from pollutant type approvals under EURO VI Regulation (EC) 582/2011 for calculating an absolute ex ante baseline has often been quoted as the main argument for setting engine-only emission standards at this stage. However, as noted in the previous point, the existing CO_2 emission data for engines cannot be used for this purpose. With regard to the calculation of a regulatory baseline at this stage, engine-only standards therefore do not offer any advantage to whole vehicle standards
- An approach to determine the engine CO_2 emissions compatible with the VECTO full-vehicle approach has been identified and is described above. The method is based on the tests results for the cold and hot WHTC as measured according to Annex V of Commission Regulation (EU) 2017/2400. From the current point of view, engine-only standards would not require the implementation of any new test procedures in addition.
- If applied to all engines on the market, engine-only standards provide the opportunity to limit also the GHG impact of CH_4 and N_2O. As alternative NTE limits may be implemented separately for these exhaust components could be incorporated to type approval for pollutant emissions) or CH_4 and N_2O measured in the WHTC could be added to the CO_2 emissions simulated with Vecto to provide total greenhouse gas emissions in the full vehicle approach.
- A segmentation of engine-only standards by taking into consideration engine rated power in a classification scheme would be necessary since brake specific CO_2 emissions were found to decrease by some 0.2 to 0.4 g/kWh per kW rated power.
- From a first comparison of data elaborated in this study with US standards, the following conclusions have been drawn:
  - The average efficiency of engines certified in the EU around the year 2016 approximately matches the efficiency of the US phase 2 2017 “base” engine
  - The average annual improvement in engine efficiencies forecasted for a scenario with vehicle based CO_2 limits until 2025 in this study is with 0.76% higher than the annual improvement as laid down in the US standards (0.52% for tractors with 15+ tons GVW)

C.9 References

[Muncrief, 2017]	Muncrief R., Rodríguez F.: A roadmap for heavy-duty engine CO_2 standards within the European Union framework. ICCT 2017. https://www.theicct.org/publications/roadmap-heavy-duty-engine-co2-standards-within-european-union-framework

Annex D Background information for reduction potentials determined for single vehicle technologies

D.1 Description of Technologies

In this Annex D, related to the saving potential presented in Chapter 3 (task 2), background information on the technologies and their saving potential is described in more detail.

To evaluate future CO_2 emissions, a detailed analysis of possible technologies regarding their CO_2 reduction potential is necessary. The assessment of considered technologies is based on a literature research as well as on expert know how. These technologies are subdivided into following sectors:

- Aerodynamic
- Tyres
- Mass reduction
- Auxiliaries
- Transmission
- Advanced driver assistance
- Engine
- Hybrids

Further information on the improvement potential and their effects on the fuel consumption simulated in VECTO of several technologies, are contained in the coming chapters.

D.2 Aerodynamic technologies

In order to reduce the CO_2 emissions of HDV, aerodynamic technologies have a major potential. Especially at driving cycles with a high average speed like long haul and regional delivery, due to the quadratic correlation between air drag force and inflow velocity (see Equation 1)

$$\mathbf{F_{air}} = \frac{\mathbf{1}}{\mathbf{2}} * \mathbf{A} * \mathbf{c_w} * \boldsymbol{\rho} * \mathbf{v^2} \qquad \text{Equation 1}$$

This section deals with current and future technologies to reduce the air drag force of HDV. Figure 36 shows the course of the drag coefficient over the vehicle length for a truck without aerodynamic technologies. It can be seen that the vehicle front, the gap between truck and trailer and the rear end of the trailer dominate the air drag. These sections of the vehicle have the highest impact on the vehicle's aerodynamic performance.

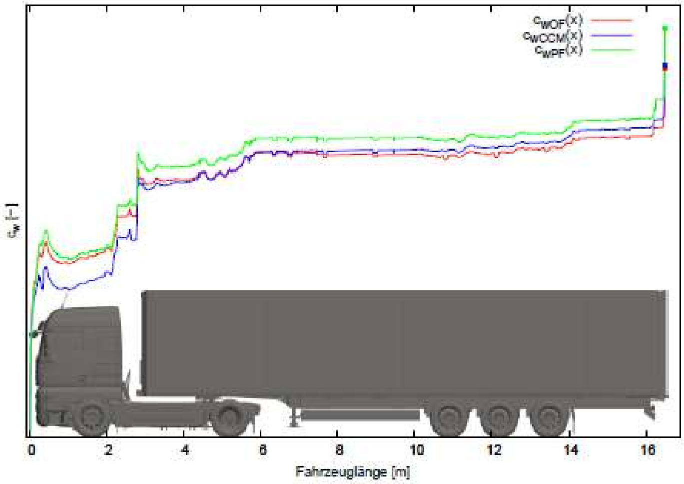

Figure 40: Cd value over vehicle length without aerodynamic technologies [FAT 298].

D.2.1 Aerodynamic technologies for trucks

D.2.1.1. Roof spoiler plus side flaps

This aerodynamic measure reduces the aerodynamic force on the vehicle by reducing the high pressure area at the trailer face and turbulences between tractor and trailer. With a given standard height of the trailer the reduction potential of a roof spoiler significantly depends on the cabin height and width and on the design of the spoiler shape. The reduction potential of side flaps depend on the gap size and design of the cabin. So for different vehicles the potential of this measure can differ quite significantly.
Table 37 lists the results found in literature for the aerodynamic package roof spoiler and side flaps and the fuel consumption reduction, which has been calculated in VECTO for comparison.

Table 37: Overview on literature data for a roof spoiler and side flaps

Technology description	Source	Impact
Roof spoiler and side flaps	[FAT 298 p.27]	-13.9 % CdxA
Roof spoiler and side flaps	[Dünnebeil, 2015]	-0.1132 m² CdxA
Roof spoiler and side flaps	JRC literature review [Zacharof, 2016]	-9 to -17% FC
Roof spoiler and side flaps	Used CdxA impact	-16% CdxA
Roof spoiler and side flaps	Calculated FC impact for Long Haul group 5	-5.14% FC

D.2.1.2 Side and underbody panels at truck chassis

The objective of side and underbody panels is a reduction of the airflow interruption to reducing turbulences at the truck end, by preventing the airflow from the bottom and the side trough the vehicle. This results in a lower pressure gradient before and behind the truck.

This study considered the underbody fairing only in combination with side panels (Figure 41). The values shown in Table 38 refers to zero yaw angle (i.e. no cross wind conditions). The effect of this technology is greater for groups 9 and 10 than for groups 4 and 5 due to the larger side and underbody area.

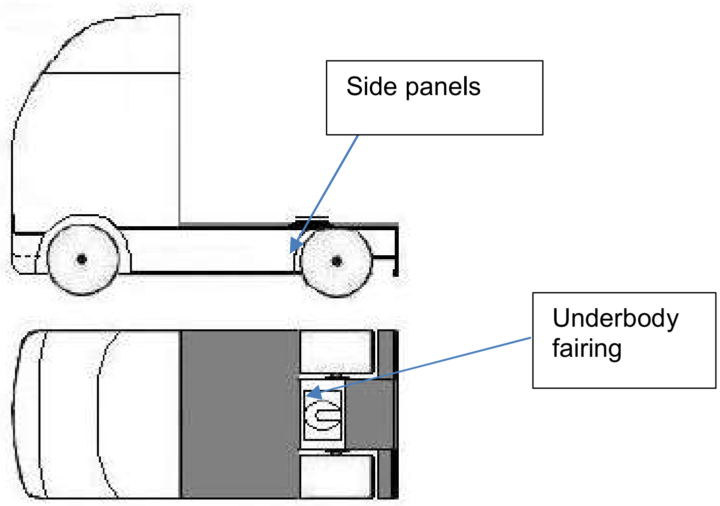

Figure 41: Exemplary presentation of side and underbody panels [FAT 241].

Table 38: Overview on literature data for side panels and underbody panels.

Technology description	Source	Impact
Side panels	[Dünnebeil, 2015]	-0,0265 m² CdxA
Underbody panels	[Dünnebeil, 2015]	-4% CdxA
Side panels	[FAT 260, p. 93]	-2.9% CdxA (group 4)
Side and underbody panels	Used CdxA impact	-3.5% CdxA (group 5,10) -4.5% CdxA (group 4,9)
Side and underbody panels	Calculated FC impact for group 5	-1.17% FC

D.2.1.3 Covers for rear truck wheels

This component covers the rim at the outside of the wheels (see Figure 42). An sufficient brake cooling has to be ensured regards to the usage of wheel covers. Concerning potential of the air drag reduction, only minor literature was found (Table 39).

Figure 42: Example for rear truck wheels (source: realwheels.com).

Table 39: Overview on literature data for rear truck wheel covers.

Technology description	Source	Impact
Wheel covers	Dünnebeil 2015	-0.002 m² CdxA
Wheel covers	FAT 237	-0.6% to -1.3% CdxA
Wheel covers	Used CdxA impact	-1% CdxA group 4 ,5 -2% CdxA group 9 ,10
Wheel covers	Calculated FC impact for Long Haul group 5	-0.34% FC

D.2.1.4 Closable front grille

A closed front grille prevents the airflow through the cooling system and the engine compartment. Figure 43 shows a truck cabin with a full covered front grill. The cover has to be variable or affect only particular areas to ensure a sufficient engine cooling. That is the reason why not 100% of the fuel saving potential of a closed front grille as found in literature was the potential of a were chosen for the fuel saving calculation in this study (Table 40).

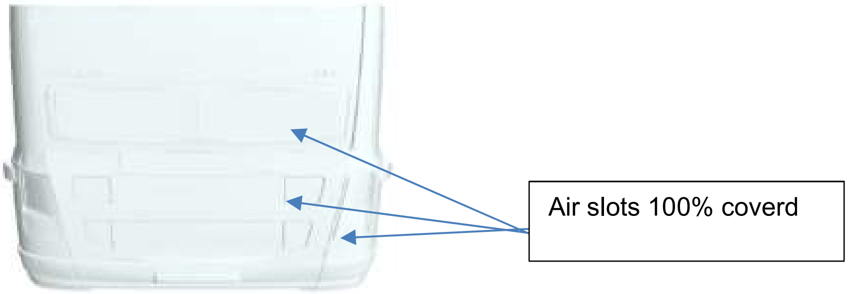

Figure 43: Vehicle front with closed front grille (source: [Larsson, 2009]).

Table 40: Overview on literature data for a closed front grille.

Technology description	Source	Impact
Closable front grille	[Dünnebeil 2015]	-0,0001 m² CdxA
Closable front grille	[Larsson, 2009]	-7% CdxA [1]
Closable front grille	Communication from CLCCR	-3 to -4% CdxA
Closable front grille	[ATZ/MTZ-Fachbuch]	-5 to -8% CdxA
Closable front grille	Used CdxA impact	-3.5% CdxA
Closable front grille	Calculated FC impact for Long Haul group 5	-1.17%FC

[1] for a 100% closed front grille

D.2.1.5 Aerodynamic mud flaps

Aerodynamic mud flaps consist of a material permeable to air in contrast to conventional mud flaps, which are airtight. Another type of aerodynamic mud flap is an undercarriage flow device (Figure 44). It accelerates the air and forward it to the wake space. This increases the pressure behind the trailer and reduce the drag from the vehicle [FAT 241].

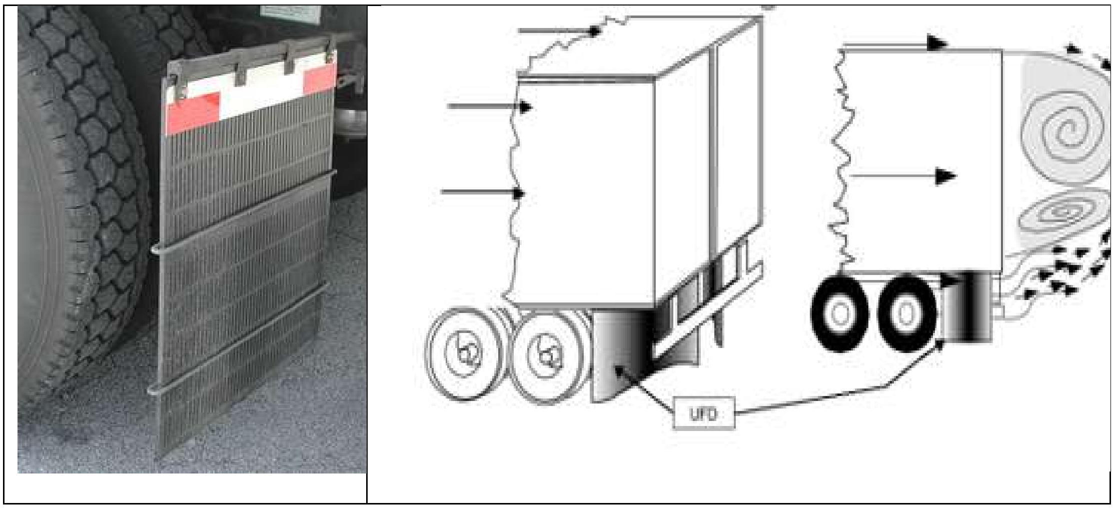

Figure 44: Aerodynamic mud flap (left, source: todaystrucking.com) and undercarriage flow device (right, source FAT 241).

Table 41 shows fuel saving potentials for aerodynamic mud flaps of some literature sources and used in this study. It is striking to see the large range between 0,5 and 3,5% for FC reduction potential.

Table 41: **Overview on literature data for aerodynamic mud flaps.**

Technology description	Source	Impact
Aerodynamic mud flaps	part20.eu	-1.5% FC
Aerodynamic mud flaps	[TNO , 2013]	-0.5% to -1.5% FC
Aerodynamic mud flaps	[FAT 237 p.6]	-3.5% m² CdxA
Aerodynamic mud flaps	[FAT 241 p.46]	-3.5% FC
Aerodynamic mud flaps (UFD)	[FAT 241 p.72]	-0.8% to -3.3% FC
Aerodynamic mud flaps	Used CdxA impact	-4% CdxA
Aerodynamic mud flaps	Calculated FC impact for Long Haul group 5	-1.34% FC

D.2.1.6 Rear view cameras

Conventional side mirrors of HDV contribute to the frontal area by about 0.16 m^2. A replacement against rear-view cameras which could be integrated in the chassis, reduces the frontal area, and thus the air drag. Figure 45 shows the application of rear view cameras instead of side mirrors.

Figure 45: **Rear view cameras (source: orlaco.de).**

Table 42: Overview on literature data for rear view cameras.

Technology description	Source	Impact
Rear view cameras	[Dünnebeil, 2015]	-4% CdxA
Rear view cameras	[FAT 237 p.59]	-2.9% FC
Rear view cameras	JRC literature review [Zacharof, 2016]	-1% FC
Rear view cameras	Used cdxA impact	-5% CdxA
Rear view cameras	Calculated FC impact for Long Haul group 5	-1.67% FC

D.2.1.7 Moveable 5th wheel

The fifth wheel is mounted on the truck for the connection between tractor and semitrailer as shown in Figure 46. At high velocities the 5th wheel is moved forward, to shorten the gap between cabin and trailer and to reduce the air drag losses. The reduction potential of a moveable 5th wheel is significantly influenced by the distance between cabin and semitrailer and highly interacts with the reduction potential of side-flaps.

Figure 46: Moveable 5th wheel.

Table 43: Overview on literature data for a moveable 5th wheel.

Technology description	Source	Impact
Moveable 5th wheel	[Dünnebeil, 2015]	-0,0163 m² CdxA
Moveable 5th wheel	JRC literature review [Zacharof, 2016]	-3% CdxA
Moveable 5th wheel	Used cdxA impact	-2% CdxA
Moveable 5th wheel	Calculated FC impact for Long Haul group 5	-1.67% FC

In the further assessment of this study, the reduction potential of a moveable 5th wheel was not considered in order to avoid double due to interaction with the “side flap” measure.

D.2.1.8 Longer and rounded vehicle front

The vehicle front has a high potential to decrease the air drag. The current design of European trucks allows not many options for aerodynamic improvements, which makes a redesign of the vehicle front necessary. The main object of a new designed front are great flanging radius and a rounded front without sharp edges to decrease the dynamic pressure in the front area and prevent stalling (see Figure 47). This new design makes a longer chassis necessary.

Figure 47: Redesigned vehicle front (source: iav.com).

Table 44: Overview on literature data for redesigned vehicle front.

Technology description	Source	Impact
Redesigned vehicle front	[FAT 237]	-4% CdxA
Redesigned vehicle front	[Dünnebeil, 2015]	-4% CdxA
Redesigned vehicle front	JRC literature review [Zacharof, 2016]	-3.2 to -5.3% FC
Redesigned vehicle front	http://articles.sae.org/13381/	-12% CdxA
Redesigned vehicle front	Used CdxA impact	-6% CdxA
Redesigned vehicle front	Calculated FC impact for Long Haul group 5	-1.96% FC

D.2.2 Aerodynamic technologies for trailer

This chapter deals with aerodynamic technologies for (semi-)trailers. Some technologies are based on the same principles as described above for the towing vehicle. For these measured, this chapter documents the results from the literature research and the used CdxA values for the VECTO calculations.

For the elaboration of cost curves, (semi-)trailer technologies have not been considered as it is not clear if and how the impact of non-standard trailers will be considered in VECTO in 2025.

D.2.2.1 Cover for trailer wheels

Table 45: Overview on literature data for trailer wheel covers.

