TU Graz Graz University of Technology	**iVT** INSTITUTE FOR INTERNAL COMBUSTION ENGINES AND THERMODYNAMICS	**TÜV NORD** Mobilität
H.S. Data Analysis and Consultancy	Heinz Steven	**TNO** innovation for life — Department for Sustainable Transport and Logistics

Development and validation of a methodology for monitoring and certification of greenhouse gas emissions from heavy duty vehicles through vehicle simulation

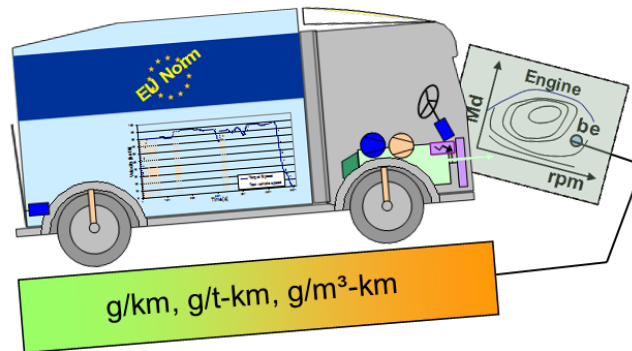Service contract CLIMA.C.2/SER/2012/0004

Final Report

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g/km, g/t-km, g/m³-km

Development and validation of a
methodology for monitoring and certification of greenhouse gas emissions from
heavy duty vehicles through vehicle simulation
Draft Final Report

Written by:	Raphael Luz		TUG		
	Martin Rexeis		IVT		
	Stefan Hausberger				
	Dalibor Jajcevic				
	Wolfgang Lang		ses-tec		
	Leif-Erik Schulte		TUEV-NORD		
	Jan Hammer		Mobilität		
	Lutz Lessmann				
	Mensch van Pim		TNO		
	Ruud Verbeek				
	Heinz Steven				

Content

1. Abbreviations

Here general abbreviations are listed. Abbreviations corresponding to equations are listed in the text below the corresponding formula for better readability.

A .... cross sectional area [m²]

a .... acceleration [m/s²]

BSFC .... Brake specific fuel consumption [g/kWh]

C_x .... Concentration of a component x in the exhaust gas [ppm]

CSE .... Constant Speed Evaluator (evaluation tool for aerodynamic drag tests)

EMS .... European Modular System

EGR .... Exhaust gas recirculation

GVM .... Gross vehicle mass (weight of truck and trailers and eventual payload)

GVW .... Gross vehicle weight = GVM

HDV .... Heavy duty vehicle (here above 7.5t max weight)

HDE .... Heavy duty engine

LDV .... Light Duty Vehicle

P_{wheel} .... Power at the wheel of a vehicle, i.e. sum of driving resistances [W]

p .... pressure [bar]

Pe .... Effective power of the engine [kW]

P_{rated} .... Rated engine power [kW]

RRC .... Rolling resistance coefficient

SOC .... State of charge of the battery [kWh]

t [°C] .... Temperature [°C]

T .... Temperature [°K]

v .... vehicle velocity [km/h] or [m/s] if specified

w .... work over the cycle, usually in this document given in [kWh]

WCF .... WHTC correction factor

WHSC .... World Heavy duty steady state test cycle

WHTC .... World Heavy duty transient test cycle

WLTP .... Worldwide harmonized Light duty Test procedure

ρ .... density [kg/m³]

ΔFC .... Extra fuel consumption (unit as statet in equation)

2. Definitions

CO_2 test cycles.................. Target speed cycles for 5 HGV mission profiles and for 5 bus mission profiles which are implemented in VECTO to calculate the certification values for HDV

SiCo-test .... Simplified Constant Speed test (predefined test cycle in VECTO consisting of constant speeds for optional later validation of the CO2 result produced for a HDV)

standard bodies................. HDV body with generic dimensions and construction designs which have to be used for the aerodynamic drag test for HDV chassis

standard trailers................ Trailers with generic dimensions and construction designs which have to be used for the aerodynamic drag test for truck-trailer combinations

standard semi-trailers........ Semi-trailers with generic dimensions and construction designs which have to be used for the aerodynamic drag test for tractor-trailer combinations

Vehicle specific data.......... input data for the certification procedure which is gained from components used in the vehicle which is certified.

Generic data...................... input data for the certification procedure which is defined similarly for all vehicles which are certified within a HDV class (can be technology specific).

Default data....................... input data for the certification procedure where the manufacturer can choose if he wants to use the generic data set or if he wants to use vehicle specific test data.

3. Introduction

LOT 2 of the project "Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles" resulted in a proposal based on component testing combined with a simulation tool to calculate the CO_2 emissions of the entire vehicle as described in the final report of LOT 2: "Development and testing of a certification procedure for CO_2 emissions and fuel consumption of HDV"[1].

The procedure suggested by LOT 2 was further tested and improved within LOT 3. Component test procedures as well as the simulation tool went through a proof of concept phase in 2013 which showed a good accuracy for all steps of the procedure. Performing the component tests showed several details which have not been described in sufficient detail. Thus a lot of effort was put into manifold details to finalise all test procedures and simulation steps. The work was done in close cooperation with ACEA and with supply industry. Without the outstanding support from industry in all tasks the level of quality achieved in the meantime for the test procedure would have been out of reach. Also the support and the extensive work performed at JRC in the course of the project contributed a lot to the success of the work in LOT 3.

Although a lot of progress was made in LOT 3 still some open points exist which are not endangering the process of a CO_2 certification for HDV in Europe but solving these issues shall further improve the quality of the test results. The open issues are described in the report and are also summarised in an extra chapter.

The deliveries of LOT 3 are:

- A "draft technical annex" describing the test procedure step by step as input into a future regulatory text.
- The software "VECTO" to calculate the HDV CO_2 emissions from the component test data. The final LOT3 release includes now already the "declaration mode", which includes the automatic allocation of generic data to the selected HDV class.
- The software "VECTO-CSE" which allows an efficient evaluation of the aerodynamic drag test data. VECTO-CSE was completely new designed since the evaluation principles in the aerodynamic drag test procedure have been changed significantly during LOT 3.
- A "draft certification report" which describes roughly how the process of the certification may look like.
- The actual report giving background information for the methods selected for component tests and for evaluation and simulation. This report gives also an overview on the generic data and on default values used in the VECTO certification mode.

Typically for large projects with many partners and manifold dependencies on data and information flow, the draft final report from LOT 3 suffers in some parts from the limited time available between compiling most recent input into software and test descriptions and the

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[1] In the following text the work performed in LOT 2 and the corresponding final report is referred to as "LOT 2".

deadline for submitting the draft report. As a result some chapters are not complete yet. We want to apologize for this and hope that the coverage and quality of the final versions of the above mentioned deliverables outweigh shortcomings in the draft versions. Certainly we look forward to any comments on the drafts since your feedback will help us to further improve the test procedure.

4. General description

This chapter explains the general approach of component testing with vehicle simulation to produce a representative certification value for CO_2 and fuel consumption. After an overview on the approach more details on the component tests are given. The simulation tool is described in detail in chapter 6. The basis for a future legislation is the "technical annex", which is provided as separate document since it shall serve as "living file" which shall be update regularly in the future. Chapter 8 summarised important open tasks towards a complete certification procedure.

4.1. Overall approach

Here just a summary on the approach is given which shall allow the reader to understand following sections easier. Details of the approach are described in the technical annex and in chapters describing the software.

Figure 1 gives an overview on the entire data processing. Typically for vehicle longitudinal dynamics simulation tools the software VECTO calculates the actual engine power and engine speed over a test cycle from the driving resistances, from losses in the transmission and from the power demand from auxiliaries. A driver model organises the gear shift manoeuvres, acceleration and braking behaviour.

For following components the relevant input data for VECTO has to be delivered from standardised test procedures for the version of the component mounted in the HDV:

- Vehicle mass
- Tires (dimensions and rolling resistance coefficients)
- Engine (engine fuel flow map, fuel consumption in the WHTC, full-load curve, drag curve)
- Transmission (transmission ratios, loss maps for gear box and axle, default values optional)
- Aerodynamic drag (Cd x A, for some vehicle classes generic values can be used)

For following components generic values are defined, which are allocated by the software VECTO to the vehicle depending on the vehicle class and mission profile. For some of these components different generic data sets exist for different technology levels:

- Auxiliaries[2] (alternator, air compressor, steering pump, cooling fan, HVAC)
- Mass of the standard bodies and trailers
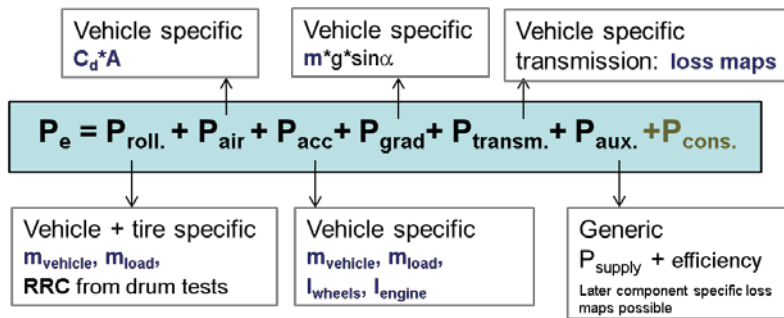- Vehicle payload or passenger weight in a bus

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[2] Some of the generic values may be replaced optional later by component specific test data. This needs an agreement on the component test procedure first.

- Test cycle.

Default values are provided for some input data, where the manufacturer can choose to use component specific test values or the default data. The default data represents rather components with worse efficiency. Using default data thus is attractive if the component has minor influence on total fuel consumption or if the manufacturer wants to safe costs for testing (e.g. for HDV with small sales numbers):

- Cd x A for low speed mission profiles
- Losses in the transmission

Simulation of engine power:

Simulation of engine speed

$$n = (v \times 60 \times i_{axle} \times i_{gear}) / (d_{tire} \times \pi)$$

Vehicle transmission ratios
i_{gear}, i_{axle}
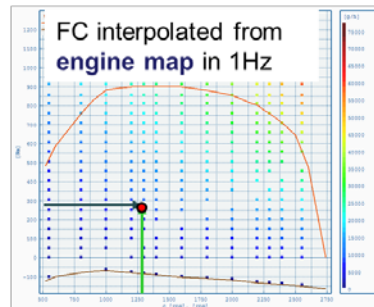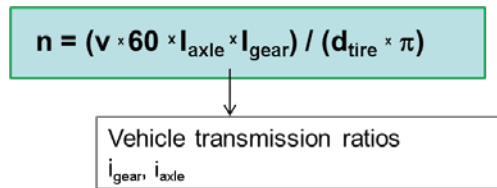
Figure 1: Overview on the VECTO method to calculate representative CO_2 and fuel consumption values from component test data

The generic values are allocated to the vehicle by the software VECTO automatically depending on the HDV class in which the vehicle falls. The HDV class is defined by the category (rigid, tractor, city bus, coach), by the axle configuration and the maximum gross weight as shown in Table 1 and Table 2. For each class the corresponding test cycles, the standard body or trailer and the payload are defined as well as the data relevant for the simulation of the generic auxiliaries.

VECTO then in the "declaration mode" automatically computes fuel consumption and CO_2 emissions for all CO_2-test cycles allocated to the vehicle for average payload, full load and empty driving. Results are given in g/km and g/ton-km or g/pass-km for buses respectively. Which of these values will be used in a final certification process is not finally decided yet.

Beside the certification mode the VECTO tool offers also an "engineering mode" all model parameters can be specified by the user to allow extensive testing and comparison with test conditions which are not in line with the standard CO_2-test cycles (e.g. for recalculation of on-board fuel tests with VECTO).

Table 1: Schema of the HDV classification for rigid trucks and for tractors

Axles	Axle configuration	Chassis configuration	Maximum GVW [t]	<-- Vehice class	Long haul	Regional delivery	Urban delivery	Municipal utility	Construction	Standard body	Standard trailer	Standard semitrailer
					Segmentation (vehicle configuration and cycle allocation)					**Norm body allocation**		
2	*4x2*	*Rigid*	>3.5 - 7.5	0 **)		*R*	*R*			*B0*		
2	4x2	Rigid or Tractor	7.5 - 10	1		R	R			B1		
		Rigid or Tractor	>10 - 12	2	R	R	R			B2		
		Rigid or Tractor	>12 - 16	3		R	R			B3		
		Rigid	>16	4	R+T	R		R		B4	T1	
		Tractor	>16	5	T+S	T+S						S1
	4x4	Rigid	7.5 - 16	6				R	R	(B3)		
		Rigid	>16	7					R	(B5)		
		Tractor	>16	8					T+S			(S1)
3	6x2/2-4	Rigid	all weights	9	R+T	R		R		B6	T1	
		Tractor	all weights	10	T+S	T+S						S2
	6x4	Rigid	all weights	11					R	(B7)		
		Tractor	all weights	12					R			(S2)
	6x6	Rigid	all weights	13					R	(B7)		
		Tractor	all weights	14					R			(S2)
4	8x2	Rigid	all weights	15					R	(B8)		
	8x4	Rigid	all weights	16					R	(B9)		
	8x6 & 8x8	Rigid	all weights	17					R	(B9)		

R = Rigid & Body
R+T = Rigid & Body & Trailer *)
T+S = Tractor & Semitrailer
() = no (Cd*A) measurement, only vehicle weight and frontal area

*) Whether it is sufficient to simulate the truck-trailer combination based on cd*A for Rigid & Body or the full-vehicle test for aerodynamic drag has to be performed additionally with Rigid & Body & Trailer has to be clarified

**) Suitability of cycles and entire process for segment <7.5t GVW to be evaluated

Table 2: Schema of the HDV classification for buses

Vehice class	Mission	First approach: classification according EU registration (2001/85/EU)	Class I or II	Class II or III	Heavy Urban	Urban	Suburban	Interurban	Coach
			Second approach: If vehicle can be registered as:		**Cycle allocation**				
B1	City	Class I	Low Floor / Low Entry (Def.: minimum 2 doors with low entrance) / Double decker (w/o luggage compartment)	---	HU	UR	SU		
B2	Interurban	Class II	luggage compartment	Floor height <= 900mm				IU	
B3	Coach	Class III	---	Floor height > 900mm / Double decker					CO

Table 3 shows the classification scheme for EMS which would have additional trailers. If such combinations shall be measured in a CdxA test procedure or if just the CdxA value from

the corresponding baseline HDV configuration shall be used (eventually with a generic correction factor) is open yet.

Table 3: Schema of the EMS classification for HDV

	Axle configuration	Chassis configuration	weight	Vehicle Class	Long haul	Regional delivery	Urban delivery	Municipal utility	Construction	Standard Bodies (B) Standard Trailer (T) Standard Semitrailer (ST)	National specific variation (0)	
EMS	4x2	Tractor	all	5A	T+CT/W	T+CT/W						T+CT = Tractor + Sem itrailer + Ceter axle trailer
				5B	T+L/W	T+L/W						T+L = Tractor + Link (ST3) + Sem itrailer
	6x2	Rigid		9D	R+D+T/W	R+D+T/W						R+D+T = Rigid + Body + Dolly + Sem itrailer
				9E	R+CT+CT/W	R+CT+CT/W						R+CT+CT=Rigid + Body + Center axle trailer + Center axle trailer
	6x2	Tractor	all	10A	T+CT/W	T+CT/W						
				10B	T+L/W	T+L/W						
	6x4	Rigid	all	11D	R+D+T/W	R+D+T/W						W = Curbweight (Truck + Standard trailer +Standard Payload)
				11E	T+CT+CT/W	R+CT+CT/W						
	6x4	Tractor	all	12A	T+CT/W	T+CT/W						
				12B	T+L/W	T+L/W						

The way how the vehicle specific input data is measured is described below and in the technical annex.

4.2. Development of Component test procedures

The relevant components where vehicle specific data has to be used as input for VECTO are:

- Vehicle mass
- Tires (dimensions and rolling resistance coefficients)
- Engine (engine fuel flow map and WHTC test results)
- Transmission (transmission ratios, loss maps for gear box and axle, default values optional)
- Aerodynamic drag (Cd x A)

4.2.1. Engine test

The specific fuel consumption of the vehicle is calculated in VECTO by interpolation from an engine map, which contains the fuel flow in [g/h] over engine speed [rpm] and engine torque [Nm]. This is a very common approach for the simulation of fuel consumption from vehicles where the engine is available for measurements.

To achieve a good accuracy at approximately 100 measured points are requested in the map (see chapter 4.2.1.1 and technical annex).

An additional correction function was introduced in the test procedure, which shall consider influences of dynamic load changes and of the preconditioning on the engine efficiency and which also shall prohibit the optimisation of the engine control parameters towards low fuel consumption but high NO_x emissions in the test points.

The engine test procedure is a mandatory component test within the HDV CO_2 test procedure. No default values shall be provided for the engine fuel map.

The engine test procedure consists of:

(A) Fuel consumption (FC) map

(B) WHTC test

(C) Set up of the WHTC correction factors

Background information on each step is given below. The technical details of the test procedure are described in the technical annex.

4.2.1.1. *Fuel consumption map*

To ensure efficient and correct measurements on the engine test bed the procedure shall follow the EURO VI WHSC/WHTC test procedure (UN/ECE, 2013) wherever possible[3]. The main difference to the certification test for regulated pollutants is that additional load points are demanded.

- The engine fuel map shall be measured at the engine dynamometer in a series of steady state engine operation points with following test conditions
  - o Stabilization time of each mode: 60 sec.
  - o Fuel flow measurement over 30 sec → total mode length 90 sec.
  - o Ramp time between modes for each speed sweep: 20 sec.
  - o Ramp time between speed steps: 45 sec.
  - o Lowest load for mapping: 0 Nm (no fuel flow measurement below 0 Nm).

- The metrics of the fuel map are engine speed [rpm], engine torque [Nm] and fuel consumption [g/h].

- The net engine torque shall be determined in a manner similar to the method in the EURO VI emission certification (Regulation 582/2011), which means that the power consumption of the oil pump, the coolant pump, the fuel delivery pump, the fuel high pressure pump and of the alternator overcoming the electricity demand of the engine itself are already covered in the fuel map.

- The grid of test points is defined as follows:

  Engine mapping shall have a minimum of 10 speed steps and a minimum of 10 load steps at maximum torque speed.

  From zero torque on the same load step distance has to be used for all speeds until maximum torque is exceeded. Fuel flow at maximum torque has to be measured for all speeds. To maintain a continuous coverage of the map, the determination of the 10 speed steps was elaborated as follows:

  i) Define the four base speeds:
  - n_{idle}
  - n_{pref} - n_{pref} *0.04
  - n_{pref} + n_{pref} *0.04
  - n_{95}

  ii) Determine the remaining minimum 6 engine speeds by adding into each of the speed ranges (1) and (2) (see below) a minimum of 3 equidistant engine speeds between the base speeds.

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[3] The accuracy demands may need to be amended against the EURO VI engine test procedure (se chapter 2.7). Before amendments the possible accuracy shall be evaluated in cooperation with ACEA.

(1) from n_{idle} to $\{n_{pref} - n_{pref} * 0.04\}$: $n_i = n_{i-1} + \{(n_{pref} - n_{pref} * 0.04) - n_{idle})\} * 0.25$

(2) from $\{n_{pref} + n_{pref} * 0.04\}$ to n_{95}: $n_i = n_{i-1} + \{n_{95} - (n_{pref} + n_{pref} * 0.04)\} * 0.25$

iii) Apply vertical mapping as shown in Figure 2.
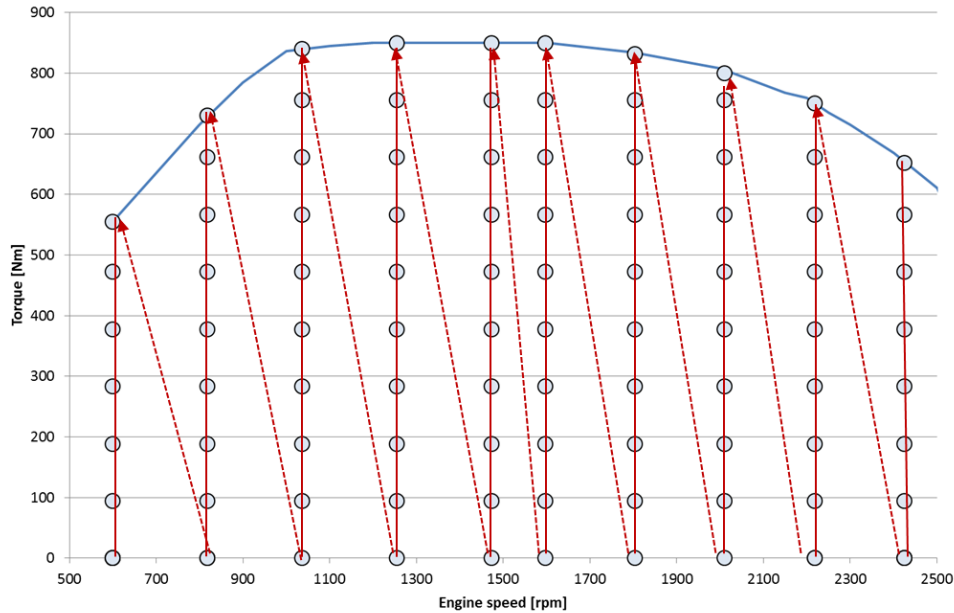
Figure 2: Schematic picture of the engine fuel flow map and of the test sequence

To calculate the CO_2 emissions the Carbon balance is the most accurate option. Thus a complete oxidation of C to CO_2 is presumed in the resulting CO_2 value. This certainly makes sense, otherwise engines with high CO and HC emissions would have advantages. The according CO_2 value consequently can be computed by VECTO from the test fuel properties:

$$\dot{m}_{CO2} = \dot{m}_{Fuel} \times m\%_C \times \frac{44}{12}$$

With $\dot{m}_{CO2}$ ....CO_2 mass flow in [kg/h]

$\dot{m}_{Fuel}$ ....Fuel mass flow in [kg/h]

$m\%_C$ ....mass fraction of Carbon in the fuel

It needs to be discussed, to which extend the variability of test fuels shall be considered in the CO_2 value and in the fuel consumption value reported by VECTO. Certainly differences between Diesel, CNG, LPG etc. are reasonably considered by the mass fraction of Carbon in the fuel. Nevertheless, within a specific fuel variations in the mass fraction of Carbon and in the specific heating value can occur (the test fuel certainly shall also fulfil the fuel properties defined in the WHTC regulations and in the European fuel directive).

The CO_2 emissions in the test cycle depend on the energy specific Carbon content of the test fuel in [kg C/kWh]. If the mechanical work of the engine as well as the engine efficiency over

the test cycle is seen as fixed value for a given combination of engine and fuel type, the CO_2 emissions result from the oxidation of the Carbon and have the value

$$CO_2[g] = \frac{W_{w-pos}}{\text{Efficiency}_{Engine}} \times \left(\frac{kg_C}{kWh}\right)_{fuel} \times \frac{44}{12}$$

With W_{w-pos} ....positive engine work in [kWh]

A correction for fuel properties thus would consequently correct the measured CO_2 value to the energy specific Carbon content of the reference test fuel:

$$\Delta CO_{2_f} = \frac{(kg_C/kWh)_{reference}}{(kg_C/kWh)_{test\,fuel}}$$

Similarly the mass specific energy content of the fuel can vary. A high energy density would result in lower fuel mass flow at the same engine power output. Thus the correction towards a common "reference value" should be based on the following equation:

$$\Delta \dot{m}_f = \frac{\left(kg_{fuel}/kWh\right)_{reference}}{\left(kg_{fuel}/kWh\right)_{test\,fuel}}$$

For this approach the mass fraction of Carbon in the fuel as well as the energy density would have to be available for the test fuel. At the moment a measurement of these values is not mandatory for the WHSC test fuel. The situation is similar for LDV with the WLTP regulation. Thus a common solution shall be soughed for LDV and HDV CO_2 regulations. Either a mandatory measurement of the test fuel with a definition of the reference values for each fuel type (gasoline, diesel, B5, B7, B10,…) to allow a correction or a common definition of the carbon mass fraction for all relevant fuels. The latter may be taken from the description of the coefficients for the Carbon balance at CVS tests for LDV in the WLTP (UN ECE, 2014). In general we suggest following the LDV regulation in this topic, since the WLTP is assumed to be implemented in EU legislation earlier than the HDV CO_2 certification.

To be prepared for both aforementioned options, VECTO foresees a variable mass fraction of Carbon in the fuel by introducing the "m_{CO2}/m_{fuel}" as input parameter. As long as the methods for LDV are not decided this value is fixed in the declaration mode of VECTO. It can be easily exchanged to use table values or test specific input later.

4.2.1.2.   WHTC correction procedure

The simple use of a steady state fuel map in the HDV CO_2 certification procedure has three major shortcomings:

1. There is no assurance of the consistency of regulated emissions and fuel consumption between the WHTC test and the steady state fuel map. This issue is one of the most important requirements for an appropriate HDV CO_2 certification method.

2. For modern engines the fuel consumption is influenced by many parameters like e.g. the temperature level of the SCR. Hence the fuel consumption level as determined in the steady state fuel consumption map (under the boundary conditions as defined by

pre-conditioning and sequence of test points) can differ from the conditions representative for the mission profiles.

3. The effect of transient engine behaviour is not considered in the steady state fuel consumption map. Typically the air to fuel ratio is lower under transient load increase than in steady state conditions due to the turbo lag. This has negative influences on the engine efficiency.

To consider these effects with reasonable effort that can be handled in a type approval procedure, the application of a mission profile specific "WHTC correction factor" approach was developed in LOT3. The correction factor depends on the measurement results of the engine in the engine fuel map and in the WHTC test and on the mission profile of the HDV in the VECTO simulation. The basic idea is in a first step to interpolate the fuel consumption of the engine in the WHTC from the measured fuel map. This interpolated fuel consumption is then compared to the measured fuel consumption. The ratio of measured fuel flow to interpolated fuel flow gives a correction factor (WHTC correction factor, "WCF"), which can be applied to any result gained from engine map interpolation to shift the steady state based interpolation result to the level which is expected under transient engine load conditions. To be in the position to consider the different dynamics of the different mission profiles in the HDV CO_2 method, separate WCF are produced for urban, road and motorway part of the WHTC. By appropriate mixing of these WCFs different cycle dynamics can be approximated.

Following method has been developed to establish the WHTC correction factors from the engine test procedure:

Measurement of WHTC

The WHTC has to be measured according to Regulation 582/2011 with the same engine as the fuel map is recorded. The engine has to meet the emission limits for criterion pollutants in the WHTC.

The fuel flow has to be recorded for the WHTC in minimum 1Hz time resolution. If possible, the accuracy of the fuel flow measurement shall be improved against Regulation 582/2011 to achieve from uncertainties in torque, engine speed and fuel flow not more than a total uncertainty of 1% for the brake specific fuel consumption in [g/kWh]. The same accuracy or better shall be demanded in the steady state test for the engine fuel map. The feasible accuracy needs to be further evaluated.

Interpolation of the WHTC fuel flow

The fuel flow in each of the 3 parts of the WHTC shall be interpolated from the steady state engine map measured.

For the interpolation of the WHTC certainly the same method as for interpolation for the HDV CO_2 test results is applied in VECTO (Delauney triangulation, see chapter 6.1). For the interpolation the motoring curve of the engine is necessary. As defined in the technical annex and also in (ACEA, 2014) for the 10 engine speeds of the fuel map the fuel flow on the motoring curve shall be to be set to zero also for the WHTC correction factor calculation. This is a correct approach, since the measurement of the motoring curve is defined in the EURO VI regulation for engine tests in a way that it fits to the zero fuel injection line.

After a long period of testing and discussion, it was decided together with the ACEA CVD group, to base the fuel flow interpolation of the WHTC on the target engine speed and on the target engine torque. Reason was, that in the highly transient phases of the WHTC rather high uncertainties of the measurement signal of the engine torque may occur on some engine test stands. This could lead to extrapolations from the fuel map and consequently could bias the results. Disadvantage of using the target rpm and torque is, that this would set incentives to run the engine at lower engine power levels than the target power, which is influenced by the controller setting for engine speed and torque ($P_e = M_d$ x n x 2π). To eliminate this loop hole, the WCFs are calculated from the brake specific results [g/kWh]. For the measured value the measured engine work is used as denominator and for the simulated fuel consumption the target engine work is used as denominator. With this approach the use of the target torque and rpm for interpolating the WHTC fuel flow cannot be used for manipulations, since a different total cycle work in the measurement than in the interpolation would be levelled out by the "kWh" from the test. In contrary to the instantaneous signals for torque and speed, the integral values from the test stand are robust and thus can be used[4]. The main steps of the WCF calculation are summarised below. A complete description is in the technical annex.

The coordinates for the interpolation are:
- Target engine speed
- Target engine torque
  - interpolated fuel flow [g/h]

Figure 3 shows a schematic picture of a fuel map and of the WHTC load points in this map in 1Hz resolution (I.e. each point represents one second). The interpolation of the WHTC in VECTO is also done in 1Hz, the target rpm and torque course of the WHTC is computed automatically from the engine data based on the standard definition of the WHTC in normalised format as described in the EURO VI regulation for HDE tests. Details are given in chapter 6.1.

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[4] As discussed before and as outlined in chapter 2.7 the overall accuracy demanded for the [g/kWh] result of the steady state points and of the WHTC should be defined more strictly for the HDV-CO2 certification than in the EURO VI regulation.
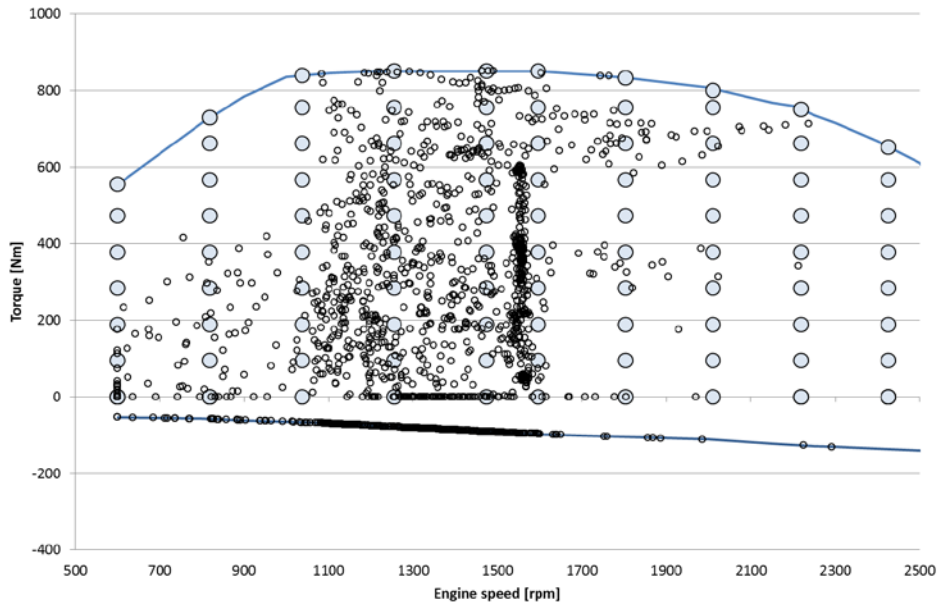
Figure 3: Schematic picture of the engine fuel flow map and the WHTC in 1Hz

The specific fuel consumption <u>from the interpolation</u> is then computed from the interpolated instantaneous fuel flow values as follows:

$BsFc_{intpol-Urban}$ [g/kWh] = (Sum $Fc_{i\ WHTC-Urban}$) / (Target positive engine work $_{WHTC-Urban}$)

$BsFc_{intpol-Road}$ [g/kWh] = (Sum $Fc_{i\ WHTC-Road}$) / (Target positive engine work $_{WHTC-Road}$)

$BsFc_{intpol-MW}$ [g/kWh] = (Sum $Fc_{i\ WHTC-MW}$) / (Target positive engine work $_{WHTC-MW}$)

      With   BsFc.......brake specific fur consumption [g/kWh$_{positive\ engine\ work}$]

                FC_i..........sum of fuel interpolated for a WHTC-sub-cycle [g]

                Target positive engine work.......... Average positive target power in WHTC sub-cycle x sub-cycle duration [kWh]

The specific fuel consumption <u>from the measurement</u> has to be computed from the WHTC and is an input parameter set for VECTO (the three [g/kWh] values for urban, road and motorway need to be provided with the engine map). The evaluation of the engine test to obtain this data shall be as follows:

$BsFc_{meas-Urban}$ [g/kWh] = (Sum $Fc_{m\ WHTC-Urban}$) / (Measured positive engine work $_{WHTC-Urban}$)

$BsFc_{meas-Road}$ [g/kWh] = (Sum $Fc_{m\ WHTC-Road}$) / (Measured positive engine work $_{WHTC-Road}$)

$BsFc_{meas-MW}$ [g/kWh] = (Sum $Fc_{m\ WHTC-MW}$) / (Measured positive engine work $_{WHTC-MW}$)

      With   BsFc.......brake specific fur consumption [g/kWh$_{positive\ engine\ work}$]

                FC_{mi}........sum of fuel measured in a WHTC-sub-cycle [g]

                Measured positive engine work .... Average positive power in WHTC sub-cycle x sub-cycle duration [kWh]

The correction factor for each part of the WHTC is calculated in VECTO by dividing the measured fuel consumption in the WHTC sub-cycle "$BsFc_{meas}$" in [g/kWh] by the fuel consumption interpolated for the same period, "$BsFc_{intpol}$" [g/kWh].