Technology description	Source	Impact
Covers for trailer wheels	[FAT 237]	-0.6% to -1.3% CdxA
Covers for trailer wheels	[Dünnebeil, 2015]	-0.0078 m² CdxA
Covers for trailer wheels	JRC literature review [Zacharof, 2016]	3.9% FC
Covers for trailer wheels	Used CdxA impact	-1.4% CdxA
Covers for trailer wheels	Calculated FC impact for Long Haul group 5	-0.49% FC

D.2.2.2 Rounded front edge

That aerodynamic device is mounted on front face side of the trailer, see Figure 48. It reduces the area between truck and trailer and decreases the airflow through the gap. The fuel saving potentials that was found in literature (Table 46) relate to US trucks and only without deflectors at the cabin. For the application at EU trucks, no reference could be found. It can be assumed that the potential of rounded front edges decrease in conjunction with a roof spoiler and/or a movable fifth wheel.

Figure 48: Rounded front edges for trailer (source: wabco-optiflow.com).

Table 46: Overview on literature data for rounded front edge of trailer.

Technology description	Source	Impact
Rounded front edges of trailer	[Dünnebeil, 2015]	-0.0369 m² CdxA [1]
	https://www.wabco-optiflow.com/products/north-america-products/	-1.8 FC[2]
	Used CdxA impact	-6% CdxA
	Calculated FC impact for Long Haul group 5	-1.96% FC

1 Only in case of no deflectors at the cabin
2 For US trucks at highway speed

D.2.2.3 Side and underbody panels

Table 47: Overview on literature data for side and underbody panels at trailer.

Technology description	Source	Reduction
Side panels at trailer chassis	[FAT 241]	-0.04 m² CdxA
Side and underbody panels at trailer chassis	[FAT 298]	-6% CdxA
Side panels at trailer chassis	[Dünnebeil, 2015]	-11% CdxA
Underbody panels at trailer chassis	[Dünnebeil, 2015]	-9% CdxA
Side and underbody panels at trailer chassis	Used CdxA impact	-10% CdxA
Side and underbody panels at trailer chassis	Calculated FC impact for Long Haul group 5	-3.28% FC

D.2.2.4 Variable height of the rear trailer body

In addition to the vehicle front and the gap between truck and trailer, the rear end is the third significant area with a great air drag reduction potential. One option to decrease the air drag in this area is shown in Figure 49. The rear end of the trailer body can be lowered when not the whole storage space is necessary. The stall at the end of the trailer and the resulting turbulences are reduced.

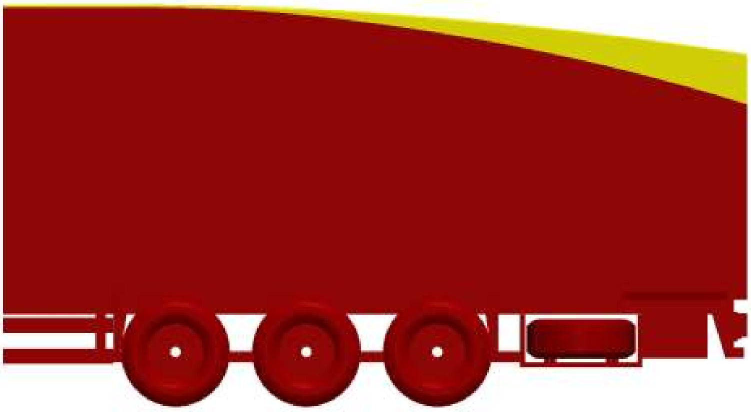

Figure 49: Variable Boat tail (source: FAT 237).

Table 48: Overview on literature data for variable height of trailer body.

Technology description	Source	Impact
Variable height of the rear trailer body	[FAT 237]	-6.8 % CdxA at 3.5 m rear end height -10 % CdxA at 3.0 m rear end height
Variable height of the rear trailer body	Used CdxA impact	-7% CdxA
Variable height of the rear trailer body	Calculated FC impact for Long Haul group 5	-2.3% FC

D.2.2.5 Boat Tail

A boat tail is the extension of the trailer with flaps on the rear end, which are slant inwards (Figure 50). The potential for air drag reduction depends on the length and angle of attack. Table 49 shows the results found in literature. Depending on the length of the device different reduction potentials can be found in literature. In this study the reduction potential of a 500mm boat tail was used in the further calculations as this dimension as compliant with Directive (EU) 2015/719 amending Council Directive 96/53/EC.

Figure 50: Boat tail application on a tractor trailer (source: part20.eu).

Table 49: Overview on literature data for a boat tail.

Technology description	Source	Impact
Boat Tail 400mm (4Kl)	[FAT 237 p.59-61]	-7.7% to - -9.5% CdxA
Boat Tail 400mm	[FAT 260 p.93]	-6.7% CdxA
Boat Tail 800mm (4Kl)	[FAT 237 p.59-61]	-6.8% - -8% CdxA
Boat Tail 1200mm (4Kl)	[FAT 237 p.59-61]	-6.5% to -8.5% CdxA
Boat Tail 1200mm	[FAT 260 p.93]	-6.1% CdxA
Boat Tail 1000mm	[part20.eu]	-3% FC (0.8l/100km)
Boat Tail 1500mm	[part20.eu]	-6% FC (1.7l/100km)
Boat Tail 500mm	[Kies 2017]	-8% CdxA
Boat Tail 1000mm	[Kies 2017]	-10% CdxA
Boat Tail 500mm	Used CdxA impact	-8% CdxA
Boat Tail 500mm	Calculated FC impact for Long Haul group 5	-2.59% FC

Technologies “Boat tail” and “variable height of the rear trailer body” are incompatible.

D.2.3 Tyres

D.2.3.1 Low rolling resistance tyres

In order to determine the potential of low rolling resistance tyres in 2025 the following approach has been used: The cumulated share of the rolling resistance coefficient was calculated according to the distribution of the tyre labels for 2014 as provided by ERTMA, for the steer-, drive- and trailer axle. Regarding the improvement of RRs over the years, ETRMA suggested an annual improvement of 1% [ETRMA, 2016]. Figure 51 shows the cumulated distribution of RRC of tyres from the steered axle for the years 2014, 2016 and 2025.
The RRC values used in VECTO are:

- Baseline vehicle: 90% percentile of 2016 distribution
- Typical vehicle: 50% percentile of 2016 distribution
- “Low RR technology”: 5% percentile of 2025 distribution

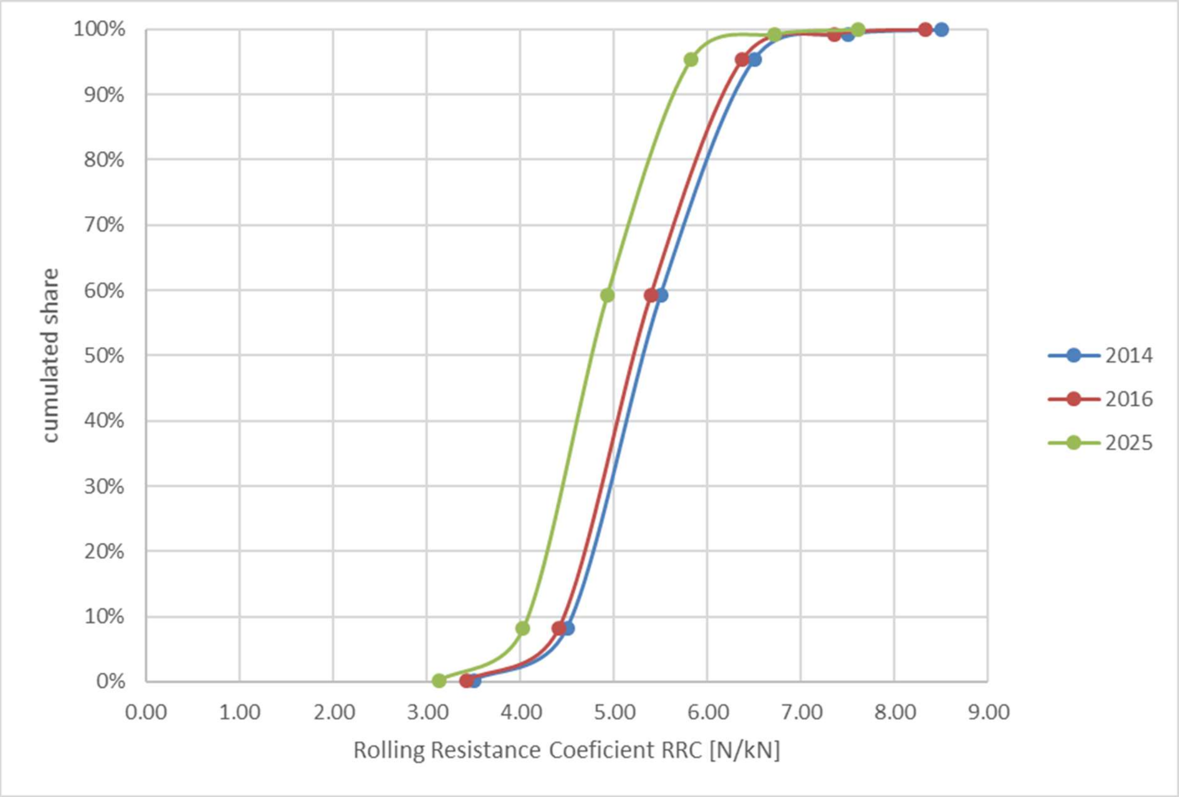

Figure 51: Cumulated distributions of rolling resistance coefficients for 2014, 2016 and 2025.

The rolling resistance coefficients for low rolling resistance tyres used in this study and the calculated fuel consumption impact in comparison to the 2016 baseline vehicle is shown in Table 50.

Please note: The shown FC reduction refers to the baseline vehicle with “worst” case RR tyres. Furthermore the “low RR” vehicle is a best case configuration which is assumed to be not applicable to all vehicle missions even in 2025.

Table 50: Used data and calculated FC reduction for low rolling resistance tyres.

Technology description	Source	Data
Low rolling resistance tyres	Used in this study	3.67 [N/kN] (steer axle) 4.28 [N/kN] (driver axle) 3.06 [N/kN] (trailer axle)
Low rolling resistance tyres	Calculated FC impact for Long Haul group 5	6.72% FC reduction compared to baseline vehicle

D.2.3.2 Tyre pressure monitoring systems (TPMS)

Tyre pressure monitoring systems indicate the driver if the tyre pressure falls below a certain threshold value. As rolling resistance increases with decreasing tyre pressure, TPMS – beside safety issues – also positively influence the fuel consumption of a vehicle. The fleet average impact of TPMS on rolling resistance levels was taken with 1.3% reduction from [van Zyl, 2013].

For a group 5 vehicle in long haul operation and reference load this results in a fuel consumption reduction of 0.24% if only the tractor is equipped with TPMS. When TPMS is also installed on the semitrailer, the impact was assessed with 0.45% reduction in the fleet.

D.2.3.3 Automated tyre inflation systems (ATIS)

Compared to TPMS automated tyre inflation systems also allows to inflate the tyres during driving. Hence the pressure can be kept at its optimum level, which gives more benefit than for TPMS where a certain threshold has to be underrun for the system to come effective.
For assessment on fleet average impact on RRC levels, data on tyre pressure distributions and correction of rolling resistance with tyre pressure from [van Zyl, 2013] have been re-evaluated. The result shows 1.6% reduction potential on RR from ATIS. For a group 5 vehicle in long haul operation and reference load this results in a fuel consumption reduction of 0.3% if only the tractor is equipped with TPMS. When TPMS is also installed on the semitrailer, the impact was assessed with 0.52% reduction in the fleet.
A possible negative impact of leakage in the pressurised air system (as indicated by ACEA in their comments) was not considered in the analysis.

D.2.3.4 Wide base single tyres

Wide base single tyres are a fuel saving alternative to twin tyres. These tyres have a reduced RRC due to lower number of sidewalls in contrast to twin tyres which decreases the flexing resistance. The advantage of weight reduction in case of wide base single tyres has not been considered in this study. According the reduction potential found in literature we assumed a reduction of 5% for the rolling resistance coefficient for such tyres (see Table 51). Figure 52 shows an example for wide base single tyre on a tractor.
According to ETRMA the market acceptance regarding wide based single tyres in Europe is very low, amongst other reasons due to safety concerns.

Figure 52: Example of wide base single tyre on a tractor (source: autokiste.de).

Table 51: Overview on literature data.

Technology description	Source	Impact
Wide base single tyres	www.autokiste.de	-1.5 [l/100km] FC
Wide base single tyres	[„LKW-Einkauf" des Fach- und Wirtschaftsmagazins LOGISTIK inside, 5/2009]	-0.7 [l/100km] FC
Wide base single tyres	[Rodriguez, 2017]	-1.7% to -2.2% FC
Wide base single tyres	Used in this study	-5% RRC
Wide base single tyres	Calculated FC impact for Long Haul group 5	-0.58% FC

D.2.4 Mass reduction

Light-weighting decreases the energy demand for propulsion due to lower acceleration resistance and braking demand and by lower rolling resistance force. In real driving also the maximum payload capacity is increased.[20]

Table 52 lists the mass reductions defined in VECTO and their fuel consumption impact, which have been considered in this study.

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[20] In VECTO the payload is defined as constant values.

Table 52: Mass reduction of lightweighting packages.

Technology	Mass reduction [kg]				FC reduction[1]			
	Gr. 4	Gr. 5	Gr. 9	Gr. 10	Gr. 4	Gr. 5	Gr. 9	Gr. 10
Mild reduction rigid truck / tractor	300	75	300	75	-0.41%	-0.10%	-0.41%	-0.10%
Strong reduction rigid truck / tractor	1000	900	1000	900	-1.36%	-1.24%	-1.31%	-1.41%
Mild reduction including trailer	---	300	---	300	---	-0.43%	---	-0.47%
Strong reduction including trailer	---	2300	---	2300	---	-3.23%	---	-3.31%

[1] Reduction potential for Long Haul and representative load

In good approximation a linear correlation between mass reduction and fuel consumption reduction can be assumed. Against this background, is it possible to determine the benefit of custom mass reductions by a linear interpolation between the values given in Table . For the elaboration of cost curves this approach was used to define light-weighting packages with different numbers for mass reductions.

D.2.5 Auxiliaries

The determination of the CO_2 reduction potential regarding auxiliary technologies was done by exchanging the “technology”[21] as selected for the baseline vehicle by the technology with the lowest power consumption in VECTO. This was done for each auxiliary type (engine cooling fan, steering pump etc.) separately. For the electric system additional a future improved alternator technology (alternator efficiency of 0.8, compared to the standard alternator, which has an efficiency of 0.7) was assumed to be applicable. Table 53 gives an overview on used technologies.

Table 53: Auxiliary technologies.

Auxiliary type	Technology
Engiune cooling Fan	Crankshaft mounted - Electronic controlled visco clutch
Steering pump	Variable displacement, elec. controlled
HVAC	Default
Electric Sytem	LED main front headlights
Electric Sytem with best performing altenator	LED main front headlights
Electric Sytem with best performing altenator	Standard
Pneumatic System	Medium supply 1-stage + ESS + AMS

The impact on fuel consumption for a group 5 vehicle in long haul mission with representative payload is listed in Table 54.

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[21] Definitions as given in Annex IX of [EU, 2017]

Table 54: Fuel consumption reduction potential of individual technologies for group 5.

Tech ID	Technology	Impact on fuel consumption
Aux-1	Electric hydraulic power steering	-0.26%
Aux-2	LED lighting	-0.06%
Aux-3	Air compressor	-1.65%
Aux-5	Engine Cooling fan	-0.50%
Aux-6.1	Standard electric system with best performing alternator	-0.19%
Aux-6.2	LED electric system with best performing alternator	-0.25%

D.2.6 Transmission

For vehicle groups considered in this study the most commonly used transmission type in Europe is the automated manual transmission "AMT" [Rodriguez, 2017]. Within the scope of this project, a 25% reduction potential of transmission as well as axle losses have been considered according to [Dünnebeil, 2015]. This results in a fuel consumption reduction of 1.52% for a group 5 over the Long haul cycle.

D.2.7 Advanced Driver Assistance Systems (ADAS)

The VECTO version used in this study does not cover ADAS technology like engine start/stop, predictive cruise control or an Eco-roll system (disengagement of engine and drivetrain in certain downhill conditions). In order to determine the impact of ADAS on fuel consumption which is compatible to a future implementation in VECTO, a post-processing method based on time-resolved VECTO results was elaborated. Assumption on functional features of ADAS systems have been taken from [ACEA; 2016].
The following sections describes the calculations of CO_2 reduction potential for above mentioned driver assistance systems.

D.2.7.1 Engine start stop (ESS)

A start-stop system shuts down and restarts the internal combustion engine to reduce the amount of idling time of the engine. This reduces fuel consumption and emissions. ESS events were considered, if the vehicle velocity is for a period of more than 2 seconds lower than 0.5 km/h. : Fuel saving potentials for engine start stop are shown in Table 55.

Table 55 : Fuel saving potentials of engine start stop.

	Group 4		Group 5		Group 9		Group 10	
Payload [kg]	Long Haul	Reg. Delivery	Long Haul	Reg. Delivery	Long Haul	Reg. Delivery	Long Haul	Reg. Delivery
VECTO representa-tive payload	0.08%	1.48%	0.09%	1.07%	0.08%	1.34%	0.10%	1.11%
VECTO low payload	0.10%	1.62%	0.12%	1.35%	0.10%	1.54%	0.13%	1.39%

D.2.7.2 Eco-roll

The benefit of Eco-roll is the reduction of engine drag losses by disengaging the engine from the wheels during certain downhill conditions. During these phases the engine is operated at idling conditions instead of overrun operation. An additional fuel saving benefit can be achieved if the internal combustion engine can be turned (ESS) off during Eco-roll. This however requires additional hardware on the vehicle, like an electric power steering system. The reduction of fuel consumption is shown in Table 56. Rows marked with “w/ ESS” indicate Eco-roll systems with ESS functionality.