The three WHTC correction factors are then:

$WCF_{Urb} = BsFc_{meas-Urban} / BsFc_{intpol-Urban}$

$WCF_{Road} = BsFc_{meas-Road} / BsFc_{intpol-Road}$

$WCF_{MW} = BsFc_{meas-MW} / BsFc_{intpol-MW}$

The total correction factor (WCF_{Tot-i}) depends on the mission profile "i" and is produced in VECTO by mission profile specific weighting factors (WF_i), see Table 4.

The overall results of the engine test procedure consist of a set of input data for VECTO:
1. Engine make and model with main engine data to de-normalise the WHTC (n_{idle}, n_{pref}, n_{95}, rated power and rated speed,..)
2. The reference fuel properties of the fuel used in the test (= future option with m%-C, kg/kWh, if the correction to a reference fuel quality is planned)
3. The engine fuel flow map
4. The full load and the motoring curve
5. The WHTC road category correction factors for
   o WHTC Urban (WCF_{Urb})
   o WHTC extra urban (WCF_{Road})
   o WHTC Motorway (WCF_{MW})

When VECTO is then used to calculate the fuel consumption of the HDV in a HDV-CO_2 test cycle, the three WCFs are weighted to fit the dynamics of the target speed cycle of the mission profile from the HDV class in which the tested HDV falls. In the beginning it was planned to base the weighting on the actual power demand computed from VECTO for the vehicle in the HDV-CO_2 test cycle ($WCFs_{motorway}$ gives a value for higher power, $WCFs_{rural}$ gives a value for medium power and $WCFs_{urban}$ gives a value for low power). This approach was not followed further since in this case the weighted WCF would depend on the vehicle loading, vehicle rated power and road gradients more than on the real cycle dynamics. The actual proposal was thus based on the following simulation approach, which was done as pre-processing, to provide the generic weighting factors from Table 4:

• VECTO was used to simulate for generic HDV the corresponding test cycles and also to simulate the WHTC for the engine of the HDV. The software provides kinematic parameters, such as engine power, engine speed as well as several derivate of these values (e.g. change in engine speed and engine power per 2 seconds) and certainly the fuel flow.

• Then weighting factors for WHTC$_{urban}$, WHTC$_{road}$ and WHTC$_{motorway}$ have been computed, which lead to best fitting with each CO_2-test cycle in terms of the parameters mentioned above.

This approach is already described in a document for the heavy Duty Hybrid-HILS test procedure (Hausberger, 2012). It was found, that the resulting weighting factors do not depend

significantly on the HDV which is simulated but mainly on the test cycle. Thus using generic weighting factors for the three WCFs was decided to simplify the procedure. Running a calculation process as described above for each vehicle calculated by VECTO in future separately to obtain vehicle specific weights would be a high effort and would not add accuracy to the final result. Thus the entire WHTC-correction factor process can be handled quite simple in VECTO:

i) VECTO interpolates the fuel flow from the fuel map according to simulated engine speed and torque to obtain the total fuel consumption per mission profile in Gramm.

ii) VECTO calculates the mission profile specific WHTC correction factor for the engine from the WHTC sub-cycle correction factors and from the generic WHTC weighting factors in Table 4:

$$WCF_{Tot-i} = WCF_{Urb} \times WF_{Urb-i} + WCF_{Rur} \times WF_{Rur-i} + WCF_{MW} \times WF_{MW-i}$$

With   i..... mission profile according to Table 4, see also chapter 6.1.

iii) VECTO multiplies the total fuel consumption interpolated for a mission profile from i) with the WHTC correction factor (WCF_{Tot-i}) from ii) to obtain the final fuel consumption in [g]. Further units, such as g/t-km and g/km are obtained by division of the final fuel consumption by the corresponding value for distance and load in the test cycle of the mission profile.

Table 4: Weighting factors for the WHTC road category correction factors (final values from the HDH GTR work)

Index	Mission profile	WF_{MW}	WF_{Road}	WF_{Urb}
1	Long haul	89%	0%	11%
2	Regional delivery	53%	30%	17%
3	urban delivery	4%	27%	69%
4	Municipial utility	2%	0%	98%
5	Construction	6%	32%	62%
6	Citybus	0%	0%	100%
7	Interurban bus	19%	36%	45%
8	Coach	78%	22%	0%

4.2.1.3. Proof of concept for approach for depiction of engine fuel consumption

The approach for depiction of engine fuel consumption in the HDV CO2 certification consists of three main elements:

1) The engine test procedure

2) The method of engine test evaluation for generation of VECTO input data

3) The simulation approach in the VECTO tool

In the following the combination of all three elements is evaluated. For this purpose two engines were measured at the engine test bed according to the latest versions of the HDV CO2 certification procedure. Additionally the engine fuel consumption was measured in real world transient engine torque and speed patterns related to the HDV CO2 mission profiles. For proof of concept these measured values for fuel consumption have then been compared to the according VECTO results.

Tested engines

For the evaluations performed OEM independently by DG JRC and LOT3 two engines have been available. Engine#1 is certified to the EURO III emission standard and has been tested at the DG JRC. **Table 5** gives the main specification of engine#1.

Table 5: Specifications of engine#1

emission standard	EURO III
rated power	2290kW at 1800 1/min
maximum net torque	1850Nm at 1080 1/min
maximum permitted speed:	2300 1/min
capacity	12 litres

Engine#1 was measured according to the engine test procedures as elaborated by the LOT3 consortium and DG JRC for the proof of concept phase (version January 14th, 2013). Engine#1 was additionally measured in three transient engine tests (related to the mission profiles "long-haul", "regional delivery" and "urban delivery") which have been used for proof of concept evaluation.

The second engine which has analysed was a EURO VI prototype engine made available by LOT3. For this engine the engine specifications cannot be made public due to confidentiality issues. The EURO VI prototype engine was measured according to the latest available proposal from the ACEA (dated with February 26, 2013). For validation the transient engine test related to the mission profile "long-haul" was available.

The differences between the two versions of the engine test procedures applied for engine#1 and engine #2 (e.g. definition of grid points for the steady state FC map) are small and are assessed to not significantly influence the evaluation results.

Results

Figure 4 shows the calculated WHTC correction factors for the EURO III engine (engine#1). For the "urban delivery" cycle a correction factor of 1.016 is applied, the according values for the "regional delivery" and the "long haul" are very close to the value of 1.
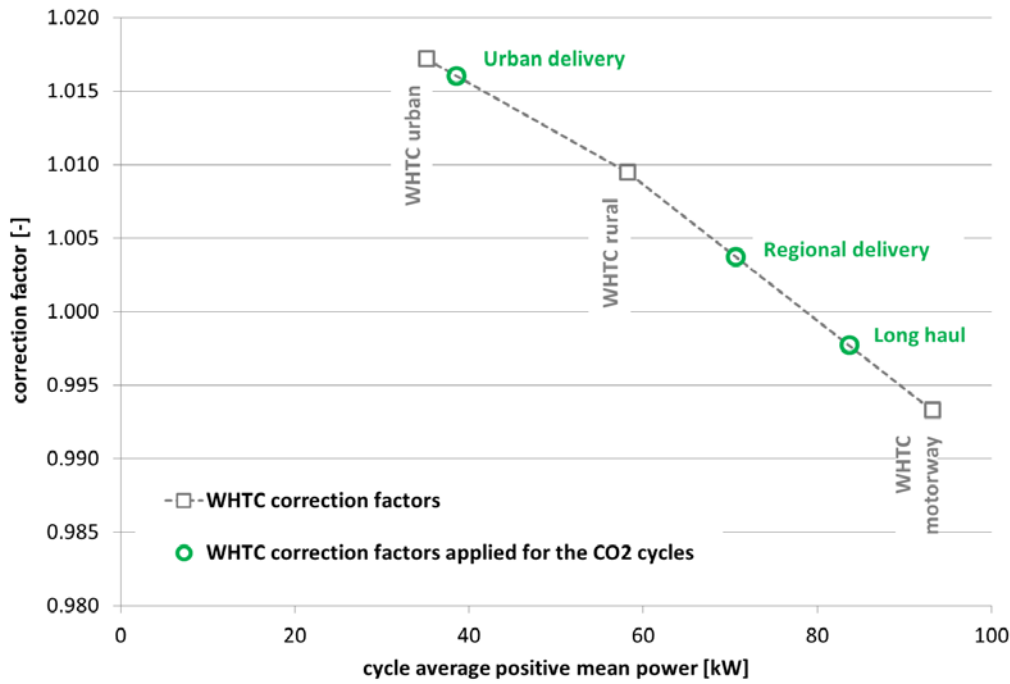
Figure 4: WHTC correction factors – engine#1

In Figure 5 the comparison between measured and simulated fuel consumption is given. Bars and numbers in grey give the simulation results before application of the WHTC correction, green bars and numbers show the final results according to the actual proposal for HDV CO2 simulation. The simulation results only deviate from the measurement values only by a few tenth of a percent.
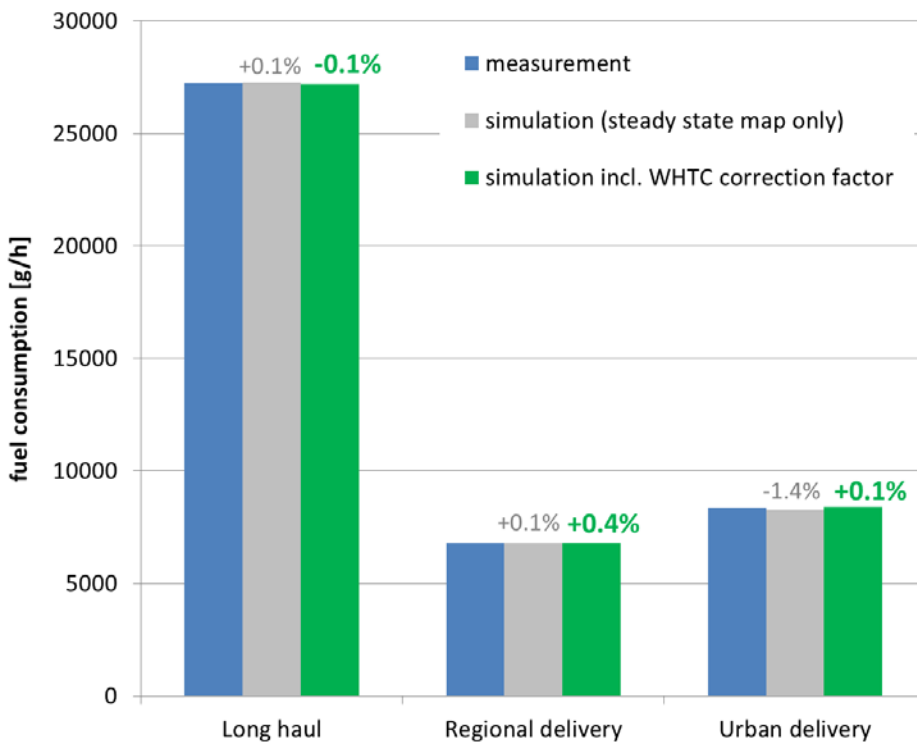
Figure 5: Comparison measured and simulated fuel consumption – engine#1

Figure 6 shows the WHTC correction factors as calculated for the EURO VI prototype engines (engine#2). This engine shows higher sensitivity of fuel consumption behaviour to different WHTC parts than the much less complex EURO III engine resulting in a higher spread of correction factors between the urban and the motorway part of the WHTC. For the validation exercise preformed here only a measurement of the "long haul" cycle was available. To get more data for validation in the analysis this measurement was divided into an "off-motorway part" (first and last 500 seconds of the cycle) and a "motorway part" (remaining 4300 seconds). The calculated WHTC correction factors for the different parts of the long-haul cycle are in a range of 0.994 to 0.997.
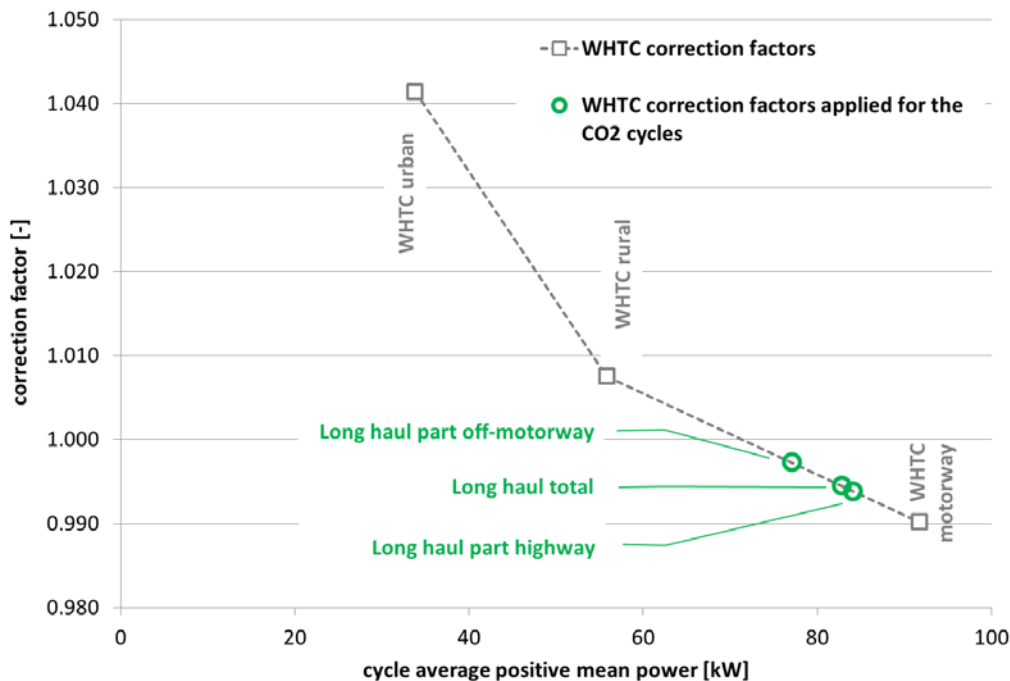
Figure 6: WHTC correction factors – engine#2

Figure 7 gives the comparison between measured and simulated fuel consumption for engine#2. The simulated values tend to underestimate the measured values; the application of the WHTC correction factors slightly increases this effect. The maximum deviation is found for the "off-highway" part of the long-haul cycle with an underestimation of 1.2%. This deviation can still be seen as acceptable as it is within the range of stated repeatability for fuel consumption measurement at the engine test bed (approx. +/-1.5%).
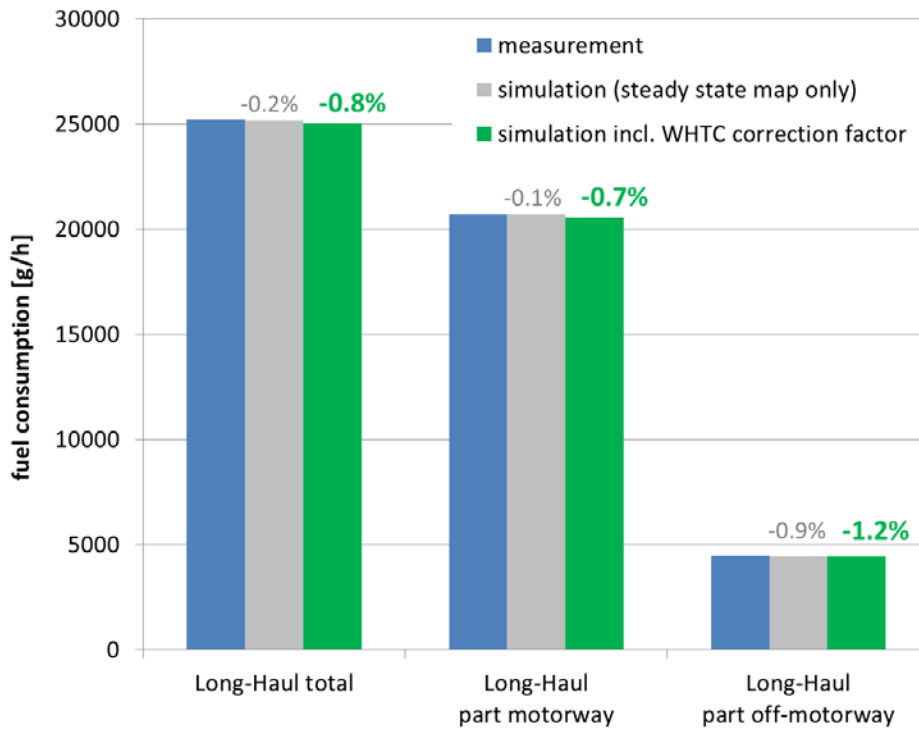
Figure 7: Comparison measured and simulated fuel consumption – engine#2

At this point it has to be mentioned that the WHTC correction factor has not only the function to make simulation more accurate but also to assure the consistency of regulated emissions and fuel consumption between the WHTC test and the steady state fuel map (see LOT2 report). This issue is one of the most important requirements for an appropriate HDV CO2 certification method.

4.2.2.   Rolling resistance tyres

The rolling resistance coefficient of tires defines the ratio of rolling resistance against driving direction to the force vertical to the driving direction:

$$RRC = \frac{F_0}{F_Z}[-]$$

Since HDV typically have mounted different tires on different axles (steering, traction, trailers) the rolling resistance of the entire vehicle is the sum of the rolling resistance force of all axles:

$$F_0 = \sum F_{Z_i} \times RRC_i$$

The RRC value depends on the vertical force on the axle (increased vertical force reduces the RRC coefficient due to higher temperatures and thus higher pressure in the tire), on ambient temperature and sun radiation (influences again tire temperatures), on the tread depth of the tire and on the road pavements.

Since pavement and ambient conditions in the road load test procedure used to determine the aerodynamic drag (chapter 4.2.3) cannot be controlled in very narrow boundaries if suffi-

cient numbers of test days per year and suitable test tracks shall remain, the rolling resistance value gained by the road load test is not used as input for VECTO.

A well-controlled test procedure for the RRC is implemented with the tire labelling directive (EC 122/2009 and 1235/2011), which allocated a label from "A" to "G" to the tire according to the RRC value measured under standardised conditions on a test drum (Figure 8). The test procedure is described in the ISO 28580 standard and the RRC determination is described in the EC regulation 117. To increase the repeatability of test results at different labs an inter-laboratory alignment procedure was established by the tire manufacturers. This procedure defines corrections for single test stands to align the results to a common standard.

It was obvious to take these aligned RRC values as input to the VECTO simulation tool. During the proof of concept phase the RRC values measured on the road and on the test track have been compared to the aligned RRC values. The finding was that the aligned RRC value from the drum test fits very well to the results from the road tests without any further correction, e.g. (Fontaras, 2014). This finding was also supported by analysis from ACEA (ACEA, 2014).

$$F_0 = \Sigma \, (RRC_{tire-i} * Fz_i)$$

RRC....Rolling resistance coefficient (corrected for F_z)

F_Z ....Tire vertical force [N]

CR.......Conversion facto road/drum (~1)
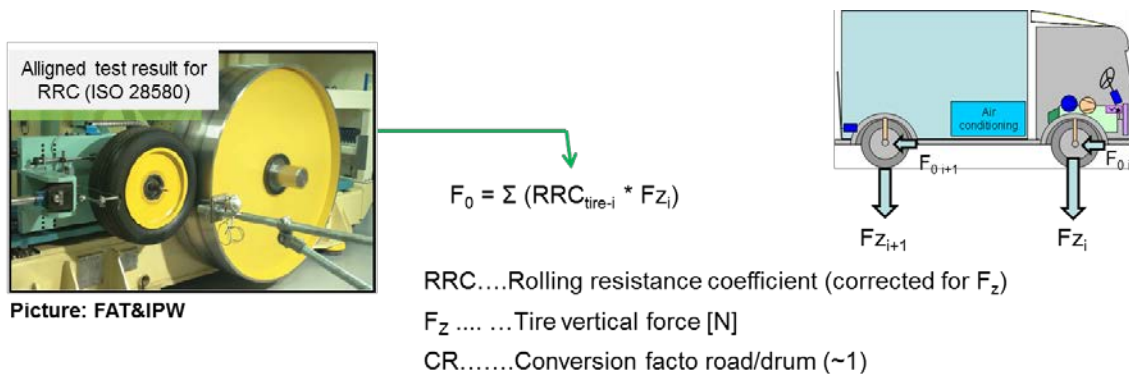
Figure 8: Schematic picture of the source and handling of tire rolling resistance coefficients

Although using the RRC values from the drum test stand eliminates several influences which occur at on road tests, still reasonable uncertainties exist which are reflected in a tolerance for RRC of 0.3 [kg/ton] for the declared tire label. Label class A covers for example tires up to RRC values of 5 [kg/ton] +0.3 [kg/ton]; Class B covers tires up to RRC values of 6 [kg/ton] +0.3 [kg/ton].

In LOT 3 it was consequently discussed with ACEA and tire manufactures which RRC value shall be used as input to VECTO. The options discussed are

- o the RRC value of the tire
- o the average RRC value of the tire label class
- o the upper RRC limit of the tire label class
- o each of the aforementioned options with or without the 0.3 [kg/ton] tolerance

With status 03/2014 it seems to be agreed between Commission, ETRMA and ACEA to apply the RRC value measured for each tire mounted on the vehicle as it is delivered to the customer. Main advantages seen with this approach is the higher accuracy of the resulting

fuel consumption value[5] and the incentive to improve the RRC values also in smaller steps than necessary to reach the next lower tire label class.

Details on the simulation of the rolling resistance are described in chapter 6.1. Details on the test procedure and data handling are described in the technical annex.

Open points for discussion are:

- Which tolerances shall be applied to the RRC values of single tires?
- How is a CoP introduced and how are responsibilities allocated?

4.2.3. Air drag test

In LOT2 possible options for measuring the aerodynamic resistance of HDV have been analysed extensively. The method of constant speed measurements has been identified to be most suitable to determine the aerodynamic resistance of an HDV as input for the CO_2 simulation. A first draft for the test procedure has already been elaborated within LOT 2, however some fundamental details (e.g. methods to consider ambient wind during the tests etc.) have not been worked out.

Within the scope of LOT 3 a detailed definition of the measurement procedure including a standardised software tool for test evaluation has been elaborated in close cooperation with industry. This section gives a brief description of the constant speed test procedure and lists the remaining open points which have to be solved before first implementation into legislation.

4.2.3.1.   Constant speed test procedure

General

Scope of the constant speed testing methodology is to determine the aerodynamic drag of the vehicle determined by the product of air drag coefficient (C_d) with the frontal area (A_{fr}) of the vehicle at zero-wind conditions (yaw angle $\beta=0$).[6]

To achieve this, the wheel torque of the driven wheels, the vehicle velocity, the actual air flow velocity (vehicle velocity plus wind) and the air flow direction are measured synchronously over straight motion on a test track. Measurements are performed at two different constant vehicle speeds (V_{low} and V_{high}) under defined conditions. The V_{low} of the testing is a constant velocity between 10 - 15 km/h while the target V_{high} should be between of 85 - 90 km/h. In case a vehicle cannot achieve the foreseen high speed, the maximum achievable vehicle speed is applied.

Given the abovementioned measured data it is possible to calculate the road load of the vehicle (see Figure 9) based on the following qualified assumptions:
- rolling resistance force (F_{rol}) (and also gradient force) independent of vehicle speed[7]

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[5] This is also relevant for the SiCo test procedure, chapter 2.6.

[6] The influence of cross wind is considered in VECTO by a generic approach, see section 4.1.

- air drag force increase being quadratic to the air velocity
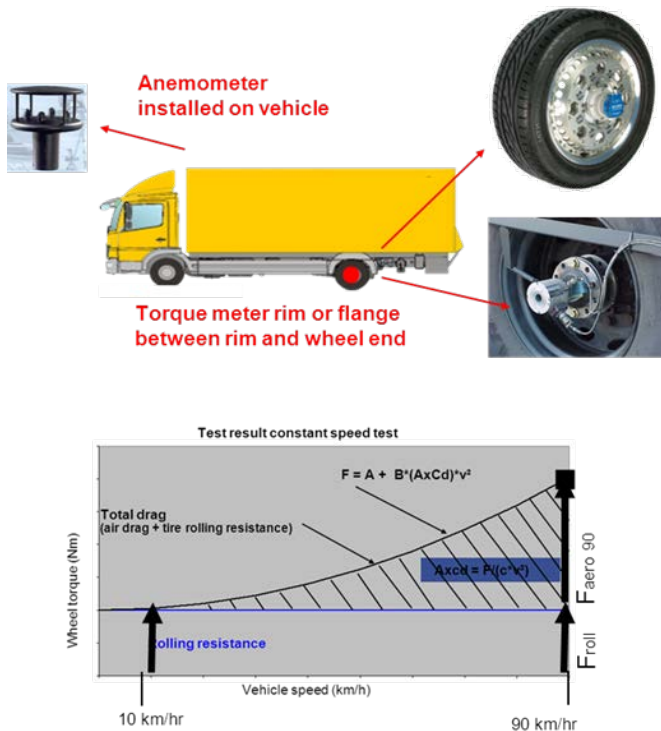
Figure 9: Key points of the constant speed testing methodology

In addition to the key elements of the test demonstrated in Figure 9, important parameters of the procedure include the use of high precision positioning instrumentation for accurate recording of vehicle position and ground speed (opto-electronic barriers or very high precision GPS system), weather information and data retrieved from vehicle sensors. Detailed specifications are foreseen for each instrument and for the sampled signals.

Test Track

In terms of the testing ground different types of test track geometries are foreseen (Figure 10). The important factor in this case is the execution of measurements in both directions in order to cancel out to the best possible extent the effects of ambient wind. The test track must have straight section(s) were the recorded data are evaluated ("measurement sections"). An extra straight length before each measurement section is foreseen in order to allow for the stabilization of wind flow around the vehicle and of the drivetrain torque after cornering.

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[7] Recent analysis of data from tire manufacturers and vehicle OEMS indicate that the assumption of a constant rolling resistance over the vehicle speed range (10km/h to 90km/h) is not fully valid. In 2014 activities are ongoing to quantify this effect and to consider this behaviour in the air drag test procedure.
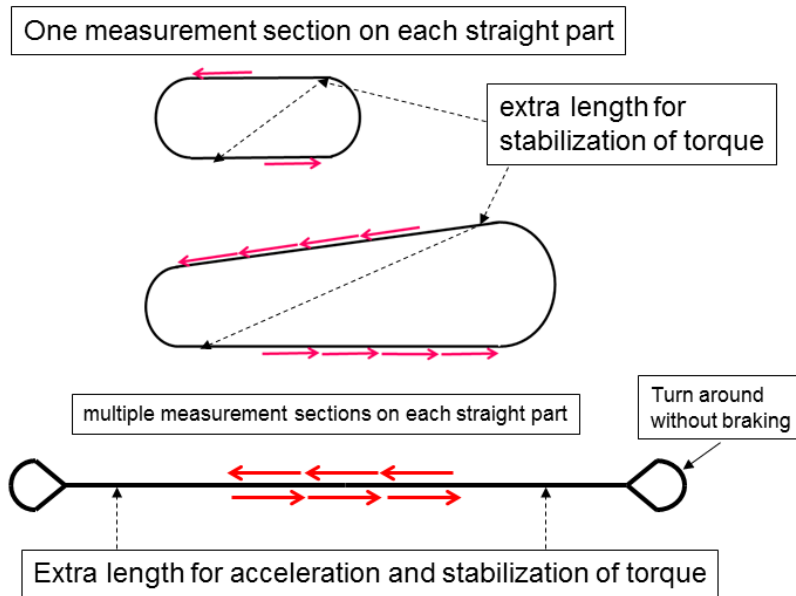
Figure 10: Types of testing grounds and definition of measurement sections

Test sequence

The test sequence consist of four main phases: the warm up phase including the calibration run, the first low speed run, the high speed run and the second low speed run as described below.

Warm-up phase including the calibration run

During this phase the vehicle is driven for 90 minutes at V_{high} to assure that the tyres reach a constant pressure and temperature level, and that the powertrain and drivetrain reach a constant coolant and lubricant temperature level. During this phase, the vehicle is driven in order to achieve a balanced warm up of the tires and to collect data for the calibration of the signals for vehicle speed, for air speed and for yaw angle ("calibration run").

At the end of the warm up phase, the vehicle is brought to a standstill on a selected area of the test track. The vehicle is slowed down carefully without braking and rolled out for the last meters, with free clutch / neutral gear and engine switched off. Once still and in zero torque conditions, the torque sensors mounted on the vehicle are checked for drift and are subsequently zeroed.

First low speed run

After the zeroing of the torque sensors the vehicle is driven for a minimum of 2 km at V_{high} in order to reach stabilization again. Subsequently the V_{low} test is performed. During testing it must be ensured that:

- the driving speed is constant at least for the defined measurement sections and the preceding stabilization sections
- the vehicle is driven through the measurement section along a straight line without steering
- the amount of recorded measurement sections leads to enough valid data for the later processing

High speed run

After the first low speed run the vehicle is driven for a minimum of 2 km at V_{high} in order to reach stabilization again. Subsequently the V_{high} test is performed. As in the case of the V_{low} test it must be ensured that the driving speed is constant at least for the measurement sections and the preceding stabilization sections, and that the vehicle is driven through the measurement section along a straight line without steering.

Second low speed run

The second test at V_{low} is performed directly after the high speed test.

In both V_{low} and V_{high} tests the beginning and end of the measurement sections should be clearly recognizable in the measurement data, either via a recorded trigger signal (opto-electronic barriers in combination with GPS) or via recorded DGPS data.

Furthermore a series of quality checks are specified in the test procedure, e.g. a control phase directly after the second low speed run to check if the drift of the torque sensors remained within acceptable value.

Post processing and data evaluation

A series of post processing corrections on measured data are foreseen. The recorded average vehicle speed is corrected based on the information retrieved from the optical barriers or from the high precision GPS. The air flow velocity signal of the mobile anemometer is corrected in three steps for the instrument's error as defined by the calibration report, the error generated by the positioning of the instrument on the vehicle (measuring position inside an accelerated flow due to the shape of the vehicle) and the air flow boundary layer effect and the yaw angle misalignment. Furthermore data recorded in invalid conditions (either too high wind velocities or yaw angles or too instable torque levels) are removed from further analysis.

The main part of the data evaluation is then the extraction of the air resistance influence by a linear regression for traction force over quadratic air speed. Based on the assumptions discussed above the air resistance is assigned to the quadratic influence of air speed to traction force. From this data the value for $C_{d}xA$ can be determined. This evaluation is done for each combination of measurement section and driving direction separately. The final value $C_{d}xA$ is then gained by the average result for the different measurement sections corrected for the influence of average cross-wind conditions during the measurements. This correction is done based on a generic dependency defined for the main vehicle body types.

For data post-processing and data evaluation a standardised software tool was developed in LOT3, see section 6.2 (VECTO-CSE).

4.2.3.2.   Repeatability, reproducibility and robustness of the method

A first evaluation of the reproducibility and repeatability metrics of the proposed method was performed as part of the "Proof of Concept" activities in 2013 based on measurements on two vehicles performed by vehicle OEMS and by DG JRC, e.g. [Fontaras, 2014]. Table 6

summarizes the calculated repeatability and reproducibility standard deviations (normalized by the average value recorded). Analysed data were measured based on an earlier version of the test procedure which is expected to be less accurate, repeatable and reproducible than the latest version.

Table 6: Repeatability and reproducibility standard deviation of the method[8]

	Veh #1 Tests JRC	Veh #1 Tests OEM	Veh #2 Tests JRC	Veh #2 Tests OEM
Standard deviation	1.6%	1.8%	1.1%	1.4%
Repeatability standard deviation (σ_r)	2.4%		1.8%	
Between labs standard deviation	1.7%		1.3%	
Reproducibility standard deviation (σ_R))	2.9%		2.2%	

Given the fact that the method is expected to be improved in the meantime the achieved figures for the repeatability standard deviation (1.8 to 2.4%) and the reproducibility standard deviation (2.2% to 2.9%) are considered satisfactory. Based on these results the repeatability limit (r), which is the value less than or equal to the absolute difference between two results, obtained under repeatability conditions, may be expected to be with a probability of 95%, is in the order of 4.9% to 6.7% of the actual C_dxA value measured, [Fontaras, 2014].