Table 56: Fuel saving potentials of Eco-roll systems.

ESS system	Payload [kg]	Group 4		Group 5		Group 9		Group 10	
		Long Haul	Reg. Delivery	Long Haul	Reg. Delivery	Long Haul	Reg. Delivery	Long Haul	Reg. Delivery
Eco-roll (w/o PPC, w/o ESS)	representa-tive load	0.31%	1.01%	0.50%	0.28%	0.31%	0.69%	0.52%	0.31%
Eco-roll (w/o PPC, w/o ESS)	low load	0.21%	0.95%	0.53%	0.74%	0.22%	0.81%	0.55%	0.74%
Eco-roll (w/o PPC, w/ ESS)	representa-tive load	0.71%	3.32%	1.06%	1.88%	0.70%	2.71%	1.13%	1.98%
Eco-roll (w/o PPC, w/ ESS)	low load	0.45%	3.28%	1.06%	2.79%	0.48%	3.08%	1.12%	2.86%

D.2.7.3 Predictive cruise control (PCC)

Predictive cruise control manages and optimises the usage of the potential energy during a driving cycle. A prerequisite is the availability of high quality road gradient data for the entire planned trip. In the assessment of the PCC functionality, according to [ACEA; 2016] a differentiation is made between three “use cases”, which are shown in Table 57.

Table 57: Modelled cases for predictive cruise control features.

Use case ID	Situation and description
1	Crest coasting: The vehicle reduces the velocity at uphill driving to reduce the downhill braking
2	The vehicle accelerates on negative slope, without any engine power
3	Dip coasting: PCC allows to increases the over-speed to end the downhill driving with a high velocity

For all three use cases, the gain of kinetic energy was in a first step calculated over the course of the cycle. This energy gain was then converted into a fuel consumption benefit over the total cycle.

Table 58 shows the fuel saving potential for vehicle groups 4, 5, 9 and 10 resulting of PCC.

Table 58: Fuel saving potentials of PCC.

	Group 4		Group 5		Group 9		Group 10	
Payload [kg]	**Long Haul**	**Reg. Delivery**	**Long Haul**	**Reg. Delivery**	**Long Haul**	**Reg. Delivery**	**Long Haul**	**Reg. Delivery**
representa-tive payload	0.95%	0.35%	1.38%	1.90%	1.21%	0.75%	1.40%	1.88%
low payload	0.18%	0.07%	0.43%	0.73%	0.23%	0.28%	0.44%	0.76%

D.2.7.4 Combined systems

PCC can be combined with ESS as well as Eco-roll. Table 59 gives the allocated reduction potentials.

Table 59: Fuel saving potentials of combined ADAS systems.

Combined ADAS system	Payload	Group 4		Group 5		Group 9		Group 10	
		Long Haul	**Reg. Delivery**	**Long Haul**	**Reg. Delivery**	**Long Haul**	**Reg. Delivery**	**Long Haul**	**Reg. Delivery**
PCC (w/ Eco-roll, w/o ESS)	represent.	1.32%	1.44%	1.94%	2.42%	1.58%	1.61%	1.97%	2.43%
	low	0.40%	1.03%	0.99%	1.61%	0.46%	1.17%	1.02%	1.67%
PCC (w/ Eco-roll, w/ ESS)	represent.	1.69%	3.70%	2.46%	3.87%	1.94%	3.55%	2.54%	3.94%
	low	0.64%	3.36%	1.50%	3.57%	0.71%	3.39%	1.57%	3.69%

D.2.8 Engine technologies

As for the other technologies, the CO_2 reduction potentials were elaborated where possible compared to an engine without the technology under consideration. Maintaining this system for all technologies proved to be not possible, since several technologies just refer to “improvements”, such as improved turbocharging or improved SCR. These technologies were defined compared to the “low efficient 2016 Heavy Duty Engine”, which has some 4% lower engine efficiency compared to the best performing 2016 engine and 2% less efficiency than the average 2016 engine. This means, that the average 2016 HDV has already a share of these “improvement” technologies on board. This definition has to be kept in mind when the CO_2 reduction potentials are interpreted.

D.2.8.1 General trends

For truck engines, the trends are indicating a reduction of cylinder number, but still with the same displacement, slightly lower compression ratio and increased charge pressure – e.g. with two-stage charged inline six-cylinder engines replacing V8 engines in the upper segment. Since downsizing of engines is becoming more challenging as NOx emission monitoring is extended, "right-sizing" is the actual trend for vehicle engines. By increasing cylinder and engine displacement, part load losses will turn up again as an engineering issue. This is already addressed by production engines which operate e.g. with a Miller cycle process and higher geometric compression ratio.

The higher geometric compression ratio helps to reduce losses at low engine load conditions, e.g. [Neugärtner, 2017]. In addition, the thermos-management of the after-treatment systems gets increasing importance, especially in the case that in future cold start emissions will be included in the on-board in-service test procedure. The energy demand for heating the SCR catalysts will rather not influence the VECTO results directly, since the engine fuel map is measured in hot conditions, but it may influence the engine technologies. EGR with bypass of the EGR cooler or cylinder deactivation may become an attractive technology to maintain the SCR temperatures in the necessary operation range and to limit raw exhaust emissions during cold SCR conditions. Thus in the assessment of isolated technologies, some main trends which the development of the complete engine is assumed to follow in the next years were considered as restriction.

In the single steps of the thermodynamic working process of the engine, following potentials are seen:

A) Charge changing:
    A-1) improved turbochargers efficiency, especially relevant for high charge pressure with EGR. EGR supports B-2) and the SCR thermos-management and is thus kept in the 2025 engine
B) Combustion process:
    B-1) high compression ratio,
    B-2) reduced heat losses to cylinder wall and piston,
    B-3) fast combustion at top dead centre (TDC),
    B-4) ideal gas property of the cylinder charge
C) Friction:
    C-1) low friction in the engine (piston, crankshaft,..)
    C-2) low friction of auxiliaries necessary to run the engine with main components being the high pressure injection system, the oil and water pump and the cooling fan.
D) Waste heat recovery: waste heat occurs from the exhaust and from the cooling system. Since only the exhaust gas has a temperature level which leads to reasonable efficiencies of waste heat recovery systems, the exhaust gas enthalpy was considered as energy source.

The packages supporting these reduction strategies and the way they have been implemented in the VECTO input data are described below.

D.2.8.2 Package 1: Improved turbocharging and EGR

EGR and turbocharging are considered in a package due to the heavy interactions between these components[22]. An improvement of the efficiency of the turbo charger leads to a positive work contribution of the charge changing process or at least reduces the work necessary for charge changing. Since high EGR rates need a high boost pressure to provide a sufficient

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[22] Turbo-compound is not considered in the technology package since it reduces the exhaust gas enthalpy upstream of the exhaust gas aftertreatment systems. This would need then more active heating of SCR for low NOx limits which most likely will outweigh efficiency benefits from the turbo compound. [US-EPA, 2016] report zero benefit at 0.3 to 0.4 gm/hp-hr engine-out NOx for turbo compound.

amount of oxygen for the combustion, the work demanded from the compressor to fill the cylinder increases with EGR rates. On the other hand the turbine produces more work from the exhaust gas enthalpy with a higher charge mass, and thus provides work input into the engine process. With actual efficiencies from turbo chargers thus increasing EGR rates decrease engine efficiency already in the charge changing process. Technologies for improving turbocharger efficiencies are described e.g. in [Wöhr, 2017].

EGR is mainly used to control NO_x formation during the combustion. Due to the dilution of the cylinder charge with inert gases from the exhaust (CO_2, H_2O) a higher mass has to be heated in the flame during the combustion. In addition the specific heat coefficient of CO_2 and especially of H_2O are higher than that from air, thus a lower temperature is reached at the combustion of the fuel. In addition the oxygen concentration is reduced by EGR, what slows down the formation of NO from N_2 and O_2 in the so called “Zeldovich NOx formation”, e.g. [Sams, 2017].

Main effects from EGR on the fuel efficiency are:

- \- The lower concentration of fuel and oxygen in the cylinder charge slows down the combustion and thus reduces the efficiency of the combustion.
- \+ The reduced combustion temperature reduces wall heat losses and thus improves the engine efficiency, the increasing specific heat capacity of the cylinder charge increases also the efficiency of the work cycle[23].
- \+ In situations where the SCR system has insufficient capacities to meet exhaust gas limits, EGR is a more efficient means of NOx engine out reduction than a later fuel injection in case without EGR.
- \+ if the intercooler is bypassed, EGR can be used for a quite efficient increasing of the exhaust gas temperature in situations where the SCR system needs to be heated to maintain high SCR efficiencies. Also the exhaust gas mass flow is reduced in such cases. This also reduces cooling of the SCR at low load driving.
- \- As mentioned above, higher work for charge changing is necessary.

Figure 53 shows an overall effect for EGR on the fuel efficiency measured at an EURO VI engine.

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[23] The efficiency of the ideal engine (i.e. ideal combustion and no heat and friction losses) depends only on the compression ratio, on the charge mass in the cylinder (or air to fuel ratio) and on the specific heat capacity of the cylinder charge.

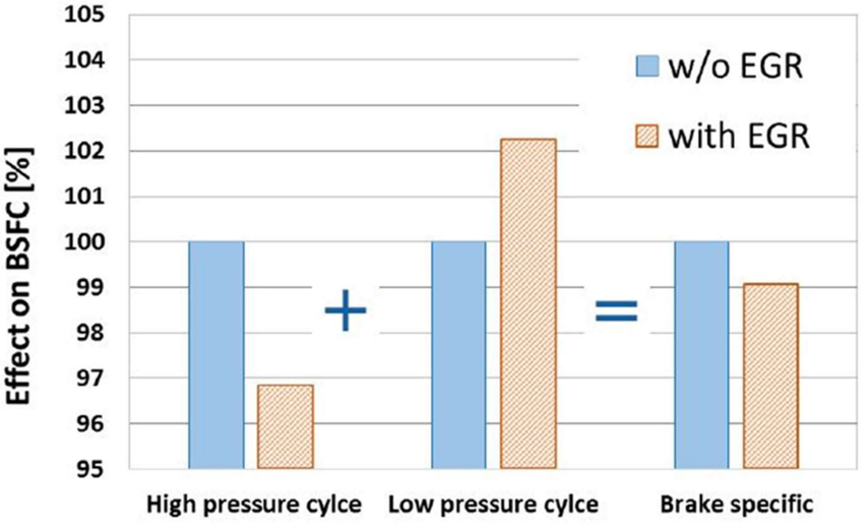

Figure 53: Effect of cooled EGR on the specific fuel consumption of an EURO VI engine at 1200 rpm and 18bar BMEP (Graf, 2017).

In the total package 1 also a Miller cycle was assumed to be applied for improved engine efficiency. The Miller cycle closes the intake valves earlier24 and needs further increased charge air pressure to bring sufficient mass into the cylinder. A part of the cylinder compression work therefore is shifted to the turbo charger what makes an efficient turbocharger even more relevant.

Figure 54 shows the fuel consumption reduction gained by improved turbocharger efficiency for a EURO VI HD engine. The blue line with 54% turbocharger efficiency is assumed to be representative for the EURO VI baseline technology. Some 4 g/kWh fuel reduction are expected to be possible compared to conventional intake valve timing until 2025, which corresponds to approx. 2% to 3% improvement in the fuel efficiency. By further increases of the cylinder charge by a higher boost pressure and a moderate compression ratio increase, overall 4% improvement in the fuel efficiency should be possible compared to the EURO VI base engine[25].

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[24] Closing the intake valve before bottom dead centre (BTC) results in a work neutral expansion over the bottom dead centre up to a cylinder volume in the compression phase which is similar to the one at intake valve close (gas spring), Thus the effective compression ratio is reduced while the expansion ratio relevant to deliver work is maintained. A part of the engines compression work thus is done by the turbocharger. Due to the intercooling after turbocharger this helps improving charge properties compared to a compression in the engine.

[25] Note that the most efficient EURO VI engines are approx. 2% more efficient than the base engine without advanced technologies.

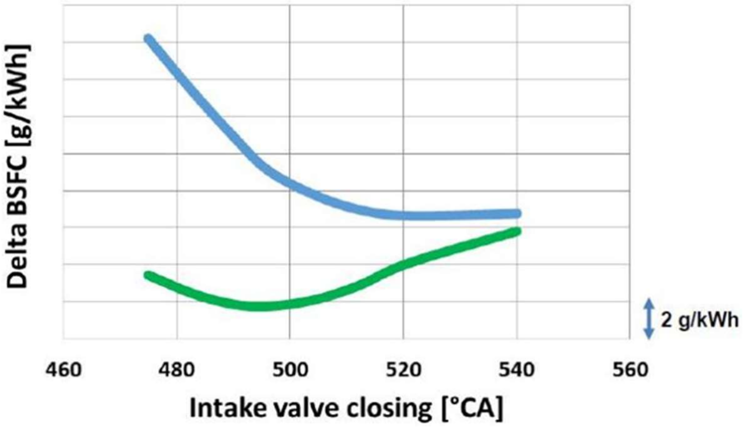

Figure 54: Change of the specific fuel consumption over intake valve closing angle for 2 turbocharger efficiencies ((blue η_{TC} = 54 %, green η_{TC} = 65 %), [Sams, 2017]

The overall potential from improved turbocharging combined with a Miller cycle and a BSFC-optimised injection timing is shown in Figure . If NOx limits will be reduced in future below EURO VI, most likely a fuel efficiency penalty has to be accepted due to higher EGR rates and energy demands for SCR heating since the NOx-fuel efficiency trade off will also exist in future engines. Reaching the targets shown as green elapse in Figure 55 may need longer development phases than until 2025.

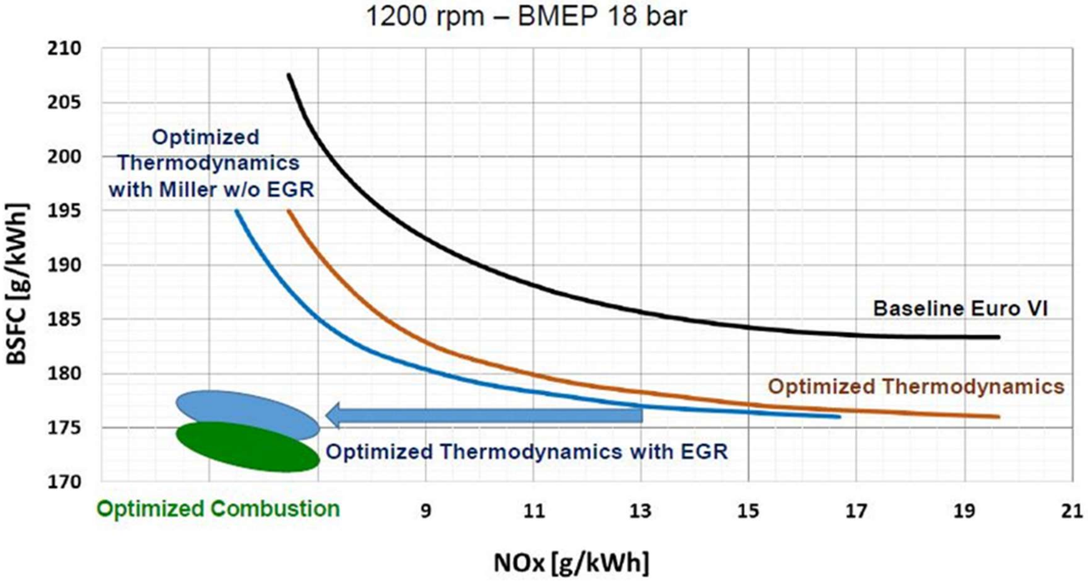

Figure 55: Potential from improved combustion with higher turbocharger efficiency, higher cylinder chare and Miller cycle for the BSFC vs. NOx trade off (Sams, 2017).

Table 60 summarises the assumptions used in the actual study and literature on effects from similar technology packages. The actual study assumes a Miller cycle with approx. 65% turbocharger efficiency, slightly further increased compression ratio but rather low EGR rates at standard engine operation points to be compatible with Package 2 (improved SCR).

Table 60: Effects from improved turbo charging and EGR.

Source	Comments	Change in BSFC compared to 2016 base engine
Used here	Miller cycle, 65% turbocharger efficiency, rather low EGR rates. Reduction assumed to be similar in all engine loads.	-4% (1)
[Graf et.al, 2017]	Improved turbo charging, higher compression ratio, increased the nozzle flow rate for faster combustion	3.5 to 4% (2)
[US-EPA, 2016]	Combination of variable intake valve closing timing (IVC), turbocharger efficiency and match improvements reported by Navistar	4%
[Delgado, 2017]	Increase in compression ratio and injection pressure; reduction in EGR rates and accessories' management	-2.2%

(1)…note that the good EURO VI engines have approx. 2% lower BSFC than the base engine which uses per definition no advanced technologies.
(2) compared to state of the art EURO VI engine

D.2.8.3 Package 2: improved SCR and optimised SCR heating methods

Usual SCR systems use Vanadium-, Copper-Zeolite- (Cu-Z) or Iron-zeolite- (Fe-Z) catalysts. Cu-Z SCRs reach from approx. 250°C to 350°C almost 100% NOx conversion. Vanadium and Fe-Z based systems need higher temperatures for best conversion (Figure 56). For NOx conversion the SCR needs Ammonia (NH_3), gained in standard applications from AdBlue, a mixture of urea and water, by hydrolysis and thermolysis in the hot exhaust gas stream. The conversion from urea to NH3 needs approx. more than 200°C. While SCR systems can store NH_3 necessary for several minutes of normal engine operation at low temperatures, the storage capacity decreases towards high SCR temperatures. Therefore SCR controllers are designed to keep the NH3 storage in the SCR on an average level for the actual temperature. High storage levels involve the risk of NH3 slip if the temperature increases, low levels involve the risk that not sufficient NH3 is available for possible operation times below 200°C where no urea can be fed.