4.2.3.3. Open issues related to the air drag test procedure
The remaining open issues which have to be solved before first implementation into legislation are summarised below:

1.) Influence of tire rolling resistance behaviour on constant speed test results

According to recent data from tire OEMs and from independent lab tests (Pflug, 2014) and (ETRTO, 2013) the assumption of a constant rolling resistance in the vehicle speed range from 10km/h to 90km/h under the boundary conditions of constant tire temperature is not fully valid. This effect might influence both the reproducibility of the test procedure (e.g. by achieving different C_dxA values for a particular vehicle if tested with different tires and on different test track and ambient conditions) and also somewhat bias the overall C_dxA numbers determined by the procedure.

In spring 2014 activities have been started to further investigate the relevant mechanisms and to adequately modify the test procedure. The measures decided in spring 2014 are:

a) There will be a preliminary updated "interim solution" for the constant speed test procedure which will be followed by the OEMs in the testing during this year. This updated procedure e.g. foresees to run the constant speed test with empty vehicles (not with standard lad-

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[8] In 2014 ACEA announced to work on an update of numbers on repeatability and reproducibility of the procedure.

en vehicles) to reduce the influence of the rolling resistance. Also using tires with minimum profile is an option to reduce the influence of rolling resistance. Also the preliminary (and voluntary) use of a particular tire model for testing is under discussion.

b) A testing program using a special test rig which is able to determine the rolling resistance in on-road driving directly (operated by CVE, Prof. Pflug) has been elaborated. Industry indicated that they will make budget available for these investigations.

c) The ACEA aero group will also propose a test program for the tire test drum to ETRTO. Main issue here is to guarantee that the drum results are really comparable to on-track testing conditions. Tire industry has indicated willingness to support the activities.

2.) Family concepts

In order to reduce the test burdens for the OEMs family concepts have to be elaborated which shall reduce the number of vehicles to be measured with the full constant speed test procedure. From ACEA such a proposal was already presented in the latest Whitebook version. This proposal has to be analysed, and if necessary further discussed with industry and finally implemented into the legislative context.

3.) Determination of relative differences of air drag by means of CFD (Computational Fluid Dynamics)

CFD might be suitable method for determination of relative differences in air drag for certain HDV design variants. Within ACEA activities are ongoing to clarify the suitability of such an approach as part of the HDV CO_2 certification and its necessary boundary conditions. CFD was also used in LOT 3 to compute standard tractors in a comparison exercise with ACEA (chapter 4.4). Before CFD can be introduced for certification purposes is seems that more details of the code and of the settings need to be harmonised but the approach is promising.

4.) Elaboration of vehicle class specific rules for C_dxA-values

As a further means to avoid unnecessary testing efforts for some HDV classes the elaboration of "special rules" for the C_dxA value to be used the in the VECTO calculation are discussed, e.g.: using default table values for vehicle class 16 (8x4 construction vehicles), where the effect of the aerodynamic characteristics on overall fuel consumption is small and the vehicles are sold in most cases with customer specific superstructures.

4.2.4.   Transmission test

For assessing the losses of the transmission, three different options have been defined:

- Option 1: Fall back values based on the maximum rated torque of the transmission

- Option 2: Measured torque independent losses, calculated torque dependent losses. Electric machine and torque sensor before transmission (output shaft free-rotating)

- Option 3: Measurement of total torque loss. Electric machines and torque sensors in front and behind transmission

The applicant is allowed to switch between these options for different gears, also within one transmission. The three options are described in detail in the Technical Annex.

A family concept to reduce test efforts has been proposed by ACEA. This concept is not implemented in the Technical Annex so far. Depending on the later legal implementation, this proposal has maybe to be revised again.

Main open issues to be addressed after Lot 3:

- Family concept

- Maybe oil family concept

- Accuracy of torque sensors / Definition of error analysis concept

4.2.5. Axle test

For assessing the losses of the axle, one of the two different methods can be applied:

- Option 1: Torque loss table values (default values) based on a generic constant efficiency and torque loss of the axle

- Option 2: Test bench measurement of torque loss maps for each individual axle and ratio

Similar to the transmission testing, the applicant is free to choose an option. The two options are described in detail in the Technical Annex.

Main open issues to be addressed after Lot 3:

- Family concept

- Verification of the generic standard table values

- Definition of a reference test cycle to find the worst case oil (necessary for application of the family concept for different oils)

- Handling of design changes during production cycle of an axle type to reduce test effort

Beside the revision of the family concept, no main open issues can be identified.

4.2.6. Auxiliaries

Auxiliary systems are devices that provide energy for functions other than propulsion. Auxiliaries are either needed for proper operation of the engine (e.g. engine cooling fan) or of vehicle related systems (e.g. compressor for pressurised air system). In conventional vehicles, auxiliary units are driven by mechanical power from the internal combustion engine.

The power consumption of some engine-related auxiliary components are already implicitly covered by the engine fuel map and hence do not have to be considered separately. These components are:

- engine oil pump
- coolant pump
- fuel delivery pump
- fuel high pressure pump

The remaining auxiliary units need to be covered in the fuel consumption modelling individually. These systems are:

- engine cooling fan
- alternator
- air compressor
- steering pump
- A/C compressor

Power take off (PTO) has so far not been addressed in the development of the HDV CO_2 certification procedure. For some HDV categories PTO would be relevant for the entire fuel consumption (e.g. garbage trucks or street cleaning vehicles). If such HDV shall be included in the CO_2 certification in combination with typical PTO power consumption is not decided yet.

The method how to cover auxiliaries was quite unclear at the beginning of LOT3. During the development of VECTO a general approach has been elaborated, which allows for a robust modelling of all types of auxiliary units. This method is based on a two-step approach which differentiates between the consumer demand (called "supply power", e.g. the electrical power which is required by the electrical consumers on the vehicle) and the efficiency of the auxiliary unit itself (e.g. the alternator efficiency map).[9] This approach was communicated with industry and was the baseline structure used in the common efforts to elaborate the data tables. The main advantage of this approach is that in future component specific efficiency values instead of the generic ones can be implemented. To be in this direction future proofed, the generic efficiency values certainly have to be carefully selected to be not too attractive. Certainly also the test procedures for single auxiliaries need to be agreed before component specific efficiency values can be introduced. Nevertheless, it seems to be very likely that in future more efficient auxiliaries with smart controllers enter the market and have to be covered by the VECTO method. An alternative option using table values with constant mechanical power demand to describe auxiliaries was also an attractive option but seemed to have limits for future extensions of the model.

For trucks the influence of auxiliaries on overall fuel consumption was assessed to be of secondary importance. Hence intentionally rather simple methods have been developed so far. As a general principle the auxiliary power demand is simulated in VECTO for trucks adding a constant power level to the internal combustion engine. At the moment only generic data are used, which are depending for most of the systems on a technology specification of the installed device. These technology specifications (e.g. for an engine cooling fan: "crankshaft mounted - electronically controlled visco clutch") has to be specified by the OEM in the vehicle declaration.[10]

In the elaboration of the generic data explicit attention has been given to be compatible that at a later point in time

- also OEM specific data on auxiliary performance or on "consumer" behaviour might be used and/or

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[9] This method is described in detail in section 4.1 (description of the VECTO model).

[10] In a pilot phase of the test procedure Technical Services shall verify if the definition of "technologies" as provided so far is sufficient or if further descriptions are required for explicit identification.

- that more advanced algorithms might be used.

For buses, the impact of auxiliary performance was found to have a much more significant impact than for trucks. Especially the HVAC system was found to be very relevant and complex in simulation. Hence it was decided to cover this topic in a separate project. Some of the methods elaborated there might also be introduced also trucks at a later point in time.

Below the methods and data as elaborated during LOT 3 for trucks are described in detail. Also remaining open points are addressed.

4.2.6.1. Engine cooling fan

The power consumption of the engine cooling fan is determined as a function of mission profile and fan technology. The according numbers have been elaborated by ACEA and are shown in Table 7. The values have been checked by the LOT3 consortium wherever data was available. A detailed derivation of the numbers via values for baseline supply power and technology dependent idling losses and efficiencies is provided in the ACEA Whitebook.

Furthermore it was discussed with industry whether a scaling of fan power demand as a function of engine size is required (e.g. scaling based on rated power). ACEA does not recommend doing so. This simplification is seen justifiable as the contribution of the engine cooling fan to the overall fuel consumption is low (smaller than 1% in most truck mission profiles).

Table 7: Power demand for the engine cooling fan

Fan technology	Mission profile				
	Long haul	Regional delivery	Urban delivery	Municipal utility	Construc-tion
	Mechanical power demand [W]				
Crankshaft mounted - Electronically controlled visco clutch	618	671	516	566	1037
Crankshaft mounted - Bimetallic controlled visco clutch	818	871	676	766	1277
Crankshaft mounted - Discrete step clutch	668	721	616	616	1157
Crankshaft mounted - On/Off clutch	718	771	666	666	1237
Belt driven or driven via transm. - electronically controlled visco clutch	889	944	733	833	1378
Belt driven or driven via transm. - bimetallic controlled visco clutch	1089	1144	893	1033	1618
Belt driven or driven via transm. - discrete step clutch	939	994	883	883	1498
Belt driven or driven via transm. - on/off clutch	989	1044	933	933	1578
Hydraulic driven - variable displace-ment pump	738	955	632	717	1672
Hydraulic driven - constant dis-placement pump	1000	1200	800	900	2100
Hydraulic driven - electronically con-trolled	700	800	600	600	1400

4.2.6.2. Electric system / alternator

The power demand of the electric system of trucks is determined based on two characteristic numbers:

1.) The power consumption of the electric consumers, which is determined from a generic table as a function of mission profile and vehicle technology

ACEA provided a draft for the table values in the Whitebook. The total average electrical load is calculated from the sum of the baseline power consumption and additional electric power consumers and of reduction effects of power saving technologies (Table 8). This table still has to be supplemented in terms of electric power saving technologies and additional con-sumers.

Table 8: Draft table values for electric consumers [W]

Vehicle technology	Mission profile				
	Long haul	Regional delivery	Urban delivery	Municipal utility	Construc-tion
Baseline electric power consumption	1240	1055	974	974	975
Electric power saving tech. 1: LED lights	-50	-50	-50	-50	-50
Electric power saving technology 2: t.b.d.	*-xx*	*-xx*	*-xx*	*-xx*	*-xx*
Additional consumer type 1: t.b.d.	*+yy*	*+yy*	*+yy*	*+yy*	*+yy*
Total average electric load (example)	1190	1005	924	924	925

2.)   An average electric efficiency of the alternator

The alternator efficiency shall be determined by a generic table as a function of mission profile and alternator technology. ACEA drafted such a table in the latest Whitebook version but did not come up with final numbers and definitions for alternator technologies so far.

LOT3 received efficiency maps from BOSCH for "typical average" alternator technology. Based on this data typical HDV configurations have been simulated in different mission profiles with VECTO. Based on the results an <u>average efficiency of 70% for standard alternator technology</u> is suggested.

This value shall be consolidated with ACEA data and possibly supplemented by further more efficient alternator technologies. However BOSCH indicated, that alternator efficiencies are not necessary well specified by the design type.[11] So an alternative option to prove higher average alternator efficiency in the declaration would be to determine the component specific value based on a test procedure (e.g. a using the 9-point test adapted from ISO8854:2012 as suggested by BOSCH, where the 9 points are then weighted to an average according to a typical operation profile).

Summary of open issues for the electric system / alternator:

- Supplementation of table with electrical consumers, power saving technologies and additional electrical consumers.
- Finalisation of table with standard alternator efficiencies.
- Agreement on a method for consideration of higher alternator efficiencies (either by technology definitions or specification of a component test procedure).

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[11] E.g. a worse performing alternator from a „better" technology might perform worse than a good alternator from a „worse" technology.

4.2.6.3. Air compressor

Industry so far did not come up with methods how to consider air compressor operation in the HDV CO_2 certification for trucks. However, a detailed simulation method for air compressors from buses and coaches was already published in the ACEA Whitebook. This method is summarised below for truck specific tasks. Since in a parallel project the approach for buses shall be further developed and implemented into VECTO by AEA-Ricardo, it shall be considered to switch also the method for truck to the new method for buses, if it proofs to be suitable.

The flow rate of compressed air to be provided by the compressor shall be computed from generic table values for the consumers over the test cycle by VECTO based on braking, suspension events etc. (e.g. Figure 11). The generic consumption values are defined by vehicle specific technology data which has to be selected. With this information the total consumption of pressurised air by the bus can be computed.

In a next step the average delivery rate [m³/min] from the air compressor is computed from a characteristic line of the compressor (volume flow = function of rpm). To interpolate the volume flow from the characteristic line a first run of VECTO is necessary to calculate the average engine speed to be able to assess the average rpm of compressor.

Then the duty time is computed which represents the share in time of the test cycle the air compressor has to run to provide over the entire test cycle the demanded air volume (Duty time = air demand / delivery rate).

The duty time is then further split into overrun phases (no fuel consumption) and traction phases to calculate the time the compressor runs at engine conditions relevant for additional fuel consumption. In this step smart compressors shall be treated differently since these are controlled to be more active during motoring where the compression work is not causing additional fuel consumption.

Table values for auxiliaris	
A: Air system	**average**
power consumption of each compressor type	refer to charts
share of overrun time that can be used for air compression	97%
air demand per braking [Nl/kg]	0.0006
increase of air demand for breaking for vehicles without retarder	35%
air demand per kneeling [Nl/kg*mm]	0.000066
air demand per door opening [Nl]	12.7
air demand per bus stop brake actuation [Nl/kg]	0.00064
additional air demand for mechanically controlled air suspension [Nl/min]	15
air demand for adblue dosing [Nl/min]	21.25
air demand for regeneration for vehicle **without** smart regeneration [percentage of total air demand without dead	26%
air demand for regeneration for vehicle **with** smart regeneration [percentage of of total air demand without	12%
dead volume [l]	30
number of dead volume blow-outs [1/h]	24

Table of vehicle specifications: auxiliaries			
A: Air system			
compressor type	type 1	type 2	type 3
		x	
ratio engine speed / compressor speed	1,3		
smart air compression	yes	no	
	x		
smart regeneration	yes	no	
	x		
retarder break	yes	no	
	x		
kneeling height [mm]	80		
air suspension control	mechanically	electronically	
		x	
adblue dosing	pneumatic	electric	
	x		
doors	pneumatic	electric	
	x		

Figure 11: Schematic picture of generic values for pressurised air consumption (left table) and bus specific technology definitions (source ACEA)

Then the average power demand of the compressor shall be computed from characteristic lines for idling and full load of the compressor (e.g. Figure 12). ACEA suggests that these characteristic lines for compressor performance shall be measured for each compressor in a standardised test procedure. For this test procedure ACEA also drafted the main boundary conditions. In addition generic default data shall be made available for OEMs who decide not to make the test efforts.

*The average mechanical power consumed by the air compressor [kW] is then calculated by: duty time [%] * power at full load [kW] + (100%-duty time) * power at idling.*

The values for "power at full load" and "power at idling" are calculated based on the air compressor characteristic lines taking into account typical engine speed distributions.
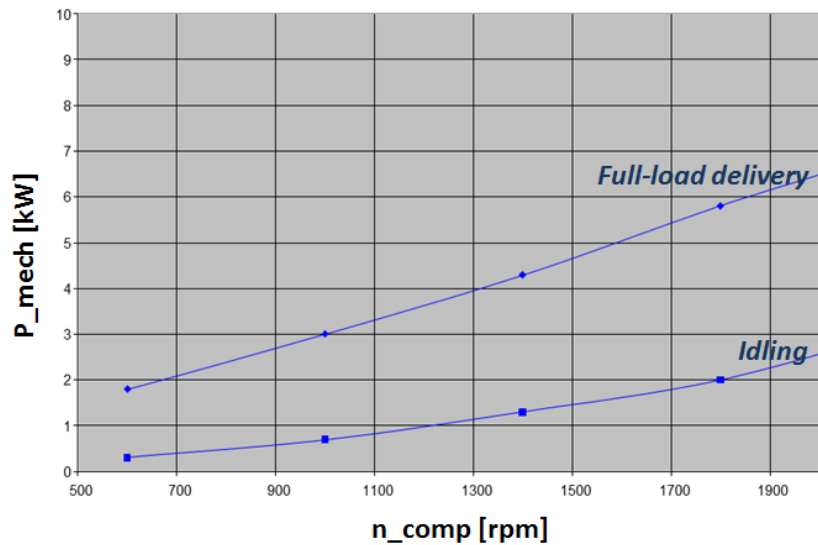
Figure 12: Schematic picture for the power demand of an air compressor (source ACEA)

The method as drafted by ACEA for city buses and coaches is estimated to allow several simplifications without big drawbacks in the accuracy. The speed levels for the compressor may be set to generic values to avoid the demand of iteration loops and smart controllers may be simulated by a pressure vessel without demand for testing. As discussed before, depending on the simplifications to be achieved by AEA-Ricardo, the model may be applied for truck too.