For high conversion rates therefore optimum temperatures in the SCR have to be maintained. The temperature management becomes more difficult for SCR systems close to the engine since the temperature changes much faster there than in catalysts downstream where the exhaust pipe, the DOC and the DPF have a large thermal inertia and are damping temperature fluctuations.

A high NOx conversion allows the engine to be operated at the most fuel-efficient settings without exceeding tailpipe NOx limits. Under standard operation on highway this temperature range is usually met without heating demands. Critical situations are phases with cold SCR, i.e. the time after cold start, after downhill driving and in general at low load driving.

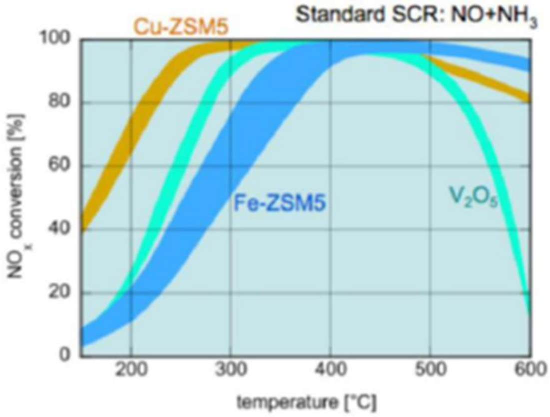

Figure 56: Typical NOx conversion efficiency from different SCR systems [Culbertson, 2015].

Since a high engine efficiency always result in a low exhaust gas temperature level (i.e. reduced losses through the exhaust mass flow), further decreases in the basic exhaust gas temperature are expected as main trend.
To heat the SCR a combination of technologies is possible:

- throttling the exhaust gas to increase charge change work
- and/or uncooled high pressure EGR with late fuel injection
- and/or early exhaust valve opening

can manage fast heat up of the exhaust gas system but heavily worsens the engine efficiency. Also cylinder deactivation at lower loads leads to higher exhaust gas temperatures combined with a reduction of fuel consumption at low load (18Nm) by 40%, e.g. [McCarthy, 2017].
In parallel, a second SCR could be mounted close to the engine which will reach necessary operation temperatures much faster than the downstream SCR. Disadvantage of a closed coupled SCR are a reduced NO_2 availability for passive DPF regeneration which results in more frequent active regeneration events. Active DPF regeneration also reduces the fuel efficiency of the engine due to necessary heating of the exhaust gas.

In addition, NH3 slip of the upstream SCR can react to N_2O in the DOC downstream. N_2O is limited in the US CO_2 regulation but not in Europe but still needs to be controlled for an overall GHG reduction. For lower N_2O formation, the closed coupled SCR could be fed with AdBlue only in phases where the downstream SCR has a temperature below the optimum efficiency area. The overall optimisation obviously is a balancing of energy needed to faster heat up the SCR versus the efficiency improvements which are possible when the SCR has his optimum operation temperature. For additional SCR certainly also the additional costs and the packaging are relevant.
Heating of the SCR is relevant already for actual engines. Effects of improvements in the heating strategy and in the SCR efficiency in general are:

a) Reduction of fuel needed for SCR heating. In the CO_2-engine certification, this effect mainly reduces the fuel consumption in the cold WHTC and consequently the “cold-hot emission balancing factor” (EU, 2017). During the fuel mapping procedure the exhaust gas temperature is sufficiently high to prevent heating demands.
b) Improvement of the fuel efficiency in all driving conditions since the engine settings can be further optimised for fuel efficiency at high SCR efficiency.

Figure 57 shows the exhaust gas before the SCR system simulated with the model PHEM for the WHTC with hot and cold start. Increased SCR temperatures would help mainly in the first 700 seconds of the test and in general in the urban driving conditions. Due to high rates of uncooled EGR, adjusted valve overlapping and also improved SCR designs the extra fuel consumption for heating could be reduced in the WHTC. In the VECTO engine map test procedure (FCMC) mainly the cool down of the SCR in the test points with lower torque could be reduced by these measures allowing a more fuel efficient setting of the combustion process.

The optimum balance of temporal applications of heating strategies – which will rather have fuel penalties - with the resulting increased SCR efficiencies and fuel benefits is expected to be an iterative process in engine optimisations which yet cannot be assessed in detail. The optimisation also benefits from the improved turbocharging and EGR systems defined in the engine package 1.

From results in a TUG research project and from literature the overall potential of this technology until 2025 was assessed to be approx. 2%. A detailed allocation of reduction potentials to WHTC cold start factor and to different engine map ranges was not possible with the resources available in the project.

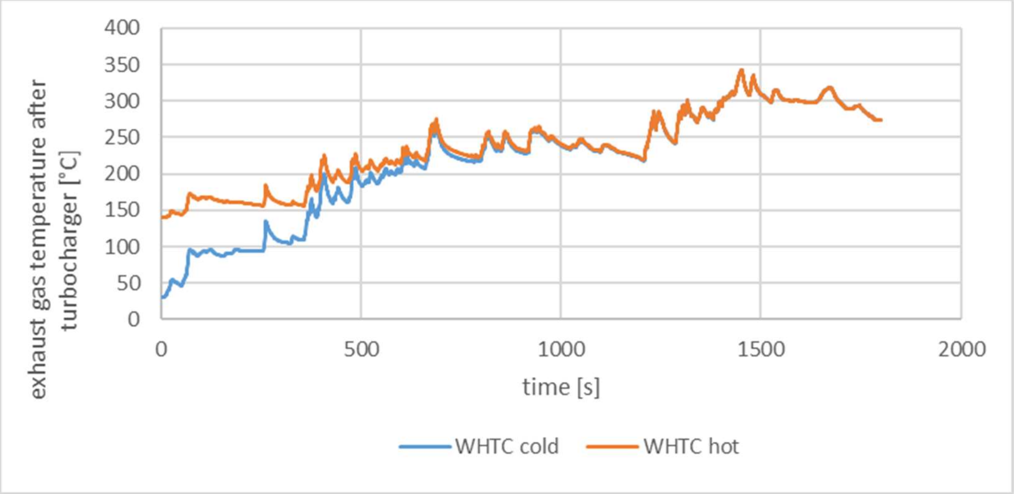

Figure 57: Exhaust gas temperature before SCR simulated for the base EURO VI engine in the WHTC (hot and cold start without engine heating technologies active).

Table 61 shows the technology effect used in the actual study compared to literature data.

Table 61: Effects from improved SCR and optimised SCR heating methods.

Source	Technology	Change in BSFC compared to 2016 base engine
Used here	Improved thermal control of the aftertreatment system.	-2% (1)
[US-EPA, 2016] according to report from Detroit Diesel	Reduced use of EGR, thinner wall DPF, improved SCR cell density, and catalyst material optimization	-2%
[ICCT, 2017]	Combined, aftertreatment improvements	2% to 4%

(1) includes effects from the “cold-hot emission balancing factor” also.

D.2.8.4 Package 3: Friction reduction and improved water and oil pumps

The friction coefficient at lubricated contacts depends on relative speed, normal load, oil viscosity, shape of contacting parts, roughness of contacting parts, temperature and material of contacting parts etc.. Since all moving parts cause friction, reducing friction during movement on one hand and reducing unnecessary movements on the other hand reduce losses. Thus the reduction of friction is an evolutionary process which is driven mainly by:

- Improving lube oils (reduced viskosity, usually characterised by the HTHS viskosity[26]): this effect is considered in package 4 separately and thus not included here.
- Hardware improvements (e.g. reduced friction in bearings, valve trains, and the piston-to-liner interface, demand controlled auxiliaries, etc.[27]). can improve efficiency

Effects from friction reduction technologies are based on literature review and own simulations. To address saving potentials from single parts to the total friction losses of HD engines, the percentages mentioned in Table 62 are used as average generic shares of losses in motoring. The values have been elaborated from different sources in [Mehta, 2017]. To the friction losses in motoring, the load dependent losses are added which are dominated by the work of the fuel high pressure pump.

Table 62: Contributions to total friction losses in motoring conditions used in the work based on data in [Wagner, 2014]

Component	@ motoring
Piston skirt	40%
Bearings	16%
Crankshaft bearing	15%
Oil pump	12%
Water pump	12%
Valve train	5%

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[26] Defined for oil temperature of 150°C and a shear rate of 106 s^{-1} to ensure lubrication also at high temperatures and high engine speeds

[27] Detailed technologies are e.g. optimised conicity of the cylinder,

To calculate corresponding fuel savings in the engine fuel map due to reductions in the friction, following approach was applied:

The fuel consumption due to a change in power demand of the base engine was described by a “Willans factor”. The Willans factor is gained from the fuel map of the engine at fixed engine speeds as shown in Figure for the base fuel map for the 325 kW engine used in this study. At a given engine speed the fuel flow can be approximated as linear equation from the effective engine power, equation (5-2). The Willans factor is the slope of the line (e.g. ~176 g/kWh for 1200 rpm speed in Figure). Increasing or reducing the engine power at this speed would change the fuel flow per kW accordingly. The Willans factor is different to the engine efficiency, since the engine efficiency includes also the fuel flow at zero power output, indicated as constant factor “D” in equation (5-2). The constant factor represents losses to be overcome by the internal engine work before any effective work is delivered at the crankshaft. The internal losses are mainly friction losses, power demand from pumps and load exchange work. With increasing engine speed the constant factor is increasing mainly due to higher losses from friction and fuel injection. Since the Willans factor is quite constant for the entire speed range, an average Willans factor is used here

$$\text{Fuelflow} = \text{D} + \text{WF} \times P_e \qquad \text{(5-2)}$$

With: WF .... average Willans factor of the base engine (175 g/kWh)
Pe .... effective engine power

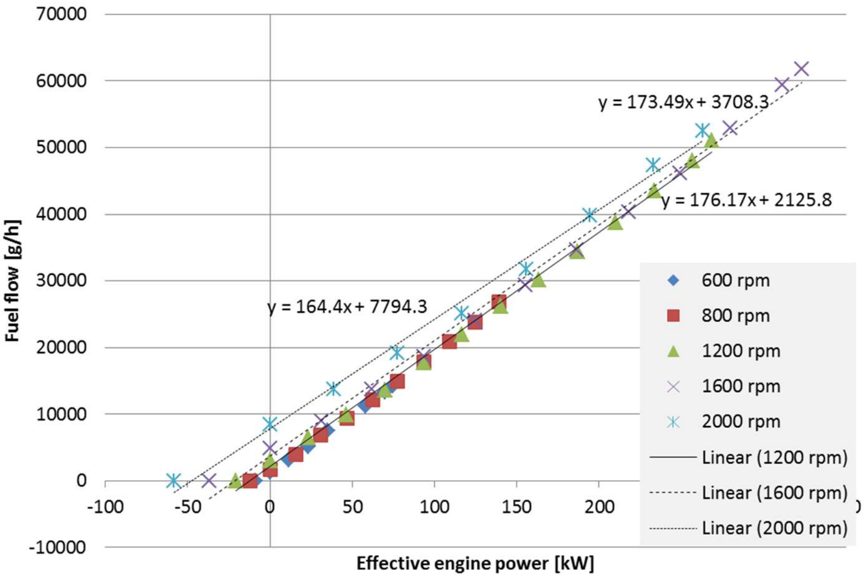

Figure 58: Willans lines for selected engine speeds in the base diesel engine (325 kW EU VI diesel).

With the average Willans factor changes in the friction losses are converted into changes in the fuel flow in the engine map. Therefore friction losses have to be converted into changes in the internal engine power or work.

Friction losses are in literature often given as FMEP (Friction mean effective pressure) or any other mean effective pressure or directly a corresponding fuel saving value is reported for reduced friction. The conversion of mean effective pressure to engine torque and finally to engine power uses the equations (5-3) and (5-4).

$$\mathrm{M} = \frac{V_h \times p_e \times 10^5}{4\pi} \qquad \textbf{(5-3)}$$

$$\mathrm{P} = (2 \times \pi \times \frac{n}{60} \times M) \times 0.001 \qquad \textbf{(5-4)}$$

With: M.............. torque, [Nm]
Vh .... displacement volume, [m³]
p_e .... mean effective pressure, [Pa]
P .... Power, [kW]
n............... engine speed, [rpm]

The overall friction losses from motoring (not fired) engine operation and the additional load dependent losses are expressed in simplified way by a linear equation (5-5) gained on the typical FMEPs. Consequently the related internal engine power (Pi) to overcome the internal friction losses can be expressed according to (5-6) and with the Willans factor the friction related fuel flow (FFf) according to (5-7).

$$\mathrm{FMEP\ [bar]} = (0.00064 \times \mathrm{n} + 0.51 \times \frac{M}{2100}) \qquad \textbf{(5-5)}$$

$$\mathrm{Pi\ [kW]} = \frac{V_h \times \mathrm{n}}{1200}(0.00064 \times \mathrm{n} + 0.51 \times \frac{M}{2100}) \qquad \textbf{(5-6)}$$

$$\mathrm{FFf\ [g/h]} = \mathrm{WF} \times \mathrm{Pi} \qquad \textbf{(5-7)}$$

With: FMEP....... Friction mean effective pressure, [bar]
Pi .... internal engine power to overcome friction losses, [kW]
FFf .... Fuel flow demand due to friction losses, [g/h]

Changes in fuel flow in the engine map due to reduced friction are calculated based on equation (5-7) using once the base FMEP values and once the reduced ones. The negative torque at the motoring curve of the improved engine map was reduced according to the reduced friction related torque losses. This method was used for package 3 and for package 4 (improved lube oils).
Technologies considered are based on literature reviews described in (Samkit, 2017) and include improved designs of cylinder and piston for friction reduction by optimising conicity under operating pressure and temperature, a demand controlled cooling pump and switching to indirect cooling systems.

For a package of a variable speed water pump and variable displacement oil pump combined with optimised cylinder, piston and bearings the fuel consumption reductions shown in Table have been calculated.
Table 63 lists also results found in literature for friction reduction technologies for comparison.

Table 63: Overview on literature data for friction reducing engine technologies.

Technology	Friction reduction [%]	Fuel consumption reduction [%]	Source
Optimised conicity of cylinder + piston	-15% in crankshaft drive		[Wichtl, 2017
Unspecified FMEP improvements		1.4% in long haul 2.3% in reg. delivery	[Norris, 2017]
Variable displacement oil pumps		1% in long haul 2% in reg. delivery	[Norris, 2017]
Variable displacement coolant water pumps		0.5% in long haul 0.8% in reg. delivery	[Norris, 2017]
Bypass oil cooler		0.2% in long haul 0.5% in reg. delivery	[Norris, 2017]
Reduced bearing friction, reduced piston and ring friction, and unspecified lube oil pump improvements		<2%	[US-EPA, 2016] referring to report from Navistart
Friction reduction, with 0.5 percent coming from improved water pump efficiency		2%	[US-EPA, 2016] referring to report from Detroit Diesel
variable speed water pump and variable displacement oil pump		0.9%	[US-EPA, 2016] referring to report from Navistart
Optimised cylinder, piston and crankcase and variable oil and water pumps	-12% Avg. -10%(1)		used here as input for engine map fuel flow calculation
Optimised cylinder, piston, crankcase and variable oil and water pumps		-2.0% long haul, 10% load -1.5% long haul, ref. load -1.4% reg. delivery, ref. load	Results from VECTO in actual study

(1)…lower reduction at low engine speed and full load since there full cooling demand remains, higher reductions towards low torque due to reduction of coolant and oil flows, also higher reduction toward high engine speeds due to higher coolant flow rates than needed with fixed link of pump rpm to engine rpm.

D.2.8.5 Package 4: Improved lubricants for the engine

The lube oil properties relevant for fuel savings are mainly a reduced viscosity, characterised by the HTHS viscosity which was assumed here to drop to approximately 2.5 from today's values above 3.5[28]. Lube oils with a HTHS viscosity below 3.5 need adjusted engine technology to keep the durability and to make use of the low viscosity to reduce fuel consumption. By using low viscosity oil also the work demand of the oil pump is assumed to decrease. Overall 12% reduction of friction losses was assumed from the optimised lube oil and engine combination.

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[28] See: https://commercial.lubrizoladditives360.com/high-temperature-high-shear-viscosity-of-engine-oils/

The change in the VECTO fuel flow map due to reduced friction was simulated as explained already before for the friction loss reduction in package 3. The engine map with the reduced friction due to the future lube oil was then used for VECTO simulations of all combinations of vehicle, loading and mission profiles relevant for the CO_2 certification.

Table 64: Literature data on effects of low viscosity oil on friction losses and fuel consumption from engines.

Technology	Fuel consumption reduction [%]	Source
HTHS viscosity ~2.5	1,5%	internal expert view
Low viscosity oil	1% in long haul 2.0 urD. & Reg. delivery%	[Norris, 2017]
Optimised cylinder, piston, crankcase and variable oil and water pumps	1.1% long haul, 10% load 0.9% long haul, ref. load 0.8% reg. delivery, ref. load	Results from VECTO in actual study

D.2.8.6 Package 5: Waste heat recovery

The waste heat recovery system considered here is a so called “organic Rankine Cycle (ORC). In the ORC, the boiler (Figure) is heated by the exhaust gas of the vehicle, waste heat from EGR cooling was not considered here to keep the system simple for a possible 2025 serial production. The integration in the exhaust gas line needs to be done after the after treatment system to maintain a sufficient temperature at the catalysts. The heated working fluid is then expanded in an expander (e.g. turbine, a scroll or a piston expander) to deliver mechanical work. The fluid is then cooled to go back to the liquid phase and is then brought on the high-pressure level again by a pump. Then the circuit starts again. Turbine expanders have higher efficiency than scroll or piston expanders, [Huscher, 2017], but are assumed to be more costly.

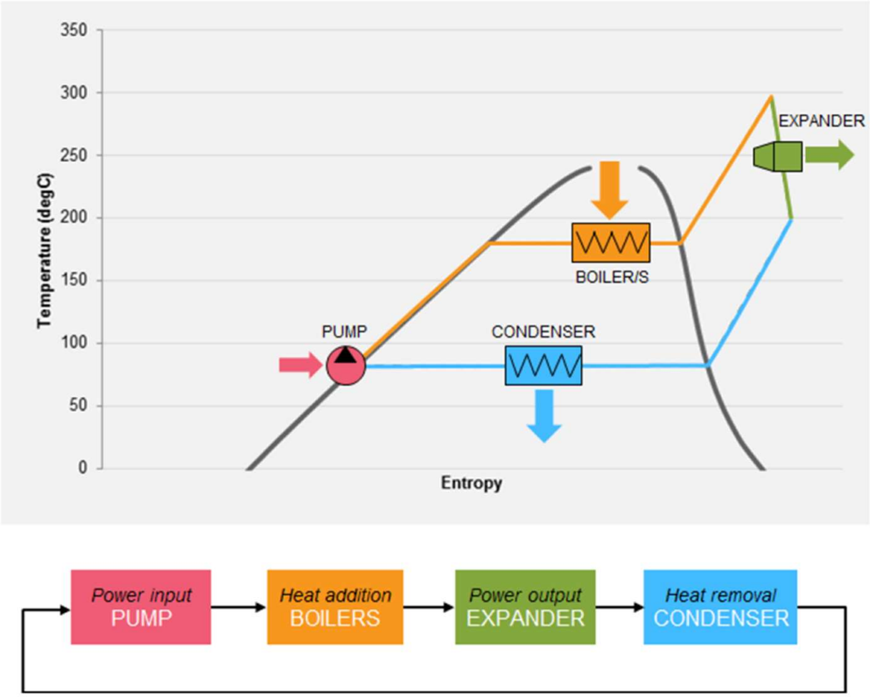

Figure 59: Schematic picture of the T-S diagram of the organic Rankine cycle [Huscher, 2017].

The overall efficiency of the ORC system depends on the temperature difference between boiler and condenser and thus on the exhaust gas temperature. For the actual study, the fluid temperature level at the expander entrance was simulated with the model PHEM for the VECTO fuel map test cycle (Figure 60).

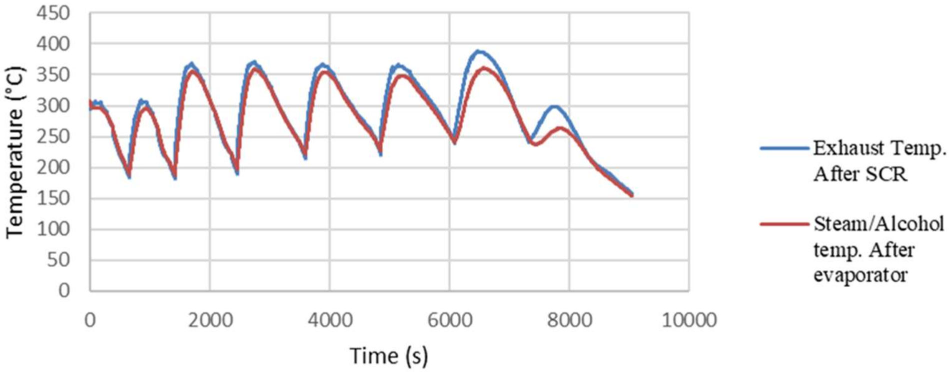

Figure 60: Simulated exhaust temperature after SCR and fluid temperature after the ORC evaporator for the VECTO engine map test cycle.

The efficiency of the ORC as function of the steam temperatures at the expander entry was gained from literature and finally the ORC efficiency was defined by a characteristic line as function of the actual exhaust gas temperature (Figure 61).

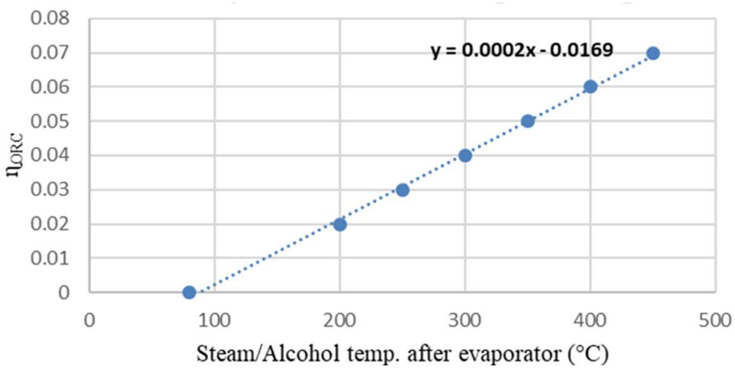

Figure 61: Characteristic line for the ORC efficiency vs the exhaust temperature at the heat exchanger (boiler).

The power provided from ORC system was calculated from the exhaust gas enthalpy and the ORC efficiency:

$$\dot{\mathrm{H}}_{\mathrm{steam-alcohol}} = \dot{m}_{exhaust} * \mathrm{C}_{\mathrm{p,air}}(\mathrm{t}_{\mathrm{steam-alcohol}} - t_{coolant}) \tag{5-8}$$

$$\mathrm{P}_{\mathrm{ORC}} = \dot{\mathrm{H}}_{\mathrm{steam-alcohol}} * \eta_{\mathrm{ORC}} \tag{5-9}$$

Where:

$\dot{\mathrm{H}}_{\mathrm{steam-alcohol}}$	exhaust Enthalpy flow of steam/alcohol, [kW]
$\dot{m}_{\mathrm{exhaut}}$	exhaust mass flow rate, [g/s]
C_p	specific heat at constant pressure, [kJ/kgk]
$t_{\mathrm{steam\text{-}alcohol}}$	temperature of steam/alcohol after evaporator (°C)
t_{coolant}	Coolant temperature (here set to 80°C)
P_{ORC}	Power derived from ORC, [kW]
η_{ORC}	Efficiency of ORC, [-]

The VECTO engine map test cycle has been simulated as defined in the actual regulation (2017/2400 from 12.12.2017). The test cycle changes load and engine speed at 95 second intervals.

The first 55 seconds is the stabilization period, followed by 30 secs of recording. The average power output of the ORC during the 30 seconds recording phase was taken into consideration. As a simplification, this power was added to the base fuel map of the EURO VI engine at given fuel flow of the base engine map. Then the original VECTO map grid was re-interpolated from this “ORC map” since no change in the engine power was assumed for this technology[29]. The literature used and details of the simulation method are described in (Samkit, 2017).

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[29] An increase of engine power would lead to higher accelerations and higher average cycle speeds in the VECTO simulation which would reduce the fuel saving potential from the waste heat recovery system due tot he higher driving resistances.

In reality, rather a conversion of the ORC power output to electric energy is expected, especially if a 48V board net is available in future. The electric generator from a WHR system could be mounted directly on the expander to avoid transmission losses.

The advantage of an electric system is mainly the higher flexibility in the energy use. E.g. the thermal inertia of the exhaust system would provide power from the waste heat recovery system after uphill driving also at the beginning of the consecutive downhill passage. In this driving situation however, no extra power is needed and bypass systems for the expander in the ORC would be needed. Since VECTO does yet not provide a detailed simulation of the electric system of the vehicles, the work around with direct power use in the map test was necessary. For a later implementation in the VECTO system, the limitations of mechanical power usability should be considered. Thus, a test method capable also of electric power generation from the waste heat recovery systems should be elaborated. Ideally also the limits from mechanical power usage in real driving should be considered in the method to be developed since the engine fuel map test would not show up these limits. If the WHTC correction factors are appropriate to correct for the limitations is open yet.

Table 65 summarises the WHR fuel saving potential from literature an the figures as elaborated in this study.

Table 65: Fuel saving potential from Waste Heat Recovery (WHR) Systems.

Technology	Fuel consumption reduction [%]	Source
Waste heat recovery system using an organic Rankine bottoming cycle instead of turbo compounding	4.1%	[Delgado, 2017]
Waste heat recovery with an ORC	3.3% in long haul operation for group 5	[Kies, 2018]
Waste heat recovery with an ORC	2.1% long haul, 10% load 2.1% long haul, ref. load 2.0% reg. delivery, ref. load	Results from VECTO in actual study

D.2.8.7 Package 6: Downspeeding (combined with DCT optimisations)

Down-speeding of the engine is simulated here by a change to a lower axle transmission to reduce engine speed at the highway velocity of 83 km/h in the VECTO long haul cycle. The transmission is adjusted to run at this speed at 1050 rpm, this results as a reduction of the axle ratio from 2.640 to 2.346. which is around the sweet spot of the generic EURO VI base engine, i.e. the area with the highest fuel efficiency. The engine full load curve needs to be increased, to ensure that the engine power is sufficient for the given driving cycle (Figure 62).

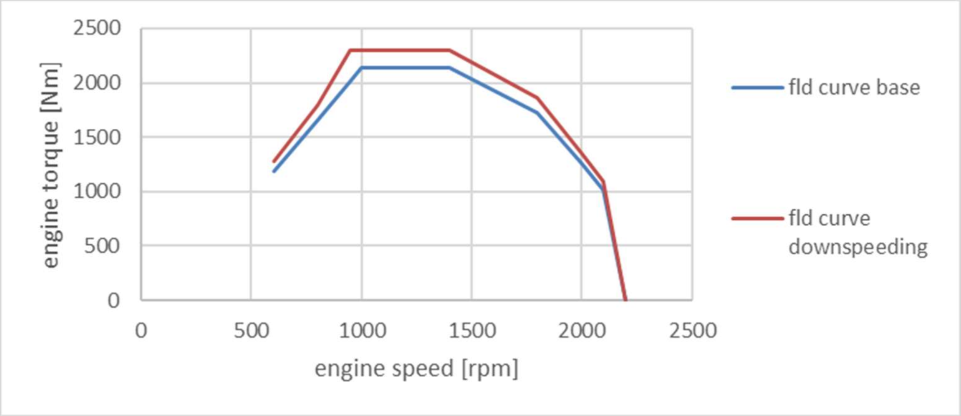

Figure 62: Optimized full load curve in case of down-speeding.

In the generic Euro VI base engine map the sweet spot is located in the area at about 1200rpm, so there is no benefit for the down-speeding technology at the simulation. The engine air handling and combustion system, as a result of down-speeding, must be re-optimized to accommodate a typical higher peak cylinder pressure rise and also the drive train needs to be adjusted to handle the higher torques at the reduced rotational speeds without durability issues. For the simulation of the benefit of these technology an optimized map, which has the sweet spot at lower engine speed, was generated.
For long haul driving of a group 5 vehicle VECTO simulations predict some 0.37% fuel consumption reduction in reference load conditions and 1.2% in low payload conditions.

D.2.9 Electric hybrid vehicles

Electric hybrid vehicles have an electric engine in addition to the internal combustion engine. Depending on the arrangement of combustion engine, transmission and electric engine the HEV architecture is labelled as parallel, serial or power split layout. The assessment of reduction potentials in this study is based on a parallel hybrid layout, which is seen as the most common type of electric hybridisations for HDV (see Figure 63).

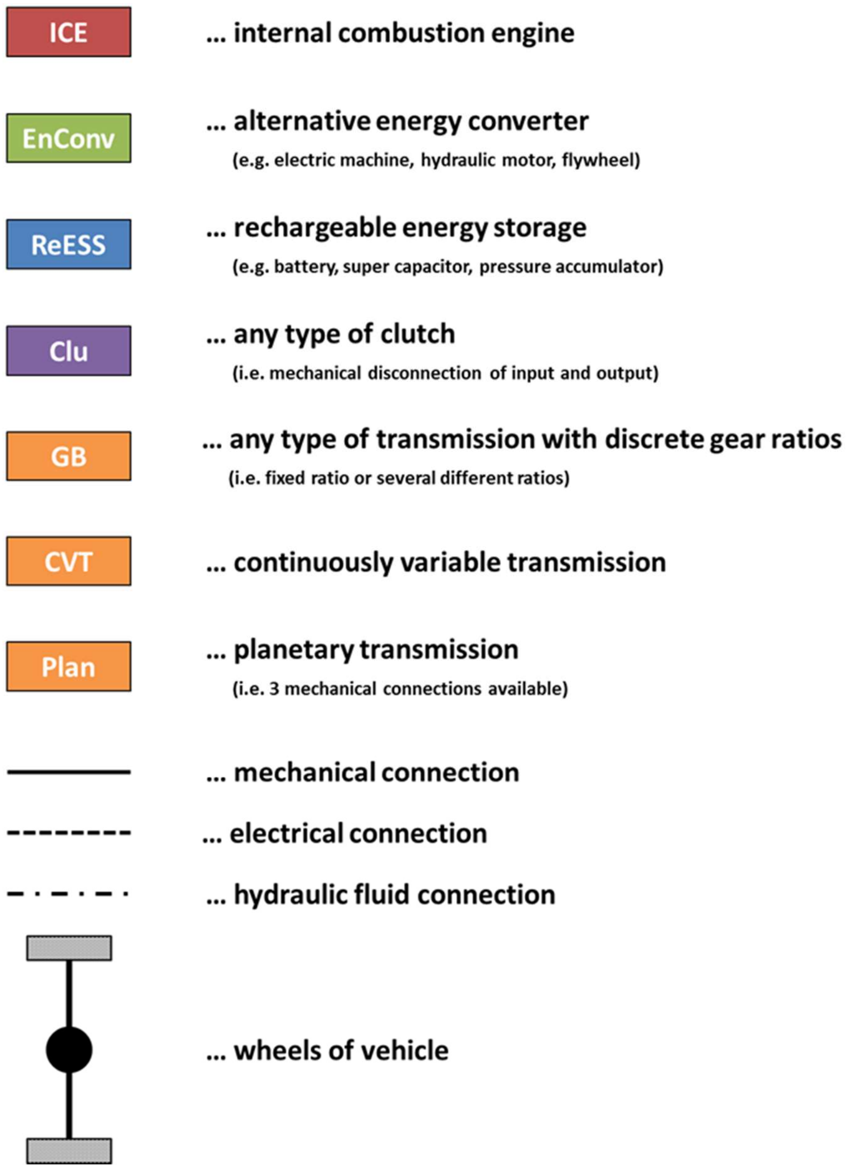

Figure 63: Layout parallel hybrid (source: IVT).

As VECTO is actually not capable to simulate xEV vehicles, the reduction potentials from hybridisation was simulated with the emission model PHEM developed at TUG. Analysed degrees of hybridisation were:

- **Mild hybridisation** using a 10kW electric engine implemented into a 48V electric system and equipped with a 0.5 kWh battery
- **Full hybridisation** with an 80 kW electric engine implemented into a 700 V electric system and equipped with a 6 kWh battery

Configuration of the full hybrid system regarding power of e-machine, energy capacity of the battery and operating strategy was selected based on sensitivity analysis performed with PHEM for different combinations of e-machines (20-100kW), battery capacities (1-10kWh) and different

HEV control characteristics. The configuration which gave lowest fuel consumption for the group 5 vehicle was selected.
Simulation runs for the full hybrid vehicle were done twice, each once for 2016 and for 2025 vehicle technology. As the 2025 vehicle has lower driving resistances than 2016 technology, more kinetic energy can be re-used by the hybrid propulsion system resulting in higher FC reduction potentials.
Table 66 summarises the fuel saving potential from HEV technology as assessed in this study.

Table 66: Fuel saving potential from HEV technology.

HEV Techno-logy	Pay-load	Group 4		Group 5		Group 9		Group 10	
		Long haul	Reg. Del.	Long haul	Reg. Del.	Long haul	Reg. Del.	Long haul	Reg. Del.
Mild Hybrid 48V (2016 vehicle)	represent.	-0.36%	-1.30%	-0.43%	-1.15%	-0.39%	-1.33%	-0.42%	-1.15%
	low	-0.34%	-1.25%	-0.44%	-1.24%	-0.34%	-1.24%	-0.44%	-1.24%
Full Hybrid (2016 vehicle technology)	represent.	-1.19%	-4.27%	-1.98%	-5.87%	-1.89%	-5.72%	-2.42%	-6.20%
	low	-0.22%	-3.00%	-0.47%	-5.47%	-0.43%	-3.09%	-0.71%	-5.51%
Full Hybrid (2025 vehicle technology)	represent.	-2.82%	-7.90%	-4.02%	-7.77%	-2.89%	-7.77%	-4.21%	-7.84%
	low	-0.72%	-5.30%	-3.19%	-7.53%	-1.22%	-7.02%	-3.19%	-7.62%

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Annex E Basic cost information

This annex E provides the basic cost information used to reach the costs as mentioned in the main text of Chapter 4 (Task 3). First, the correction factors for calculating the various results will be presented in Section E.1. These correction factors include US inflation rates, EU inflation rates and the US dollar – Euro exchange rates.

From Section E.2 onwards, the final costs will be presented for each technology for each truck group. The various costs found in the literature, based on stakeholder consultations and own research will also be presented, for each technology and each vehicle group. The final cost that was chosen will be highlighted.