For the time being in LOT3 a simpler approach has been elaborated for trucks consolidating parts of the data as provided by ACEA for busses and a simple compressor model which was elaborated by TUG.

In a first step the baseline air consumption (in the unit "standard litres per minute" [sl/min]) is determined for each combination of HDV vehicle class and mission profile (see Table 9). The mechanical power consumption of the compressor is then determined in a second step by multiplication of the baseline air consumption by a generic specific power demand of 0.02 [kW/(sl/min)] (value for standard compressor technology). Based on this approach e.g. for a class 5 vehicle operated on a long haul mission the power consumption of the compressors is calculated with 1.34 kW.

Table 9: Baseline air consumption [sl/min]

Axle configuration	Chassis configuration	Maximum GVW [t]	<-- Vehice class	Long haul	Regional delivery	Urban delivery	Municipal utility	Con-struction
				HDV vehicle class	**Mission profile**			
4x2	Rigid or Tractor	7.5 - 10	1	---	65	62	---	---
	Rigid or Tractor	>10 - 12	2	59	64	66	---	---
	Rigid or Tractor	>12 - 16	3	---	68	69	---	---
	Rigid	>16	4	65	67	---	n.a.	---
	Tractor	>16	5	67	91	---	---	---
4x4	Rigid	7.5 - 16	6	---	---	---	n.a.	n.a.
	Rigid	>16	7	---	---	---	---	n.a.
	Tractor	>16	8	---	---	---	---	n.a.
6x2/2-4	Rigid	all weights	9	67	77	---	n.a.	---
	Tractor	all weights	10	67	91	---	---	---
6x4	Rigid	all weights	11	---	---	---	---	n.a.
	Tractor	all weights	12	---	---	---	---	n.a.
6x6	Rigid	all weights	13	---	---	---	---	n.a.
	Tractor	all weights	14	---	---	---	---	n.a.
8x2	Rigid	all weights	15	---	---	---	---	n.a.
8x4	Rigid	all weights	16	---	---	---	---	n.a.
8x6 & 8x8	Rigid	all weights	17	---	---	---	---	n.a.

Open issues:

The values in Table 9 shall be further consolidated with data from industry and supplemented for the vehicle classes where not values are specified.[12] Also the generic specific power demand of the air compressor shall be further checked by industry, and possibly supplemented by additional values specified per compressor technology.

4.2.6.4. Steering pump

The power consumption of the steering pump is determined based on the combination of vehicle class and mission profile and the applied steering pump technology. Methods and data have been elaborated by ACEA and were checked by the LOT3 consortium wherever data was available. A detailed derivation of the final numbers based on background data can be found in the ACEA Whitebook. Below the method and the data implemented into VECTO are explained.

The power demand (in [W]) from the steering system is split into four parts "U", "F", "B", and "S":

- U(nloaded): Pumping of the oil without steering pressure demand

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[12] For these classes the baseline air consumption could not be calculated as no representative vehicle masses were available.

- F(riction): Friction in the pump (e.g. bearing friction)
- B(anking): Steer correction due to banking of the road or side wind
- S(teering): Steering pump power demand due to cornering and manoeuvring

These values are specified by a generic table per vehicle class and mission profile (Table 10).

Table 10: Generic table for power demand in the steering system (source: ACEA Whitebook)

Identification vehicle configuration			Class	Long haul (1)				Regional delivery (2)				Urban delivery (3)				Municipal utility (4)				Construction (5)			
Axle configuration	Chassis configuration	Weight	Vehicle Class	U	F	B	S	U	F	B	S	U	F	B	S	U	F	B	S	U	F	B	S
2 axles — 4x2	Rigid + (Tractor)	7,5t - 10t	1					110	130	20	0	100	120	20	30								
	Rigid + (Tractor)	> 10t - 12t	2	150	190	30	0	130	160	30	0	120	140	20	30								
	Rigid + (Tractor)	>12t - 16t	3					140	170	30	0	130	150	30	40								
	Rigid	> 16t	4	230	280	100	0	220	270	40	0					?	?	?	?				
	Tractor	>16t	5	270	330	120	0	250	290	90	0	220	260	80	60								
4x4	Rigid	7,5t - 16t		exclude all-wheel-drive vehicles 4x4 (sales volume < 1%)																			
	Rigid	> 16t	7																	?	?	?	?
	Tractor	> 16t		exclude all-wheel-drive vehicles 4x4 (sales volume < 1%)																			
3 axles — 6x2/2-4	Rigid	all	9	270	330	120	0	220	270	60	0					?	?	?	?				
	Tractor	all	10	200	250	120	0	200	240	90	0												
6x4	Rigid	all	11																	?	?	?	?
	Tractor	all	12																	?	?	?	?
6x6	Rigid	all		exclude all-wheel-drive vehicles 4x4 (sales volume < 1%)																			
	Tractor	all																					
4 axles — 8x2	Rigid	all		exclude 8x2 (very low sales volume <1%)																			
8x4	Rigid	all	16																	?	?	?	?
8x6	Rigid	all		exclude all-wheel-drive vehicles 4x4 (sales volume < 1%)																			

The total mechanical power demand from the steering pump is then calculated as shown in Equation 1 using "scaling factors", which are applied to differentiate between different steering pump technologies.

$$P_{tot} = P_U \cdot CF_U + P_F \cdot CF_F + P_B \cdot CF_B + P_S \cdot CF_S \qquad \text{Equation 1}$$

where:

P_{tot} = total mechanical power demand from the steering pump [W]

P_i = power demand from the steering system (i="U", "F", "B", "S") (Table 10) [W]

CF_i = technology dependent scaling factor (i="U", "F", "B", "S") [-]

The scaling factors CF_i are shown in Table 11. For two technologies numbers have not been finalised so far.

Table 11: Technology dependent scaling factors (source: ACEA Whitebook)

Technology	CF_U (Unloaded)	CF_F (Friction)	CF_B (Banking)	CF_S (Steering)
Fixed displacement	1,0	1,0	1,0	1,0
Dual displacement	Unknown	Unknown	Unknown	Unknown
Variable displacement	0,6	0,6	0,6	0,6
Hydraulic supported by electric	0,7	1	0,9	0,9
Electric	Unknown	Unknown	Unknown	Unknown

4.2.6.5. A/C compressor

The average power consumption of the air conditioning compressor is allocated by the combination of HDV class and mission profile. The according numbers have been provided by ACEA and verified by the LOT3 consortium based on a simulation tool and data elaborated in the MAC project on LDV (Hausberger, 2013). Data for HDV classes not provided by ACEA have been adjusted from other HDV classes by the LOT3 consortium. The final numbers which have been implemented are shown in Table 12.

Table 12: Average power demand of the air compressor from the AC system

HDV class				Mission profile				
Axle configuration	Chassis configuration	Maximum GVW [t]	<-- Vehice class	Long haul	Regional delivery	Urban delivery	Municipal utility	Construction
				power demand [W]				
4x2	Rigid or Tractor	7.5 - 10	1	---	150	150	---	---
	Rigid or Tractor	>10 - 12	2	200	200	150	---	---
	Rigid or Tractor	>12 - 16	3	---	200	150	---	---
	Rigid	>16	4	350	200	---	300	---
	Tractor	>16	5	350	200	---	---	---
4x4	Rigid	7.5 - 16	6	---	---	---	300	200
	Rigid	>16	7	---	---	---	---	200
	Tractor	>16	8	---	---	---	---	200
6x2/2-4	Rigid	all weights	9	350	200	---	300	---
	Tractor	all weights	10	350	200	---	---	---
6x4	Rigid	all weights	11	---	---	---	---	200
	Tractor	all weights	12	---	---	---	---	200
6x6	Rigid	all weights	13	---	---	---	---	200
	Tractor	all weights	14	---	---	---	---	200
8x2	Rigid	all weights	15	---	---	---	---	200

HDV class				Mission profile				
Axle configuration	Chassis configuration	Maximum GVW [t]	<-- Vehice class	Long haul	Regional delivery	Urban delivery	Municipal utility	Construction
8x4	Rigid	all weights	16	---	---	---	---	200
8x6 & 8x8	Rigid	all weights	17	---	---	---	---	200

The power demand of the ventilation system is considered in the power consumption of the electric system and not included in the numbers from Table 12.

4.3. CO$_2$ test cycles

As described in chapter 6.1, VECTO uses target speed cycles ("CO$_2$" test cycles") to calculate the fuel consumption and emissions of the HDV. The target speed cycles define the velocity the driver wants to reach over the distance of the trip. To properly reflect the different mission profiles in which different HDV classes are used in real world traffic, a set of five CO$_2$ test cycles for HGV and of five CO$_2$ test cycles for buses and coaches have been developed. The cycle development was coordinated by ACEA with support by the LOT 3 consortium. The cycles are described in the technical annex. In the following an overview on the development and validation process is given.

4.3.1. Introductory remarks, validation approach

The determination of the CO$_2$ emissions by the HDV vehicle simulation tool is based on target speed cycles specific for different mission classes. The following mission classes are implemented:

- Urban delivery,
- Regional delivery
- Long haul,
- Construction,
- Municipal utility,
- Citybus heavy urban,
- Citybus urban,
- Citybus suburban,
- Interurban bus,
- Coach.

The cycles were developed on the basis of extensive analyses of in-use driving behaviour data. An in-use cycle consists of short trips (v > 1 km/h) and stop sections. The short trips of the resulting representative cycles were replaced by target speed sections combined by the

corresponding stop sections. Short trips with varying speeds were replaced by sections with varying target speeds.

In a validation step these cycles were compared with the EU part of the WHDC database which built the basis for the WHDC development. In order to establish such a comparison, the target speed cycles had to be transformed into vehicle cycles with acceleration and deceleration phases between the target speed sections.

The problem that needs to be resolved was, that the target speed cycles are distance based (resolution 1 m) while the in-use database contains time based (resolution 1 s) speed traces.

In order to solve this problem acceleration and deceleration phases for the target speed cycles were calculated based on constant specific acceleration power values (v*a) with an additional upper acceleration limit, so that the acceleration decreases with increasing vehicle speed, in line with the in-use data analysis results.

The time duration for each 1 m sample of the target speed cycle was then calculated on the basis of the vehicle speed.

Sensitivity calculations were performed in order to determine appropriate variation ranges for the v*a values. One side condition was that the target speeds should be reached within a target speed section. An average acceleration/deceleration case was then chosen for the comparison of the resulting vehicle speed distributions with corresponding in-use distributions.

This approach implies that acceleration distributions and other key parameters based on the target speed cycles cannot be generalised.

Apart from this validation work further checks were performed with respect to the road gradient profiles that were added to the target speed cycles. These checks focussed on altitudes balances (the altitude at the beginning and the end of the cycles should be the same) and the necessity for smoothing of the gradient pattern in case of "rippled" traces. The road gradient profiles itself could not be validated because the WHDC database does not provide road gradient information.

4.3.2. Urban delivery cycle

With respect to trucks, the WHDC database consists of 8 rigid trucks and 12 trailer/semitrailer trucks. 4 of the rigid trucks could be assigned to urban delivery, 1 to regional delivery and 3 had mixed mission profiles. 5 trailer/semitrailer trucks could be assigned to regional delivery, the other 7 to long haul mission.

Figure 13 shows the vehicle speed frequency distributions of the WHDC in-use data for the 4 vehicles (indicated by their vehicle number) with urban delivery missions together with their average and the frequency distribution of the VECTO cycle. The frequency basis is the time duration. Figure 14 shows the corresponding distance based distributions.
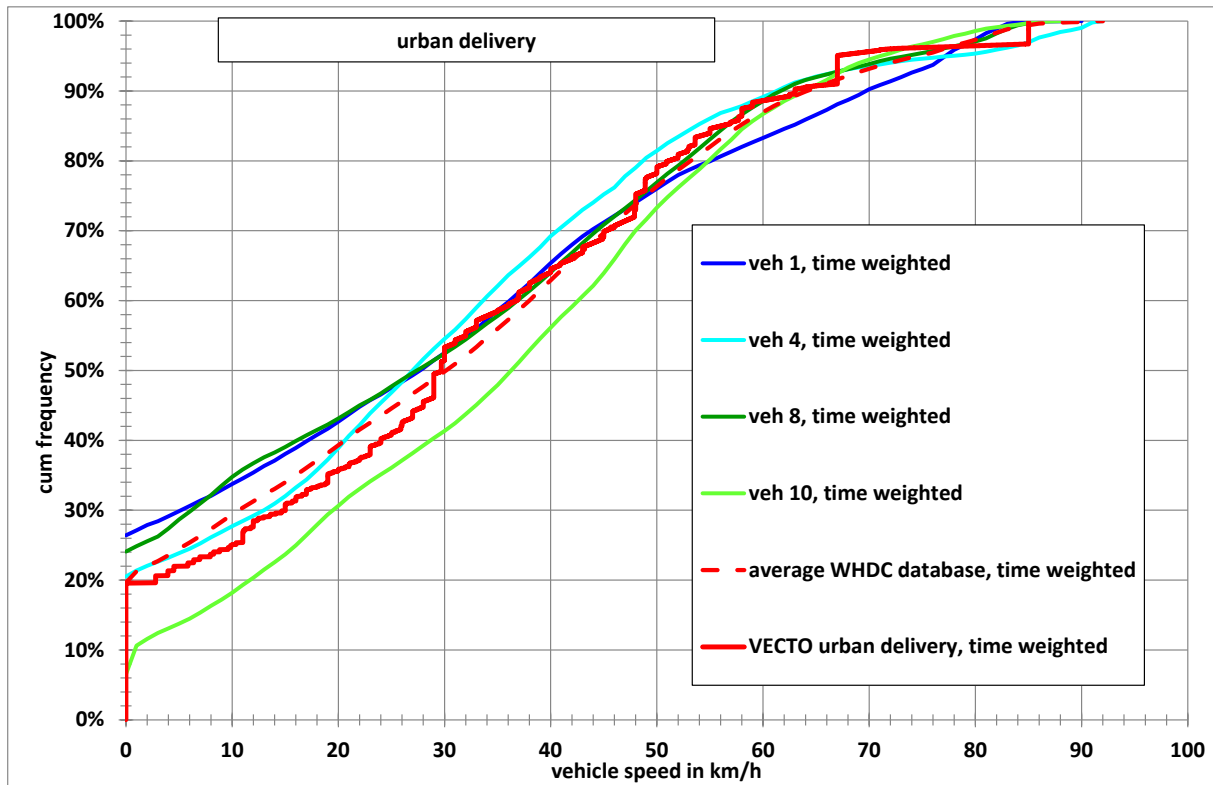
Figure 13: Time weighted cumulative vehicle speed frequency distributions for urban delivery
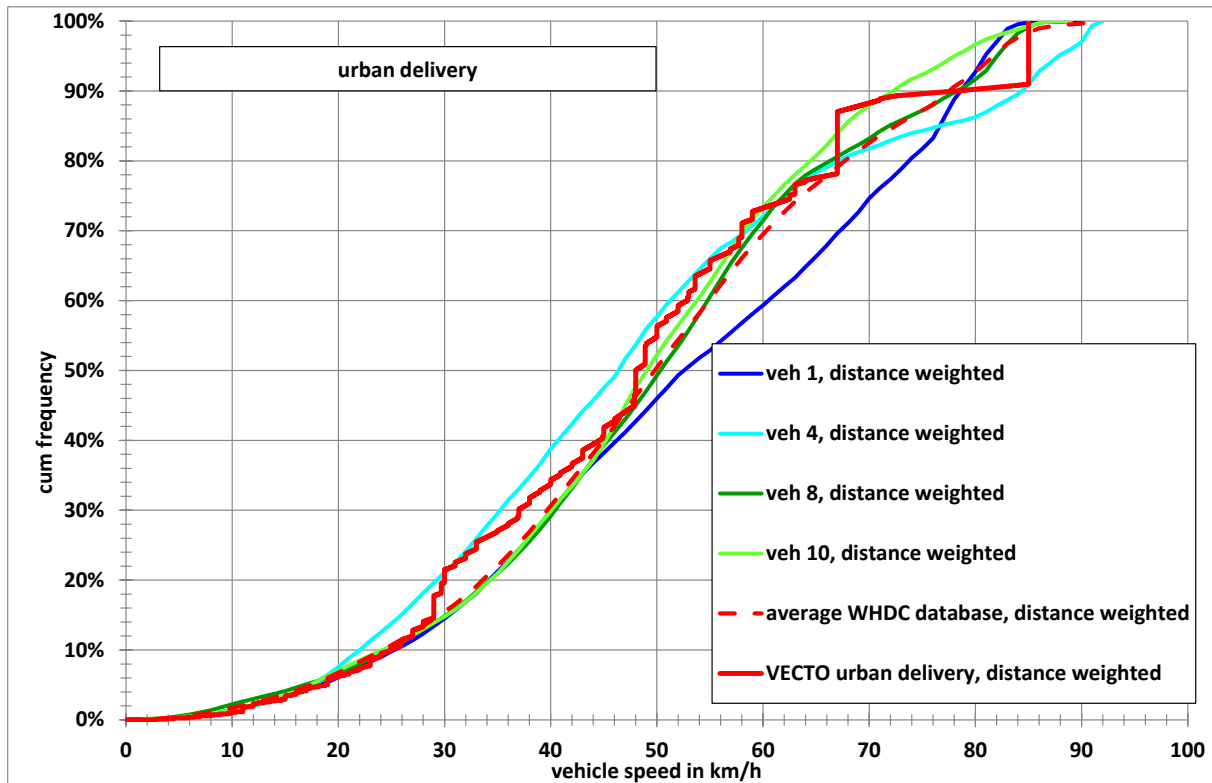
Figure 14: Distance weighted cumulative vehicle speed frequency distributions for urban delivery