E.1 Correction factors

Table 67 shows the steps taken to transform any cost value found in the literature to 2015€. As outlined in section 4.3, the methodology follows the steps of first correcting for inflation until 2015 in the original currency the cost is given in. After that the cost is then converted to 2015€ using the US Dollar – Euro exchange rate where necessary. Any potential indirect cost factors or learning curve corrections for the year 2025 that have not been taken into account into the creation of the original costs will only take place after the cost value has been translated to 2015€.

Table 67: Correction factors used to reach harmonised costs

	US inflation rates	**EU inflation rates**	**US Dollar – Euro exchange rate**
2011		2.70 %	
2012	2.07 %	2.50 %	
2013	1.46 %	1.30 %	
2014	1.62 %	0.40 %	
2015	0.12 %	0.00 %	0.9019

Source: OECD CPI, ECB

E.2 Aerodynamics

E.2.1 Roof spoiler (plus side flaps)

There was relatively little variation observed in the literature. The costs from Ricardo 2017 were chosen for all groups as the study is recent, extensive and of high quality. The same cost value was used for all four groups of trucks.

Table 68: Roof spoiler costs for all groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
TIAX	€ 961	2010 €		TIAX/NAS study (2009)	
Ricardo 2011	€ 1,180	2010 €		Ricardo estimates based on public domain information	
Ricardo 2017	€ 1,000	2015 €		Consultation with manufacturers	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo 2017	No	No	No	No	**€ 1,000**

E.2.2 Side and underbody panels at truck chassis

There was some variation observed in the literature. The costs from the report by the NHTSA was chosen. A range was provided with the costs, of which an average was taken. This value was considered representative for a group 5/10 truck. The correction that was applied to reach the value for group 4/9 trucks was carried out based on the floor surface area of the truck. Group 4/9 trucks were assumed to have a floor area equal to twice the size of the group 5/10 trucks (for more detail see Annex D). Therefore the costs were calculated for group 5/10 and subsequently doubled for group 4/9 trucks.

Group 4/9

Table 69: Side and underbody panel costs for a group 4/9 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
TIAX	€ 2,306	2010 €		TIAX/NAS study (2009)	
NHTSA (2015)	$ 1,595-1,750	2011 $		Own modelling. Range provided, average value of range was taken as representative for Class 5/10. For a Class 4/9 that value was doubled.	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
NHTSA (2015)	No	No	Yes	Yes	**€ 3,079**

Group 5/10

Table 70: Side and underbody panel costs for a group 5/10 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
TIAX	€ 2,306	2010 €		TIAX/NAS study (2009)	
US Dept. of Transport	€ 1,595-1,750	2011 $		Own modelling. Range provided, average value of range was taken as representative for Class 5/10..	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
US Dept. of Transport	No	No	Yes	Yes	**€ 1,539**

E.2.3 Side and underbody panels at trailer chassis

This technology explicitly refers to tractor-trailer combinations. Therefore, this technology is not considered for class 4 or 9 trucks. In researching these costs, we came across a wide variety of costs. Therefore, we decided to consult a manufacturer of the side panels, who gave an estimate of what this technology costs now, and the anticipated price developments in the future. Costs are identical for both class 5 and class 10 trucks.

Table 71: Side and underbody panels at trailer chassis for Class 5/10 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2011	€ 3,500	2010 €		Ricardo expert estimate	
Dünnebeil et al. 2015	€ 4,800-5,200	2015 €		Industry expert	
NHTSA 2015	$ 843-925	2011 $		Own modelling	
Own research	€ 2,000	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 2,000**

E.2.4 Aerodynamic mud flaps

There was some variation observed in the literature. The costs from Ricardo 2011 were chosen, and scaled up to the vehicle groups using the number of tyres on the truck (see Annex D).

Table 72: Aerodynamic mud flaps for a group 4 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2011	€ 14 per tyre	2010 €		Ricardo research	
TNO TvdT 2013	€ 125 per axle	2013 €		Own assumption/research	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2011	No	Yes - Low	Yes	No	**€ 54**

Table 73: Aerodynamic mud flaps for a group 5 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2011	€ 14 per tyre	2010 €		Ricardo research	
TNO TvdT 2013	€ 125 per axle	2013 €		Own assumption/research	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2011	No	Yes - Low	Yes	No	**€ 135**

Table 74: Aerodynamic mud flaps for a group 9 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2011	€ 14 per tyre	2010 €		Ricardo research	
TNO TvdT 2013	€ 125 per axle	2013 €		Own assumption/research	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2011	No	Yes - Low	Yes	No	**€ 81**

Table 75: Aerodynamic mud flaps for a group 10 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2011	€ 14 per tyre	2010 €		Ricardo research	
TNO TvdT 2013	€ 125 per axle	2013 €		Own assumption/research	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2011	No	Yes - Low	Yes	No	**€ 162**

E.2.5 Rear view cameras instead of mirrors

This was a technology which wasn’t found in the literature at all. Some online research was conducted, resulting in the costs as illustrated below. It was assumed the costs for this technology will be the same for all truck groups.

Table 76: Rear view cameras for all groups of HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Own research	€ 250	2015 €		Online research	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	Yes - Low	No	No	**€ 250**

E.2.6 Redesign, longer and rounded vehicle front

Due to the newness of this technology, we decided to consult stakeholders on top of the literature review. As anticipated, the value we came across in the literature is a very low estimate of this cost, and is unrealistic according to experts. Redesigning the vehicle front requires new EU legislation but most of all, redesigning of items in the engine due space limitations, new safety tests, certification, etc. If this process is not synchronised with the launch of a new model of a HDV, the costs of the redesign are very high. We assume a redesign of the vehicle front that is synchronised with the launch of a new model of an HDV. Therefore, we decided to use our own educated guess in combination with input from stakeholders. The costs are assumed to be the same for all vehicle groups.

Table 77: Redesign of vehicle front for all groups of HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Own research	€ 2,000	2015 €		Stakeholder consultation	
Invalid source specified.	€ 400	2012 €		Own estimate	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 2,000**

E.2.7 Boat tail short

Only one reference to costs for this technology was found in the literature, therefore, a stakeholder was contacted. Costs are identical for all truck groups.

Table 78: Short boat tail for all groups of HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 532-847	2015 €		Based on ICCT 2014 and adjusted	
Own research	€ 750	2015 €		Expert consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 750**

E.2.8 Boat tail long

Although multiple values were found in the literature, a stakeholder consultation took place anyways. This revealed that the costs are considered identical for all types of trucks.

Table 79: Long boat tail for all groups of HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 760 – 1,210	2015 €		Based on ICCT 2014 and adjusted	
TIAX 2011	€ 1,345	2010 €		Based on TIAX/NAS (2009)	
NHTSA 2015	$ 1,094 – 1,200	2011 $		Own modelling	
Own research	€ 1,000	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 1,000**

E.3 Tyres

E.3.1 Low rolling resistance tyres on truck/tractor

Despite being prevalent in the literature, we decided to consult stakeholders because there is an ongoing debate about the additional costs of LRR tyres. One stakeholder told us that LRR tyres are currently already offered at prices equal to that of ‘normal’ tyres. According to him, the biggest barrier to adoption of these tyres is lack of acceptance by the truck drivers (due to reduced grip), not the price. Another stakeholder informed us that there are a lot of R&D expenses associated with LRR tyres, therefore suggested we use an incremental price of € 35 (10% of average truck tyre price). Costs were scaled in accordance with the number of tyres (see Annex D). The ‘cost as mentioned in original source’ is presented as the additional costs of one low rolling resistance tyre compared to a ‘normal’ tyre.

Final costs are presented as the total costs for the truck/tractor, for one complete set of tyres. It should be noted that, in contrast to the other technologies presented in this annex, the costs for this technology does not equal the cost over the lifetime of the vehicle. This is because the lifetime of the tyres is dependent on the annual mileage. The costs presented below are costs for the lifetime of one complete set of tyres for the truck.

Table 80: Low rolling resistance tyres on truck/tractor for group 4/5 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 20	2015 €		Based on Lanxess (2013) and TIAX (2009)	
NHTSA 2015	$ 27 – 40.50	2011 $		Own modelling	
EPA & NHTSA 2016	$ 17 - 20	2013 $		Own research	
Own research	€ 0	2015 €		Stakeholder consultation	
Own research	€ 0-35	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 210**

Table 81: Low rolling resistance tyres on truck/tractor for group 9/10 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 20	2015 €		Based on Lanxess (2013) and TIAX (2009)	
NHTSA 2015	$ 27 – 40.50	2011 $		Own modelling	
EPA & NHTSA 2016	$ 17 - 20	2013 $		Own research	
Own research	€ 0	2015 €		Stakeholder consultation	
Own research	€ 35	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 350**

E.3.2 Low rolling resistance tyres on truck/tractor + trailer

In comparison with the measure above, the costs for this measure do not change for trucks that do not have a trailer (i.e. group 4 and 9). This measure is widely investigated in the literature. The costs as mentioned in the source refer to costs per tyre, with the exception of Ricardo 2011 & Ricardo 2017, where prices are for the entire vehicle. Total costs were calculated based on costs per tyre and subsequently scaled according to the number of tyres per truck (see Annex D).

Table 82: Low rolling resistance tyres on truck/tractor + trailer for group 4 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 20	2015 €		Based on Lanxess (2013) and TIAX (2009)	
NHTSA 2015	\$ 27 – 40.50	2011 \$		Own modelling	
EPA & NHTSA 2016	\$ 17 - 20	2013 \$		Own research	
Ricardo 2011	€ 350[30]	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 420[25]	2015 €		Ricardo expert estimate	
TNO TvdT	€ 0	2013 €		Own assumption/modelling	
Own research	€ 0	2015 €		Stakeholder consultation	
Own research	€ 35	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 210**

Table 83: Low rolling resistance tyres on truck/tractor + trailer for group 5 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 20	2015 €		Based on Lanxess (2013) and TIAX (2009)	
NHTSA 2015	\$ 27 – 40.50	2011 \$		Own modelling	
EPA & NHTSA 2016	\$ 17 - 20	2013 \$		Own research	
Ricardo 2011	€ 350[31]	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 420[26]	2015 €		Ricardo expert estimate	
TNO TvdT	€ 0	2013 €		Own assumption/modelling	
Own research	€ 0	2015 €		Stakeholder consultation	
Own research	€ 35	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 420**

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[30] These are the costs for the entire vehicle. Other sources mention the costs per tyre.

[31] These are the costs for the entire vehicle. Other sources mention the costs per tyre.

Table 84: Low rolling resistance tyres on truck/tractor + trailer for group 9 HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
Dünnebeil et al. 2015	€ 20	2015 €		Based on Lanxess (2013) and TIAX (2009)	
NHTSA 2015	$ 27 – 40.50	2011 $		Own modelling	
EPA & NHTSA 2016	$ 17 - 20	2013 $		Own research	
Ricardo 2011	€ 350[32]	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 420[27]	2015 €		Ricardo expert estimate	
TNO TvdT 2013	€ 0	2013 €		Own assumption/modelling	
Own research	€ 0	2015 €		Stakeholder consultation	
Own research	€ 35	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 350**

Table 85: Low rolling resistance tyres on truck/tractor + trailer for group 10 HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
Dünnebeil et al. 2015	€ 20	2015 €		Based on Lanxess (2013) and TIAX (2009)	
NHTSA 2015	$ 27 – 40.50	2011 $		Own modelling	
EPA & NHTSA 2016	$ 17 - 20	2013 $		Own research	
Ricardo 2011	€ 350[33]	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 420[28]	2015 €		Ricardo expert estimate	
TNO TvdT 2013	€ 0	2013 €		Own assumption/modelling	
Own research	€ 0	2015 €		Stakeholder consultation	
Own research	€ 35	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 560**

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[32] These are the costs for the entire vehicle. Other sources mention the costs per tyre.

[33] These are the costs for the entire vehicle. Other sources mention the costs per tyre.

E.3.3 Tyre pressure monitoring system (TPMS) on truck

There was some variation observed in the literature. The costs from TNO 2013 were chosen, as it was a specific study focussing on TPMS.

Table 86: TPMS on truck for all groups of HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
TNO TvdT 2013	€ 450	2013 €		Own assumption/research	
TNO 2013	€ 185	2013 €		Questionnaire among TPMS suppliers and other stakeholders	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
TNO 2013	No	Yes - medium	Yes	No	**€ 149**

E.3.4 Tyre pressure monitoring system (TPMS) on truck and trailer

For vehicles that do not have a trailer (group 4/9) the cost value will be identical to the value in in the section above. For the tractor-trailer combinations a significant range of costs was found in the literature, ranging from € 338 to over € 1,000. It was chosen to use the cost values from a study specifically looking at TPMS (TNO, 2013).

Table 87: TPMS on truck for group 4/9 HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
TNO TvdT 2013	€ 450	2013 €		Own assumption/research	
TNO 2013	€ 185	2013 €		Questionnaire among TPMS suppliers and other stakeholders	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
TNO 2013	No	Yes - medium	Yes	No	**€ 149**

Table 88: TPMS on truck and trailer for group 5/10 of HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
TNO TvdT 2013	€ 1,000	2013 €		Own assumption/research	
TNO 2013	€ 338	2013 €		Questionnaire among TPMS suppliers and other stakeholders	
Ricardo 2017	€ 475	2015 €		Based on EPA & NHTSA 2016 and converted to European situation	
US Dept. Trans	$ 1,041 – 1,142	2011 $		Own modelling	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
TNO 2013	No	Yes - medium	Yes	No	**€ 271**

E.3.5 Automated tyre inflation systems (ATIS) on truck

The wide range of costs found in the literature was disconcerting, therefore stakeholders were contacted. The cost information provided was given for ATIS on the entire vehicle (tractor and trailer). Using an adjustment factor, the costs for ATIS on the truck only resulted in 80% of the costs of ATIS on the entire vehicle (see next section).

Table 89: ATIS on truck for all groups of HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
EPA & NHTSA 2016	$ 707	2013 $		Own modelling	
TIAX 2011	€ 3,459	2010 €		Based on TIAX/NAS (2009)	
Own research	€ 1,080	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 1,080**

E.3.6 Automated tyre inflation systems (ATIS) on truck and trailer

Although a significant spread of cost estimates was found in the literature, most of the higher estimates were found in earlier research. More recent research finds significantly lower cost estimates. Stakeholder consultation was conducted.

Table 90: ATIS on entire vehicle for group 4/9 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
EPA & NHTSA 2015	$ 707	2013 $		Own modelling	
TIAX 2011	€ 3,459	2010 €		Based on TIAX/NAS (2009)	
Own research	€ 1,080	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 1,080**

Table 91: ATIS on entire vehicle for group 5/10 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
EPA & NHTSA 2016	$ 1,202	2013 $		Own modelling	
TIAX 2011	€ 3,728	2010 €		Based on TIAX/NAS (2009)	
Ricardo 2011	€ 11,790	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 746	2015 €		Based on EPA & NHTSA 2016 and converted to European situation	
Own research	€ 1,350	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 1,350**

E.3.7 Wide base single tyres

This technology works by replacing two ‘normal’ tyres by one wide base tyre on driver axles. The ranges found in the literature all suggest this technology is more expensive than the conventional two tyre technology used. However, stakeholder consultation provided valuable information. The single tyre takes up less space than two conventional ones, freeing up potentially valuable storage space (e.g. for batteries in future hybrid trucks). It was also found that such wide base single tyres have been around for quite some time. The technology is therefore relatively mature, and the major issue is stakeholder acceptance. The stakeholder argued that, on average, the costs are 5% less expensive for one wide base single tyre, compared to two ‘normal’ tyres. It was assumed that normal tyres cost, on average, € 350.

However, the literature suggests one wide base single tyre costs more than two normal tyres. To balance this, we chose to use prices where one single wide base tyre was as expensive as two normal tyres. The total costs were scaled according to the number of driver axles.

Table 92: Wide base single tyres for group 4/5 HDV

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
TIAX 2011	€ 346	2010 €		Based on TIAX/NAS (2009)	
Ricardo 2011	€ 825	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 346	2015 €		Ricardo expert estimate	
Dünnebeil et al 2015	€ 660	2015 €		Based on NESCCAF 2009 & TIAX/NAS 2009	
NHTSA 2015	$ 128 - 141	2011 $		Own modelling	
Own research	- € 35-70	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 0**

E.4 Mass

The mass reduction measures are separated into measures for the truck/tractor only, and measures for the entire vehicle (tractor-trailer). Furthermore, two measures are generally identified. Mass reduction I represents a 5% reduction in mass. Mass reduction II represents a 10% reduction in mass. For vehicle reference weights, please see Annex B.

E.4.1 Mass reduction chassis (truck/tractor) I

Although light weighting is a measure frequently investigated in the literature, we opted to use the values from Ricardo's study specifically dedicated to light weighting. On the basis of Ricardo's values, we interpolated the costs per kilogram for all different percentages in weight reductions.

Table 93: **Mass reduction chassis (truck/tractor) I for group 4/9 HDV**

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2015	5% reduction against € 1.91 per kg	2014 €		The precise values were interpolated on the basis of Ricardo's light weighting study.	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Final source of cost chosen**	**Correction for indirect costs needed**
Ricardo-AEA 2015	No	Yes - Medium	Yes	No	**€ 471**

Table 94: **Mass reduction chassis (truck/tractor) I for group 5/10 HDV**

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo-AEA 2015	5% reduction against € 3.75 per kg	2014 €		The precise values were interpolated on the basis of Ricardo's light weighting study.	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2015	No	Yes - Medium	Yes	No	**€ 1,124**

E.4.2 Mass reduction chassis (truck/tractor) II

to the previous section, only accounting the next 5% of the original mass reduction. Mass reduction I and II can thus be added together.

Table 95: Mass reduction chassis (truck/tractor) II for group 4/9 HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
Ricardo-AEA 2015	10% reduction against € 3.28 per kg	2014 €		The precise values were interpolated on the basis of Ricardo's light weighting study.	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2015	No	Yes – High 1	Yes	No	**€ 951**

Table 96: Mass reduction chassis (truck/tractor) II for group 5/10 HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
Ricardo-AEA 2015	10% reduction against € 5.93 per kg	2014 €		The precise values were interpolated on the basis of Ricardo's light weighting study.	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2015	No	Yes – High 1	Yes	No	**€ 1,988**

E.4.3 Mass reduction tractor + trailer I

This technology is not relevant for group 4/9 trucks.

Table 97: Mass reduction tractor + trailer I for group 5/10 HDV

<table>
<tr><th></th><th>Cost as mentioned in original source</th><th colspan="2">Year and unit of cost</th><th colspan="2">Source</th></tr>
<tr><td>Ricardo-AEA 2015</td><td>5% reduction against € 2.37 per kg</td><td colspan="2">2014 €</td><td colspan="2">The precise values were interpolated on the basis of Ricardo’s light weighting study.</td></tr>
<tr><th>Final source of cost chosen</th><th>Correction for indirect costs needed</th><th>Learning curve correction needed</th><th>Inflation correction needed</th><th>Exchange rate correction needed</th><th>Final cost in 2015 €</th></tr>
<tr><td>Ricardo-AEA 2015</td><td>No</td><td>Yes - Medium</td><td>Yes</td><td>No</td><td>**€ 1,380**</td></tr>
</table>

E.4.4 Mass reduction tractor + trailer II

This technology is not relevant for group 4/9 trucks.

Table 98: Mass reduction tractor + trailer II for group 5/10 HDV

	Cost as mentioned in original source	Year and unit of cost		Source	
Ricardo-AEA 2015	10% reduction against € 4.16 per kg	2014 €		The precise values were interpolated on the basis of Ricardo's light weighting study.	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo-AEA 2015	No	Yes – High 1	Yes	No	**€ 2,954**

E.5 Auxiliaries

For all technologies in this section, the costs were assumed to be identical, irrespective of truck groups.

E.5.1 Electric hydraulic power steering

There was some variation found in the literature. It was chosen to adopt the cost value from Ricardo 2017 for all vehicle classes, as it matched information received from stakeholders

Table 99: Electric hydraulic power steering for all truck groups

	Cost as mentioned in original source	Year and unit of cost		Source	
EPA & NHTSA 2016	$ 114	2013 $		Own calculations	
Ricardo 2017	€ 360	2015 €		Own estimate based on EPA & NHTSA 2016	
Dünnebeil et al. 2015	€ 160	2015 €		Own assumption	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo 2017	No	No	No	No	**€ 360**

E.5.2 LED lighting

Although Dünnebeil et al. 2015 provided a value from the literature, we chose to also conduct our own online research. This was done as LED technology has developed very quickly in recent years. We ultimately made the decision to choose the value we researched ourselves.

Table 100: LED lighting for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Own research	€ 300	2015 €		Own online research	
Dünnebeil et al. 2015	€ 700	2015 €		Online research	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	Yes - Medium	No	No	**€ 240**

E.5.3 Air compressor

The literature on air compressor costs was not extensive, but we managed to find two sources and received data from stakeholder consultation. It was ultimately decided to use the data from stakeholder consultation.

Table 101: Air compressor for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo 2011	€ 140	2010 €		Ricardo expert estimate	
NHTSA 2015	$ 300 - 350	2011 $		Own modelling	
Stakeholder consultation	€250	2015			
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Stakeholder consultation	No	No	Yes	No	**€ 250**

E.5.4 AC efficiency

The range of costs for improved AC efficiency presented in the literature was not very broad. Ricardo 2017 values were chosen.

Table 102: AC efficiency for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo 2017	€ 210	2015 €		Ricardo expert estimate based on EPA & NHTSA 2016	
NHTSA 2015	$ 272 - 318	2011 $		Own modelling	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo 2017	No	No	No	No	**€ 210**

E.5.5 Cooling fan

Only one value that was applicable to our situation was found for the cooling fan technology. The value, however, seemed realistic and was therefore chosen.

Table 103: Cooling fan for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo 2017	€ 180	2015 €		Ricardo expert estimate based on EPA & NHTSA 2016	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo 2017	No	No	No	No	**€ 180**

E.6 Transmission

E.6.1 Reduced losses (lubricants, design)

Stakeholder consultation was utlised for this technology, and shared with us his estimate of costs for tractor-trailer combinations. To arrive at the costs for class 4/9 trucks, we scaled the costs for class 5/10 trucks implying the costs for class 4/9 trucks are roughly 20% lower than the costs for class 5/10 trucks.

Table 104: Reduced losses for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 103	2015 €		Based on Öl-Engel (2014) and Texaco (2014) and adapted to vehicle	
TIAX 2011	€ 192	2010 €		TIAX/NAS (2009)	
NHTSA 2015	$ 228 - 250	2011 $		Own modelling	
Own research	€ 250	2015 €		Stakeholder consultation combined with own calculation correction	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 250**

E.7 Driver assistance

E.7.1 Engine stop-start

The same cost value is considered for all truck groups, based on stakeholder consultation.

Table 105: Engine stop-start for all groups of trucks

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo 2011	€ 640	2010 €		Ricardo expert estimate	
NHTSA 2015	$ 1,287 – 1,500	2011 $		Own modelling	
Dünnebeil et al. 2015	€ 940	2015 €		Own assumption	
EPA & NHTSA 2016	$ 1,156	2013 $		Own modelling	
Own research	€ 600	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 600**

E.7.2 Eco-roll

There were no cost estimates in the literature on this measure. The same cost value, resulting from stakeholder consultation is considered for all truck groups.

Table 106: Eco-roll for all groups of trucks

	Cost as mentioned in original source	Year and unit of cost		Source	
Own research	€ 150	2015 €		Stakeholder consultation in combination with own expertise	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 150**

E.7.3 Predictive cruise control

Recent literature diverges significantly from more older literature. We opted to go with a more recent estimate. The same cost value is considered for all truck groups.

Table 107: Predictive cruise control for all groups of trucks

	Cost as mentioned in original source	Year and unit of cost		Source	
Ricardo 2011	€ 1,400	2010 €		Ricardo expert estimate	
Dünnebeil et al. 2015	€ 640	2015 €		Based on EPA & NHTSA 2016 and adjusted to European situation	
Own research	€ 600	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 600**

E.7.4 Speed limiter 80 km/h

Literature indicates that there are no additional costs associated with this technology (€0). The same cost value is considered for all truck groups.

Table 108: Speed limiter for all groups of trucks

	Cost as mentioned in original source	Year and unit of cost		Source	
Dünnebeil et al. 2015	€ 0	2015 €		Their own assumption, this is the standard now	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Dünnebeil et al. 2015	No	No	No	No	**€ 0**

E.8 Engine

E.8.1 Improved turbocharging and EGR

A small range of cost estimates was provided by the literature, but the value from the Ricardo 2017 study was chosen. The same cost value is considered for all truck groups.

Table 109: Improved turbocharging and EGR for all groups of trucks

	Cost as mentioned in original source	Year and unit of cost		Source	
Ricardo 2017	€ 1,050	2015 €		Ricardo expert estimate	
NHTSA 2015	$ 1,193 – 1,390	2011 $		Own modelling	
Own research	€ 1,050	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo 2017	No	No	No	No	**€ 1,050**

E.8.2 Friction reduction + improved water and oil pumps

The multiple studies that were found in the literature revealed costs that spread a significant range. Stakeholder consultation ended in a figure that ranges between the figures cited in literature.

The same cost value is considered for all truck groups.

Table 110: Friction reduction + improved water and oil pumps for all groups of trucks

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 75 - 300	2015 €		Own expertise compared with literature research	
NHTSA 2015	$ 550 – 600	2011 $		Own modelling	
EPA & NHTSA 2016	$ 284	2013 $		Own modelling	
Own research	€200	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
EPA & NHTSA 2016	No	No	No	No	**€ 200**

E.8.3 Improved lubricants

Although there were three studies in the literature that revealed costs for this technology, it seemed the Dünnebeil et al. 2015 study resembled our definition closest, and was therefore chosen.

Table 111: Improved lubricants for truck group 4/5

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 26	2015 €		Based on Öl-Engel (2014) and Texaco (2014) and adapted to vehicle	
NHTSA 2015	$ 12.75 – 14	2011 $		Own modelling	
EPA & NHTSA 2016	$ 5	2013 $		Own modelling	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Dünnebeil et al 2015	No	Yes - Low	No	No	**€ 23**

Table 112: Improved lubricants for truck group 9/10

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 27	2015 €		Based on Öl-Engel (2014) and Texaco (2014) and adapted to vehicle	
NHTSA 2015	$ 12.75 - 14	2011 $		Own modelling	
EPA & NHTSA 2016	$ 5	2013 $		Own modelling	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Dünnebeil et al. 2015	No	Yes - Low	No	No	**€ 24**

E.8.4 Waste heat recovery

Although the literature revealed a significant range, the value from the Ricardo 2017 study was chosen conform the methodology outlined. This value was confirmed by multiple stakeholders. The same cost value is considered for all truck groups.

Table 113: Waste heat recovery for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Dünnebeil et al. 2015	€ 11,000	2015 €		Based on NESCAFF (2009) and adapted to this vehicle class	
Ricardo 2011	€ 11,570	2010 €		Ricardo expert estimate	
Ricardo 2017	€ 5,000	2015 €		Ricardo expert estimate	
EPA & NHTSA 2016	$ 3,496	2013 $		Own modelling	
Own research	€ 5,000	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Ricardo 2017	No	No	No	No	**€ 5,000**

E.8.5 Downspeeding (combined with DCT optimisation)

Although a cost estimate was found in the literature, we chose to consult stakeholders as well. The cost value used was based on stakeholder consultation. The same cost value is considered for all truck groups.

Table 114: Downspeeding for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
NHTSA 2015	$ 2,232 – 2,600	2011 $		Own modelling	
Own research	€ 750	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 750**

E.9 Hybridisation

E.9.1 48V system with starter/generator

There was no literature which had cost estimates for this technology available for trucks. Therefore we had to conduct stakeholder consultations. The same cost value is considered for all truck groups.

Table 115: 48V system with starter/generator for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Own research	€ 5,000	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 5,000**

E.9.2 Full electric hybrid

In contrast to the previous hybrid technology, the literature had some estimates on costs for trucks. Nonetheless, we went with the cost estimated revealed by stakeholder consultations. The same cost value is considered for all truck groups.

Table 116: Full electric hybrid for all truck groups

	Cost as mentioned in original source	**Year and unit of cost**		**Source**	
Ricardo 2011	€ 24,000	2010 €		Ricardo expert estimate	
Dünnebeil	€ 60,000	2015 €		Weighted average of literature and industry experts	
ICCT (2015)	$ 15,225 – 16,917	2013 $		Own research	
Own research	€10,000	2015 €		Stakeholder consultation	
Final source of cost chosen	**Correction for indirect costs needed**	**Learning curve correction needed**	**Inflation correction needed**	**Exchange rate correction needed**	**Final cost in 2015 €**
Own research	No	No	No	No	**€ 10,000**

Annex F Scaling of costs

F.1 Scaling according to vehicle parameters

The scaling of costs presented in this annex is used in Chapter 4 (Task 3). Table 117 shows the relevant vehicle parameters used in case the scaling of costs was necessary.

Table 117: Vehicle parameters used to scale costs

Vehicle parameter	group 4	group 5	group 9	group 10
Mass (kg)	6,200	14,550	6,200	14,550
Number of tyres including trailer	10	12	16	16
Number of tyres excluding trailer	6	6	10	10
Surface area correction for underbody panels truck chassis	2	1	2	1

The vehicle mass was used in the scaling of costs for the light weighting measure. These measures were phrased in the following manner: “5% weight reduction is available against € X costs per kg” or “10% weight reduction is available against € Y costs per kg”. To calculate the total costs for these light weighting measures, assumptions needed to be made regarding the weight of the various vehicle groups. These weight assumptions can be found in the table above.

The number of wheels on a truck is important for a range of technologies, such as introducing low rolling resistance tyres or wide base single tyres. The costs for these technologies are usually given on a per wheel basis, and translated to a per truck basis in accordance with the number in the table above.

The parameter surface area correction for underbody panels was used in scaling of costs for the measure “side an underbody panels at truck chassis”. Costs were found in the literature for the equivalent of group 5/10 trucks. Online research was then conducted to investigate the size of the surface area at the bottom of the truck chassis. This research indicated that this surface area for box trucks (group 4/9) is about twice as large as it is for group 5/10. As a result, costs were scaled by a factor 2 for group 4/9 trucks compared to group 5/10 trucks.

Annex G Short description of EXIOMOD

Source: Tatyana Bulavskaya, Jinxue Hu, Saeed Moghayer and Frédéric Reynès (2016). EXIOMOD 2.0: EXtended Input-Output MODel: A full description and applications. TNO Working Paper Series 2016-02

EXIOMOD is an economic model able to measure the environmental and economic impacts of policies[34]. As a multisector model, it accounts for the economic dependency between sectors. It is also a global and multi-country model with consistent bilateral trade flows between countries at the detailed commodity level. Based on national account data, it can provide compressive scenarios regarding the evolution of key economic variables such as GDP, value-added, turn-over, (intermediary and final) consumption, investment, employment, trade (exports and imports), public spending or taxes. Thanks to its environmental extensions, it makes the link between the economic activities of various agents (sectors, consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases, wastes).

Compared to other existing multi-country economic models such as GTAP (Center for Global Trade Analysis - GTAP, 2014), ENV-Linkages (Chateau, Dellink, & Lanzi, 2014), GEM-E3 (Capros, Van Regemorter, Paroussos, & Karkatsoulis, 2013), E3ME (Cambridge Econometrics, 2014), GINFORS (Lutz, Meyer, & Wolter, 2010) or NEMESIS (ERASME, n.d.), EXIOMOD 2.0 has several important features that allow customization of the model setup for each study:

- Based on a flexible modular structure, EXIOMOD can run (and compare) several standard economic modelling approaches. Where Input-Output (IO) analysis concentrates on the interdependence between economic sectors, general equilibrium analysis takes also into accounts price effects. Separating IO from general equilibrium effects simplifies the analysis of the results which overcome certain criticisms formulated to Computational General Equilibrium Models (CGEM) (see below).
- EXIOMOD can have the properties of the two main types of CGEM. Walrasian CGEMs (such GTAP, ENV-Linkages or GEM-E3) assume perfect prices flexibility whereas neo-Keynesian CGEMs (such E3ME, GINFORS or NEMESIS) assume market imperfections (e.g. involuntary unemployment) due to slow adjustment of prices and capital, labour and consumption. This difference may lead to major differences in the results.
- EXIOMOD uses the EXIOBASE database that covers a high level of detail on economic sectors (up to 200 products) as well as environmental extensions on emissions, resources, water and land use.

With these features, EXIOMOD is particularly well suited to evaluate the impact of policies related to climate change, energy and resource efficiency at the macroeconomic, sector and household levels:

- Environmental extensions allows for measuring the impact of economic activities on the use of a large variety of resources and other environmental indicators.
- The international trade flows allows for analyzing the impact of national consumption pattern on the economy and on the resource use in other countries. This feature is particularly convenient to confront production based and consumption based indicators of resource footprint per country.
- The modular approach allows for separating direct and indirect effects, and in particular rebound effects.

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[34] For a full description and examples of applications of EXIOMOD see Bulavskaya, Hu, Moghayer, & Reynès (2016).

G.1 A modular approach

EXIOMOD's name stands for EXtended Input-Output MODel. "Extended" refers to the fact that EXIOMOD can extend the standard Input-Output (IO) analysis in two main directions: (1) to Computational General Equilibrium Model (CGEM) analysis, and (2) to specific topics such as environmental impacts, energy, resources or transport. EXIOMOD is based on a modular approach specifically designed to conduct both IO analysis and CGEM simulation. With this modular approach and depending on the subject under investigation, the modeller can easily change the regional and sectorial segmentation as well as the level of complexity regarding the specification of the model by switching on or off specific blocks. This allows for customization, resulting in an appropriate model setup for each research question.

The main objective of this modular approach is to overcome several criticisms formulated to standard CGEMs. In particular, an important issue for the analyses of results obtained with a multi-sector and/or multi-region CGEM is the abundance of linkages and effects which are difficult to separate from one to another. This is all the more true that the results heavily depend on many assumptions such as the level of elasticity, closing rule, underlying data for the sector disaggregation. To some extent, CGEMs have become too complex to answer specific questions which are paradoxically embedded in them. Typically, whereas CGEMs use IO database, the complexity of their production and consumption structure makes it difficult to isolate IO from CGE effects.

On the contrary, EXIOMOD can distinguish different key effects embodied in CGEM which can greatly help the interpretation of the results. In particular, it can separate volume and price effects. The volume effects are directly derived from the IO analysis whereas price effects come from the general equilibrium framework. Within volume effects, EXIOMOD can isolate direct and indirect effects through the calculation of different type of multipliers (multipliers of intermediaries, of investments and of consumption).

G.2 Economic and environmental data

The current version of EXIOMOD uses the detailed Multi-regional Environmentally Extended Supply and Use (SU) / Input Output (IO) database EXIOBASE[35] (www.exiobase.eu). This database has been developed by harmonizing and increasing the sectorial disaggregation of national SU and IO tables for a large number of countries, estimating emissions and resource extractions by industry, harmonizing trade flows between countries per type of commodities. Moreover, it includes a physical (in addition to the monetary) representation for each material and resource use per sector and country.