Table 13 shows a comparison of the key parameter of the Vecto cycle and the average WHDC cycle. The following parameters are listed:

- Vehicle speed percentiles v05, v10, v15, v50, v85, v90 and v95, based on the time distributions without stop,
- Average speeds without and with stops,
- Stop percentage,
- Number of stops per km,
- Total driving time in h and total driven distance in km,
- Average positive acceleration,
- Time percentages of acceleration, cruise and deceleration phases. The phases are defined as follows: acc, when $v*a > 1$ m²/s³; cruise, when -1 m²/s³ $<= v*a <= 1$ m²/s³; dec, when $v*a < -1$ m²/s³

| | urban delivery | |
	WHDC database	Vecto cycle
v_05 in km	4.0	7.9
v_10 in km/h	8.3	11.7
v_15 in km/h	12.4	16.0
v_50 in km/h	38.0	36.4
v_85 in km/h	61.0	59.0
v_90 in km/h	68.0	67.0
v_95 in km/h	77.0	71.1
v_ave wo stop in km/h	38.3	38.3
v_ave w stop in km/h	30.8	30.8
p_stop	19.6%	19.6%
# stops per km	1.0	1.0
time in h	35.8	0.88
distance in km	1,103	27.8
a_pos_ave in m/s²	0.42	0.45
p_acceleration	34.4%	22.5%
p_cruise	35.7%	58.4%
p_deceleration	29.9%	19.1%

Table 13: Key parameter of the urban delivery Vecto cycle and the average WHDC database cycle

If one considers that the target speed concept is chosen in order to emphasize individual vehicle performance, the urban delivery Vecto cycle is in good accordance with the in-use data, especially for average speeds, stop percentages and number of stops per km. Bigger differences are shown for the driving condition phases (acc, cruise and dec), As expected from the concept and as could already be concluded from the vehicle speed distributions, the cruise phase has a significantly higher percentage in the Vecto cycle than in the WHDC database cycle.

4.3.3. Regional delivery cycle

The results of the validation exercise for the regional delivery cycle are shown in Figure 15 and Figure 16. The VECTO CO2-test cycle tends to the lower envelope of the in-use data, but still within the variation range. The transition from urban to rural (speeds between 52 km/h and 63 km/h) and rural to motorway (74 km/h to 84 km/h) seems to be too rapidly compared to the in-use data and motorway operation is overestimated compared to the average of the in-use data.

The latter result needs to be further investigated, because the WHDC database is already quite old and the VECTO CO2-test cycle might better reflect the trend in the mileage share between urban, rural and motorway.

It also needs to be mentioned that the maximum speed of the VECTO cycle (85 km/h) is quite frequently exceeded (up to 90 km/h or even more).

Additional cycle parameters are compared in Table 14 for the Vecto cycle and the average WHDC cycle. Further explanations to these parameters can be found in the explanatory text of Table 13. It should only be mentioned that the vehicle speed percentiles are related to time weighted distributions without stop percentages.

The stop percentages and the number of stops for both cycles are quite close together. The difference in average speeds (58,7 km/h for the VECTO cycle vs 56,3 km/h for the average in-use data) reflects the higher motorway operation percentage of the VECTO cycle. The values for the driving condition phases (acc, cruise, dec) show the same trend as for the urban delivery case. But the extremely low deceleration percentage of the Vecto cycle needs also further notice.

Figure 15: Time weighted cumulative vehicle speed frequency distributions for regional delivery
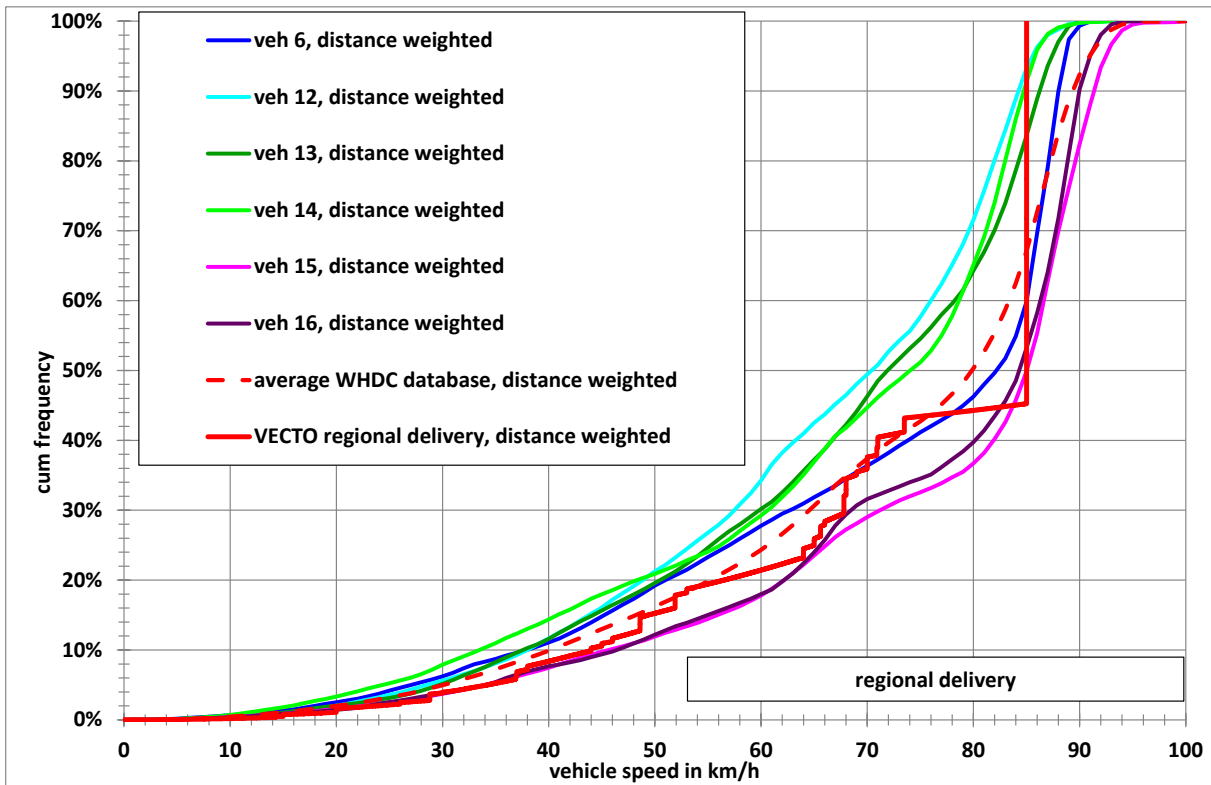
Figure 16: Distance weighted cumulative vehicle speed frequency distributions for regional delivery

	regional delivery	
	WHDC database	Vecto cycle
v_05 in km	11.0	16.9
v_10 in km/h	19.0	26.8
v_15 in km/h	27.0	34.1
v_50 in km/h	65.8	68.0
v_85 in km/h	86.3	85.0
v_90 in km/h	88.3	85.0
v_95 in km/h	90.0	85.0
v_ave wo stop in km/h	60.5	63.1
v_ave w stop in km/h	56.3	58.7
p_stop	6.9%	7.1%
# stops per km	0.23	0.23
time in h	50.4	0.44
distance in km	2,836	25.8
a_pos_ave in m/s²	0.24	0.26
p_acceleration	30.9%	20.7%
p_cruise	42.7%	71.0%
p_deceleration	26.4%	8.3%

Table 14: Key parameter of the regional delivery Vecto cycle and the average WHDC database cycle

4.3.4. Long haul cycle

As already said, the WHDC in-use database contains 7 vehicles with long haul mission cycles, 2 of them (no 17 and 18) were monitored during real operation. The other 5 were fully laden 40 t semitrailer trucks (no 31 to 35), driven from Finland to Spain on the same route and at the same time within a project of a vehicle manufacturer, intended to monitor long haul driving behaviour.

The results of the validation exercise for the long haul cycle are shown in Figure 17 and Figure 18. Further key parameters are listed in Table 15. Explanations to these parameters can be found in the explanatory text of Table 13. It should only be mentioned that the vehicle speed percentiles are related to time weighted distributions without stop percentages.

The distribution curves for the 5 vehicles, measured by order of a manufacturer, are of course quite close together, since the vehicles drove identical routes. The curves of the other 2 vehicles are closer to the VECTO CO_2-test cycle, which seems to have a too abrupt transition from rural to motorway operation. Vehicle speeds between 60 km/h and 84 km/h have far too low shares in the distributions compared to the WHDC database distributions.

The motorway share might have become significantly higher in the meantime compared to the WHDC database, but the transition between rural and motorway needs to be made more smoothly in any case. That means that intermediate target speeds between 60 km/h and 85 km/h need to be inserted and the 85 km/h percentage needs to be reduced accordingly. This would also better reflect the fact, that motorway operation does not only consist of free flowing traffic but includes also saturated traffic at decreased target speeds.

Another finding is the same as for the regional delivery cycle: The maximum speed of the VECTO CO_2-test cycle (85 km/h) is quite frequently exceeded in real operation. In this context it must be mentioned that it was possible to indicate uphill and downhill driving for vehicles 31 to 35, when related to longer distances and that the highest speeds (above 90 km/h) correspond to downhill driving in most cases. If in VECTO the Eco-Roll function is activated, the vehicle speed is also allowed to be above the target speed in downhill phases. A comparison from VECTO results simulated with input data from real long haulage HDV with the in-use data base shall clarify if then still discrepancies exist.

The stop percentage is 4,6% for the Vecto CO_2-test cycle and varies between 1,7% and 4,2 % in the in-use data (average 3,5%). The average speed of the Vecto cycle is 73,9 km/h, which is almost identical with the average speeds of vehicles 17 and 18. The average speed of vehicles 31 to 35 is 72,0 km/h.

The number of stops are pretty close together but the driving condition phases (acc, cruise, dec) show quite high differences. The cruise percentage of the Vecto cycle is twice as high as for the average WHDC database cycle and consequently the percentages for acc and dec are significantly lower.
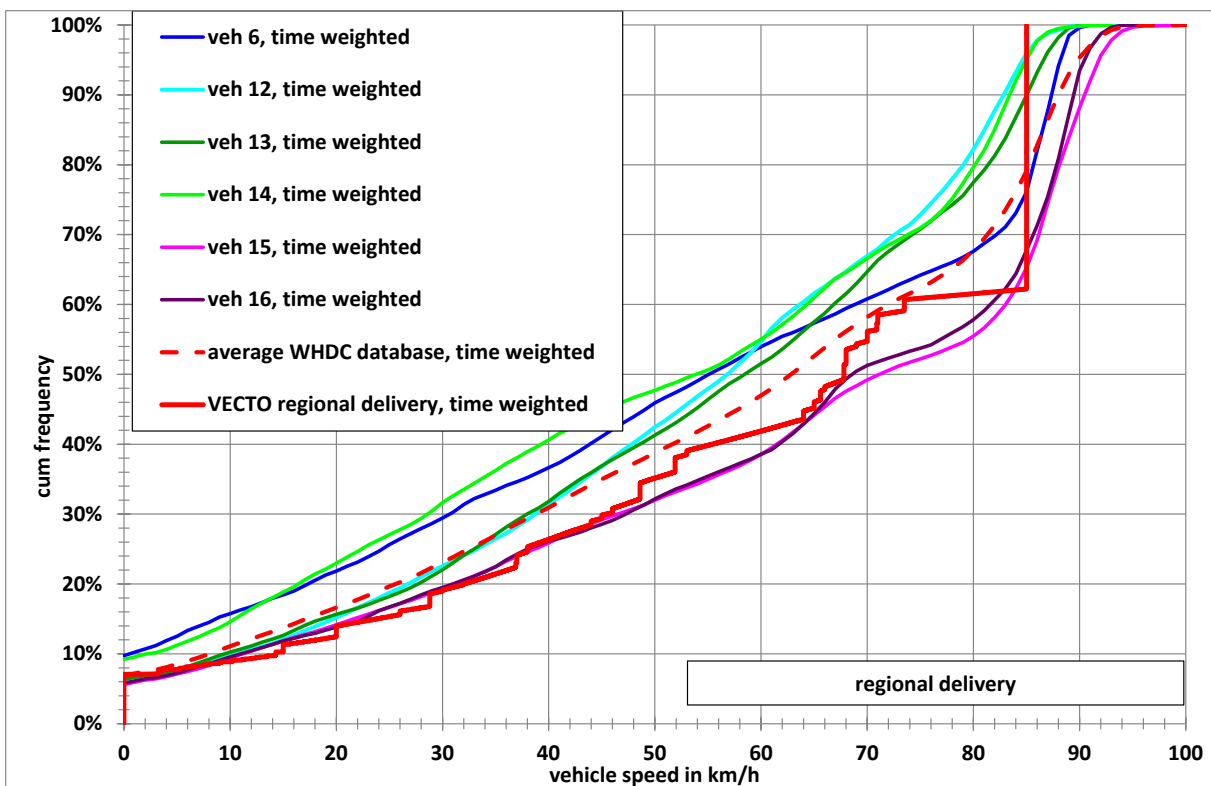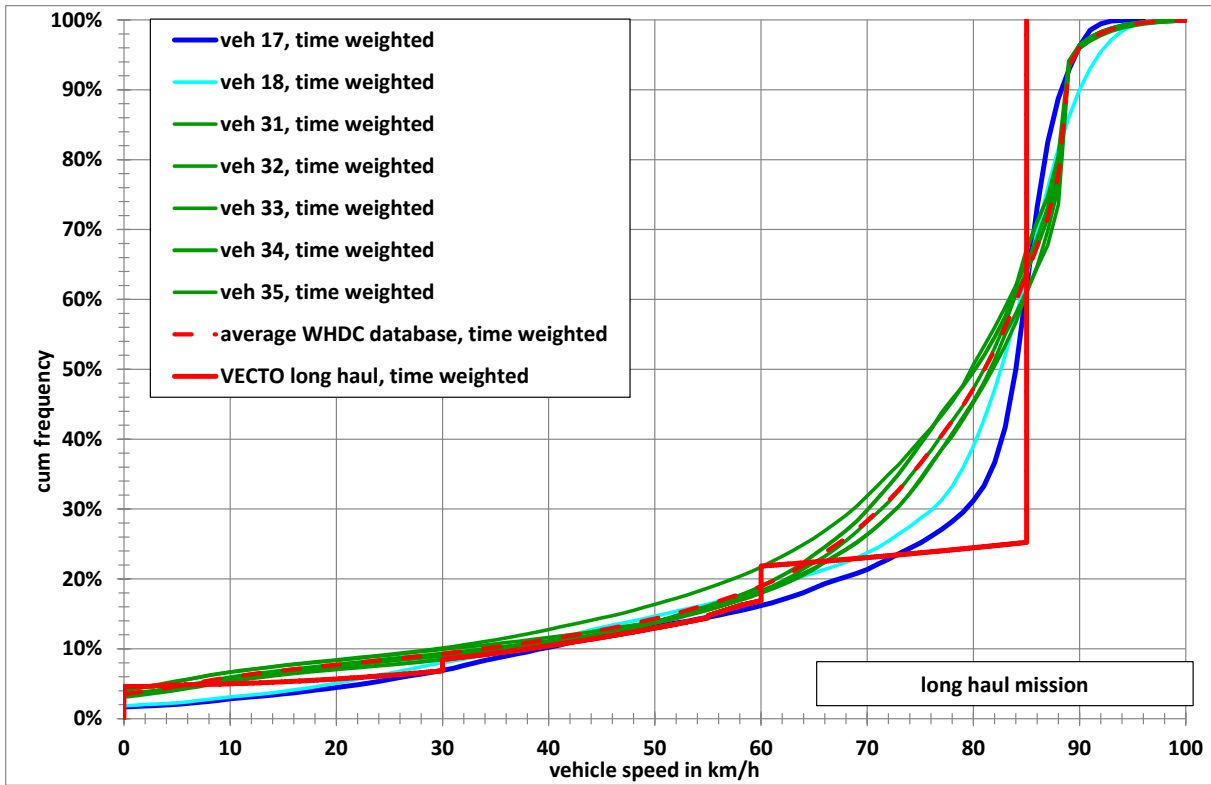
Figure 17: Time weighted cumulative vehicle speed frequency distributions for long haul mission
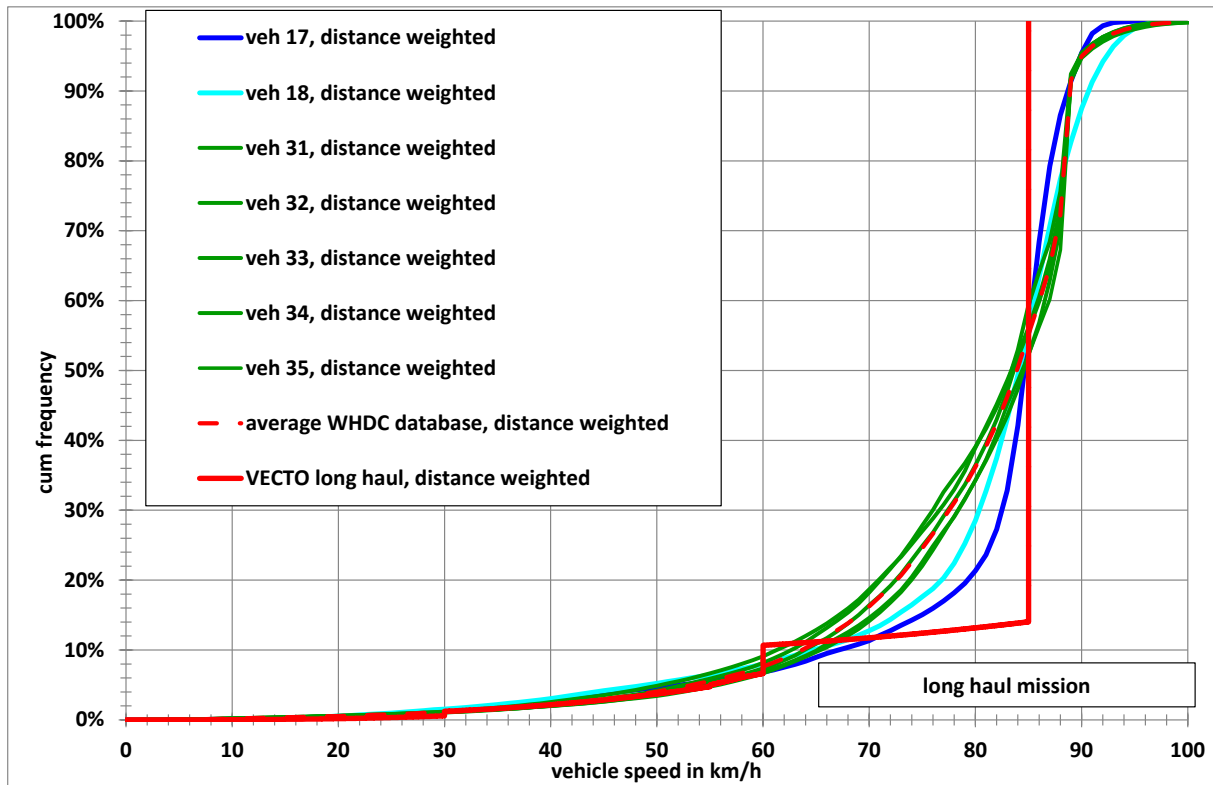
Figure 18: Distance weighted cumulative vehicle speed frequency distributions for long haul mission,