The EXIOBASE database has one of the most detailed products and environmental extensions that are currently available from input-output tables. The database covers 49 regions (44 countries representing around 90% of the world GDP and five rest of the world regions), 200 products and various environmental indicators. The environmental indicators are available as an extension to the input-output tables and are listed in the table below. Note that the 165 types of crops follow the FAO classification and are much more disaggregated than the crops in the input-output tables.

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[35] Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J. M., … Bouwmeester, M. (2009). Towards a global multi-regional environmentally extended input-output database. Ecological Economics, 68(7), 1928–1937. http://doi.org/http://dx.doi.org/10.1016/j.ecolecon.2008.11.010

Table 118: Environmental indicators covered in the EXIOBASE v3 database

Indicator	Level of detail	Examples
Emissions in kg	31 GHG and non GHG emissions	• CO_2 • CH_4 • NH_3
Land use in ha	12 types of agricultural land use	• Arable land used for rice • Arable land used for wheat • Arable land used for sugar crops
Resource use in kg	165 types of crops	• Soybeans • Almonds • Cocoa beans
	8 types of non-metallic minerals	• Slate • Gravel and sand • Salt
	9 types of fossil fuels	• Anthracite • Peat • Crude oil
	10 types of metals	• Iron • Copper • Lead
Water use in Mm^3	• Consumption green • Consumption blue • Withdrawal blue	

G.3 Conducting IO and CGEM analysis

EXIOMOD can perform a standard IO analysis which is typically useful to answer to the following type of questions. What is the economic impact of developing a particular sector (in terms of employment, value-added, investment, etc.)? Will domestic or foreign producers benefit the most? Which other economic sectors will benefit from it? With the inclusion of environmental extensions, IO tables can also be used to derive and compare various indicators of resource use: e.g. consumption-based versus production-based indicators. An example is the world map in terms of resource footprints shown in Figure 64 as published in the CREEA booklet[36].

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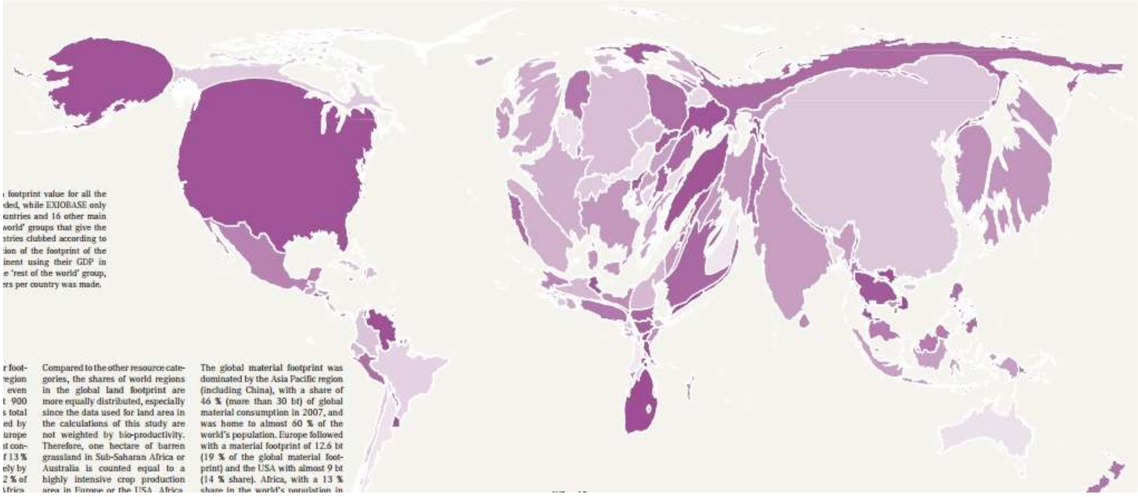
[36] Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., … Wood, R. (2014). The Global Resource Footprint of Nations - Carbon, water, land and materials embodied in trade and final consumption calculated with EXIOBASE 2.1. (J. Mohan, Ed.). Leiden/Delft/Vienna/Trondheim: The Netherlands Organisation for Applied Scientific Research, Leiden University, Vienna University of Economics and Business and Norwegian University of Science and Technology. Retrieved from http://exiobase.eu/index.php/publications/creea-booklet/72-creea-booklet-high-resolution/file



footprint value for all the
ded, while EXIOBASE only
untries and 16 other main
world' groups that give the
tries clubbed according to
ion of the footprint of the
inent using their GDP in
e 'rest of the world' group,
rs per country was made.

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egion
even
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s total
ed by
urope
t con-
f 13 %
ely by
2 % of

Compared to the other resource categories, the shares of world regions in the global land footprint are more equally distributed, especially since the data used for land area in the calculations of this study are not weighted by bio-productivity. Therefore, one hectare of barren grassland in Sub-Saharan Africa or Australia is counted equal to a highly intensive crop production

The global material footprint was dominated by the Asia Pacific region (including China), with a share of 46 % (more than 30 bt) of global material consumption in 2007, and was home to almost 60 % of the world's population. Europe followed with a material footprint of 12.6 bt (19 % of the global material footprint) and the USA with almost 9 bt (14 % share). Africa, with a 13 %

Figure 64: World map of resource footprints by country

Source: CREEA Booklet, see Tukker et al. (2014)

But IO analysis has the disadvantage to leave price effects aside. The CGE module can be activated to overcome this limit. EXIOMOD is then used as a CGEM. A CGEM takes into account the interaction and feedbacks between supply and demand as schematized in Figure 65. Demand (consumption, investment, exports) defines supply (domestic production and imports). Supply defines in return demand through the incomes generated by the production factors (labor, capital, energy, material, land, etc.). To ensure the equilibrium between supply and demand, an assumption regarding the “closure” of the system has to be done. Existing CGEMs generally choose between two main closures. The Walrasian closure assumes that perfect price flexibility insure the instantaneous equilibrium between supply and demand. On the contrary, the Keynesian closure assumes that demand defines supply whereas price and quantities are rigid and adjust slowly to the optimum. Depending on the application, EXIOMOD can be run with different closures.

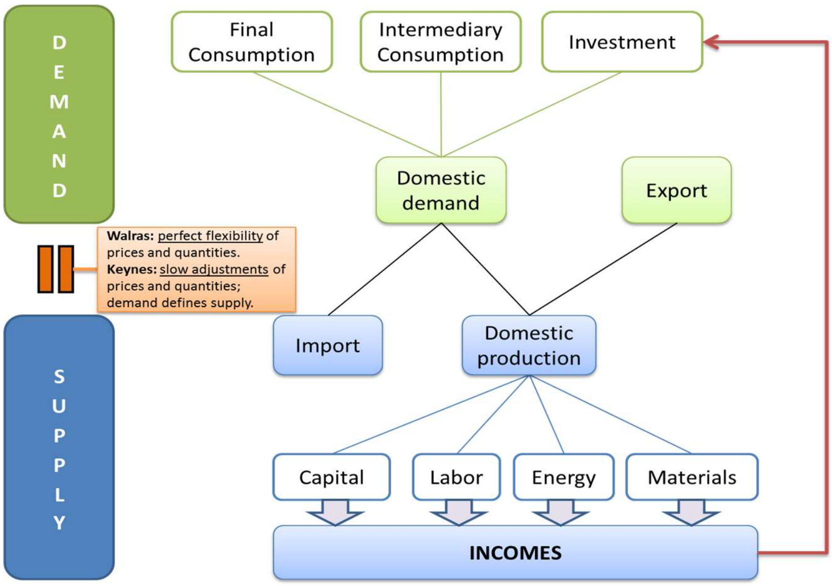

Figure 65: Architecture of a CGEM

G.4 Producers

The nesting structure used in the current version of the model is shown in Figure 66 but can be easily adjusted using the modular approach of EXIOMOD. The production technology is modelled as a nested Constant Elasticity of Substitution (CES) functions. The nesting structure allows for introducing different substitution possibilities between different groups of inputs. At the first level, we assume that material inputs for production are perfectly complementary to the aggregate input of capital, labor, energy, that is no substitution is possible. At the second level, energy can be substituted to the aggregate input capital-labor. At the third level, the elasticity of substitution between labor and capital is equal to one and equals the Cobb-Douglas function.

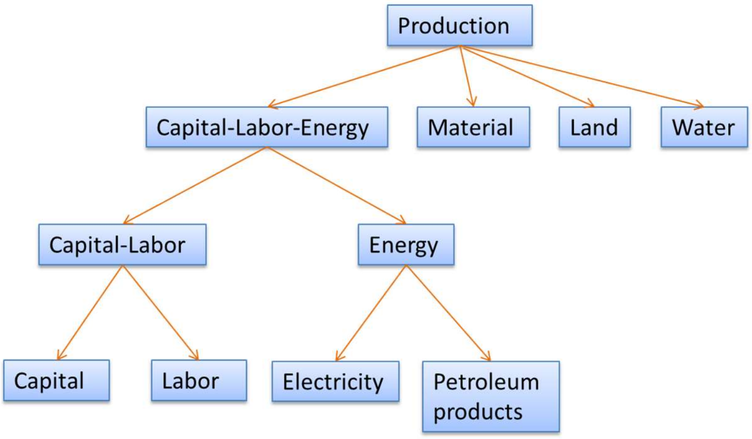

Figure 66: Production structure in EXIOMOD

G.5 Households

The household's utility is specified as a LES-CES function (Linear Expenditure System - Constant Elasticity of Substitution) allowing to differentiate between necessity and luxury products. This function defines a subsistence level for each good consumed which lead to an elasticity between consumption and revenue lower than one. For instance for food we have a high subsistence level, whereas for other products consumption is more sensitive to the level of income. For instance, the overall subsistence level of consumption corresponds to 33 percent of total consumption, but this level jumps to 80 percent for food products. Above this minimum level of consumption, substitution between good is possible depending on the price. In the modular approach of EXIOMOD the household's utility function could be switched to the standard CES function in order to simplify the model.

G.6 Trade

The trade structure is schematized in Figure 67. At the first level, the user (e.g. final consumer or sectors) can either import a good buy the good from the domestic market. In a second step, all imported products from the different users are aggregated to calculate the total level of imports. In a third level, imports can be supplied by different countries. We assume a CES function characterized by possibilities of substitutions between regions of origin. We assume that trade in energy, water and construction is much less flexible in terms of changing trade partners compared to trade of other products.

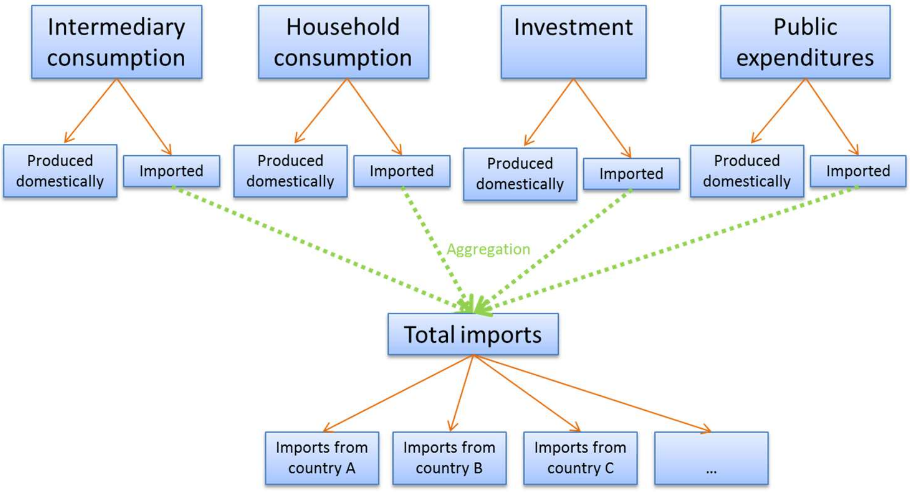

Figure 67: Trade structure in EXIOMOD

G.7 Environment

EXIOMOD related the resource use to the economic activity in several ways. CO_2 emissions are directly related to the level of consumption of the energy commodities responsible of the emission. Water consumption of economic activities is related to the level of production. For households, it is related to the water consumption (purchased from the water supply sector). Materials (such as metal, non-metallic minerals, etc.) are related to the production of the mining sector responsible of the extraction.

An example application is a baseline scenario on CO_2 emissions until 2050. This baseline scenario was applied in the FP7 POLFREE project (see D3.7b on www.ucl.ac.uk/polfree). One of the outcomes was a trajectory of CO_2 emissions as shown in Figure 68. The figure shows how far we are off from the climate targets in 2050 if we follow the economic projections and no additional climate policy is assumed.

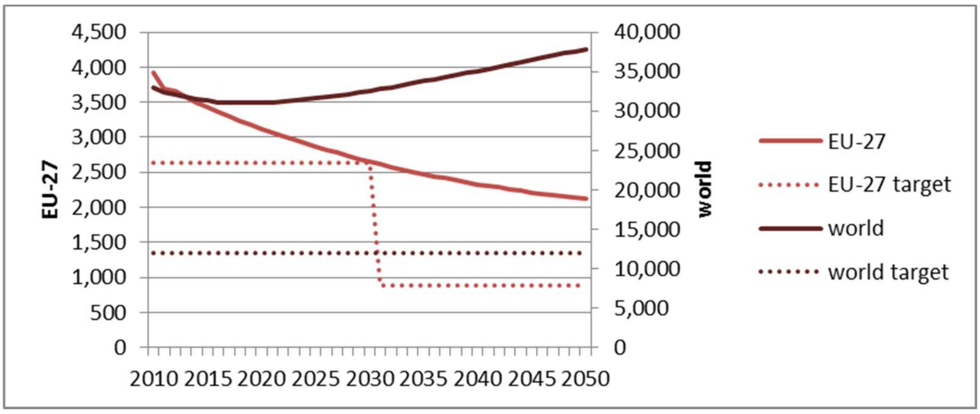

Figure 68: CO_2 emissions by region in Mt in the baseline scenario in the POLFREE project, 2010-2050

Annex H Region definition Task 4

Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Dem. Rep., Congo, Rep., Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, French guiana, Gabon, Gambia, The, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Sudan, St. Helena, Sudan, Swaziland, Tanganjika, Tanzania, Togo, Tunisia, Uganda, Western sahara, Zambia, Zanzibar, Zimbabwe, South Africa
Australia	Australia
China	China
EU28	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Latin America	Brazil, Mexico, Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, The, Barbados, Belize, Bermuda, Bolivia, Bonaire, Saint Eustatius and Saba, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), Greenland, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Sint Maarten (Dutch part), St. Kitts and Nevis, St. Lucia, St. Pierre and Miquelon, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, RB, British Virgin Islands, Virgin islands (u.s.)
Middle East	Bahrain, Egypt, Arab Rep., Iran, Islamic Rep., Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen, Rep.
Rest of Europe	Switzerland, Norway, Turkey, Albania, Andorra, Belarus, Bosnia and Herzegovina, Channel Islands, Faeroe Islands, Gibraltar, Iceland, Isle of Man, Kosovo, Liechtenstein, Macedonia, FYR, Moldova, Monaco, Montenegro, San Marino, Serbia, Svalbard and jan mayen islands, Ukraine, Vatican city state (holy see)
Russian Federation	Russion Federation
South East Asia	Indonesia, India, Japan, South Korea, Taiwan, Afghanistan, American Samoa, Antarctica, Armenia, Azerbaijan, Bangladesh, Bhutan, Bouvet Island, British Antarctic Territories, British Indian Ocean Territory, Brunei Darussalam, Cambodia, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Georgia, Guam, Heard and mc donald islands, Hong Kong SAR,

	China, Kazakhstan, Kiribati, Korea, democratic people's republic of, Kyrgyz Republic, Lao PDR, Macao SAR, China, Malaysia, Maldives, Marshall Islands, Micronesia, Fed. Sts., Mongolia, Myanmar, Nauru, Nepal, New Caledonia, New Zealand, Niue, Norfolk Island, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Philippines, Pitcairn, Samoa, Singapore, Solomon Islands, South georgia and the south sandwich is, Sri Lanka, Tajikistan, Thailand, Timor-Leste, Tokelau, Tonga, Turkmenistan, Tuvalu, United states minor outlying islands, Uzbekistan, Vanuatu, Vietnam, Wallis and futuna Islands
United States	United States and Canada

Annex I Input for the different cost curve scenarios

The cost curves used in the impact assessment were made by the JRC and were reported in [Krause, 2018]. In the JRC report several scenarios were presented of which information was used from the SR9 project. The information used for the different cost curve scenarios and the description of which input data is used, is reported in this Annex.

I.1 Typical scenario

The results from the SR9 project was used as a basis for the 'typical' or 'base' cost curve scenario. This basis consists of the list of measures, penetration rates, CO_2 reduction potential and costs. The results are reported in the chapters and annexes of this report. For the technology uptake rate, all cost-effective measures which are already available today were set to 100%, while other innovative, not readily available technologies were not considered yet.

I.2 Realo scenario

Based on dialogue between industry, experts and the Commission an alternative scenario was set up, in which maximum penetration rates of certain technologies in the year 2025 were introduced (see table 7 in section 3.3), such that limitations in practical use of the vehicles and a low efficiency of some technologies in specific missions are considered. Cost and CO_2 reduction parameters of the 'realo' scenario are identical to the 'typical' scenario.

I.3 High cost scenario

Based on dialogue between OEM's and the Commission a second alternative scenario were set-up, in which the costs of the CO_2 reduction technologies were adjusted based on the input from the OEM's. Due to confidentiality reasons these data are not available.