	long haul	
	WHDC Database	Vecto cycle
v_05 in km	24.5	34.7
v_10 in km/h	46.8	53.8
v_15 in km/h	58.3	60.0
v_50 in km/h	81.7	85.0
v_85 in km/h	88.5	85.0
v_90 in km/h	88.5	85.0
v_95 in km/h	89.8	85.0
v_ave wo stop in km/h	74.6	77.5
v_ave w stop in km/h	72.0	73.9
p_stop	3.5%	4.6%
# stops per km	0.050	0.055
time in h	721.4	1.46
distance in km	51,937.9	108.2
a_pos_ave in m/s²	0.16	0.18
p_acceleration	30.1%	9.0%
p_cruise	42.8%	85.7%
p_deceleration	27.1%	5.3%

Table 15: Key parameter of the long haul mission Vecto cycle and the average WHDC database cycle

4.3.5.   Bus cycles

In VECTO three different citybus CO_2-test cycles and an interurban bus cycle are differenti-ated. The citybus cycles are called heavy urban, urban and suburban. These 3 cycles should enable to cover the whole range of urban operation from city centres with low speeds and short distances between bus stops to suburban areas with higher speeds and long distances between bus stops.

The VECTO citybus cycles are based on an analysis of extensive in-use data from different European regions. Compared to this the WHDC in-use database contains only a limited amount of citybus data from Germany and Switzerland.

Nevertheless, the comparison with the results of this database shows good agreement (see Figure 19 and Figure 20). The heavy urban cycle is close to the upper (left side) envelope of the in-use data variation range and the urban cycle is almost in the centre of that range. The same accounts for stop percentages and average speeds.The suburban cycle tends to the lower (right side) envelope. Only the Vecto interurban bus cycle is outside the range of the WHDC database cycles, because this database does not contain such bus mission data.

Apart from this must be mentioned that the Vecto citybus cycles are more consistent with in-use driving, because the target speeds are varied more frequently and in smaller speed steps than for the truck cycles, so that abrupt transitions are avoided.

Table 16 shows a comparison with the Vecto cycle parameters and average bus cycle from the WHDC database corresponding to the three mission types. Explanations to these pa-rameters can be found in the explanatory text of Table 13. It should only be mentioned that the vehicle speed percentiles are related to time weighted distributions without stop percent-ages.

Except for the number of stops per km the differences between the in-use data and the Vecto cycles are generally higher than for the heavy goods vehicles, but this might be related to the fact, that the WHDC bus database is much smaller than the WHDC heavy goods vehicle da-tabase.

In contrast to that, the differences between the driving condition percentages are lower than for the heavy goods vehicles, which can be explained by the higher variations of target speeds in the Vecto cycles compared to heavy goods vehicles.
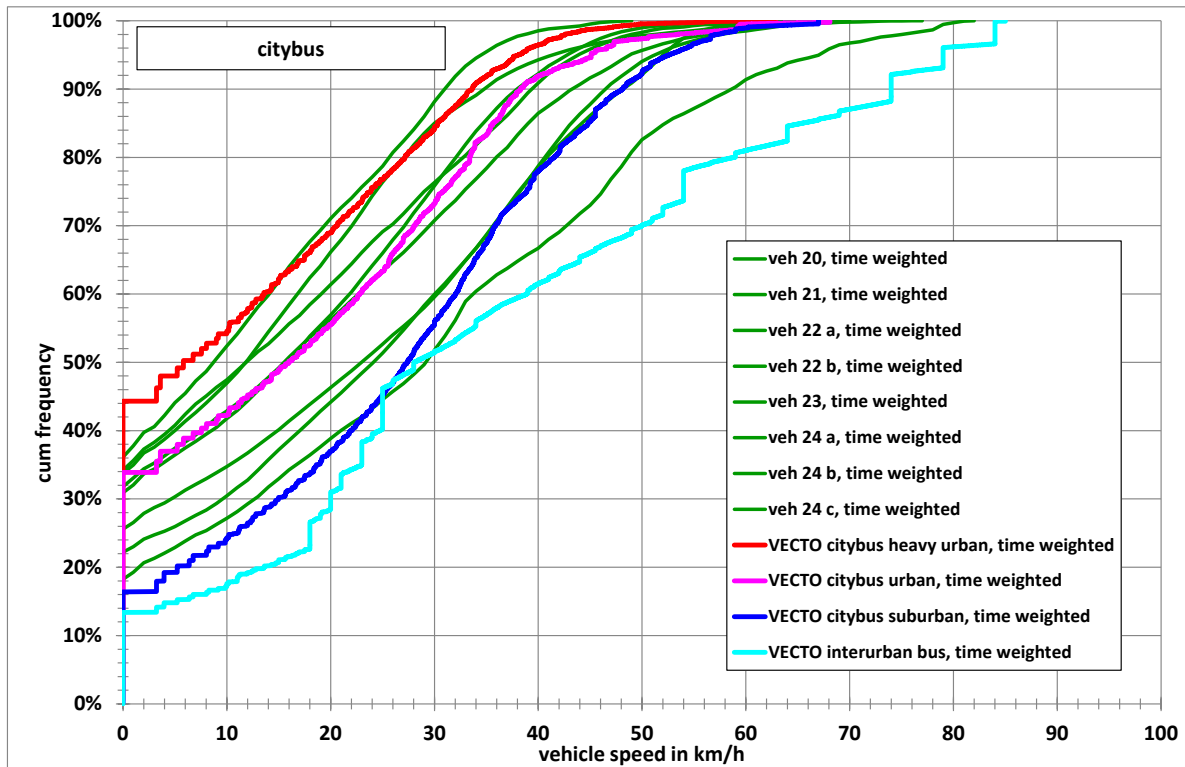
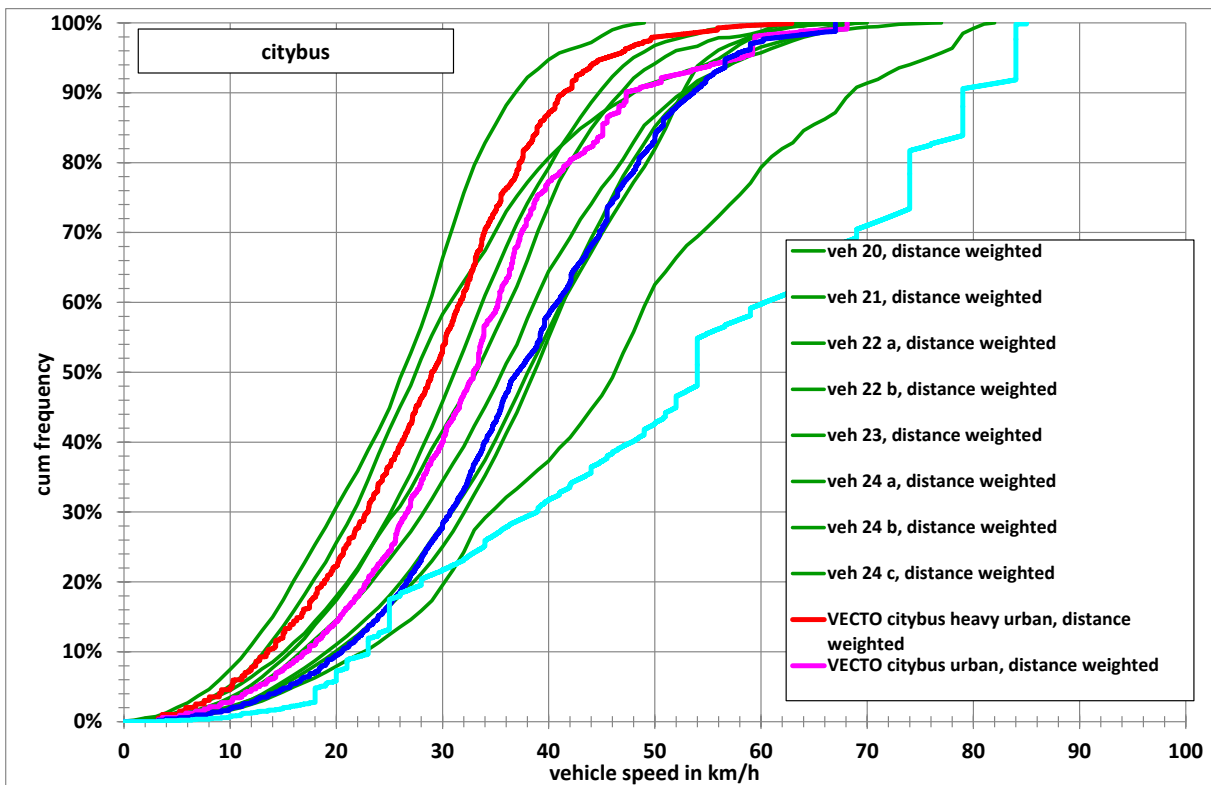**Figure 19:** Cumulative vehicle speed frequency distributions for citybus and interurban bus missions, time weighted

Figure 20: Cumulative vehicle speed frequency distributions for citybus and interurban bus mission, distance weighted

	citybus heavy urban		citybus urban		citybus suburban		inter urban bus	
	WHDC Database, veh 23 and 24 b	Vecto cycle	WHDC Database, veh 22 and 24 c	Vecto cycle	WHDC Database, veh 20 and 24 a	Vecto cycle	WHDC Database (no vehicle)	Vecto cycle
v_05 in km	2.0	3.6	2.8	5.2	4.8	6.4		10.2
v_10 in km/h	4.8	5.8	6.0	8.0	9.4	10.2		16.8
v_15 in km/h	6.9	8.0	9.0	11.1	12.9	14.2		18.0
v_50 in km/h	19.5	21.9	25.0	26.5	31.9	31.2		34.7
v_85 in km/h	32.6	34.7	39.5	38.3	47.0	46.0		69.7
v_90 in km/h	35.8	37.5	42.8	42.4	53.0	49.3		74.0
v_95 in km/h	40.8	40.9	47.2	47.3	59.4	53.9		79.0
v_ave wo stop in km/h	20.7	22.2	25.4	26.3	32.5	30.7		40.3
v_ave w stop in km/h	13.5	12.4	17.3	17.4	25.7	25.7		34.9
p_stop	35.0%	44.3%	31.9%	33.9%	20.7%	16.4%		13.4%
# stops per km	4.9	5.1	3.2	3.1	1.8	2.0		0.72
time in h	5.63	2.5	13.1	2.3	12.4	0.9		3.5
distance in km	79.8	30.5	225.7	39.6	300.8	23.5		123.6
a_pos_ave in m/s²	0.61	0.68	0.62	0.58	0.54	0.64		0.50
p_acceleration	30.4%	34.8%	34.8%	33.4%	38.3%	39.0%		23.6%
p_cruise	37.2%	34.5%	29.7%	40.0%	29.4%	26.8%		58.9%
p_deceleration	32.3%	30.7%	35.5%	26.6%	32.3%	34.2%		17.5%

Table 16: Key parameter of the bus mission Vecto cycles and corresponding average WHDC database bus cycles

4.3.6. Cycles for other missions

The cycles for the remaining missions (municipal utility, construction and coach) could not be validated by comparison with in-use data, because such vehicles are not included in the WHDC database. One exception is the coach, as there is just one example in the WHDC database, but this is not enough for validation.

Nevertheless, the results of this vehicle are included in Figure 21 and Figure 22, which show the frequency distributions of the cycles. Further cycle parameters are shown in Table 17. Explanations to these parameters can be found in the explanatory text of Table 13. It should only be mentioned that the vehicle speed percentiles are related to time weighted distributions without stop percentages.

The VECTO cycles for municipal utility and construction vehicles show too abrupt transitions between rural and motorway operation and no reason can be found, why the maximum speed of the construction cycle is 3 km/h lower than the maximum speed for other Vecto cycles, which include motorway operation.

The differences between the VECTO coach cycle and the WHDC in-use data (vehicle 30) are quite significant for the frequency distributions and it needs to be checked whether the extremely high cruise percentage is representative. Such behaviour could at least not be found for the coach in the WHDC database.
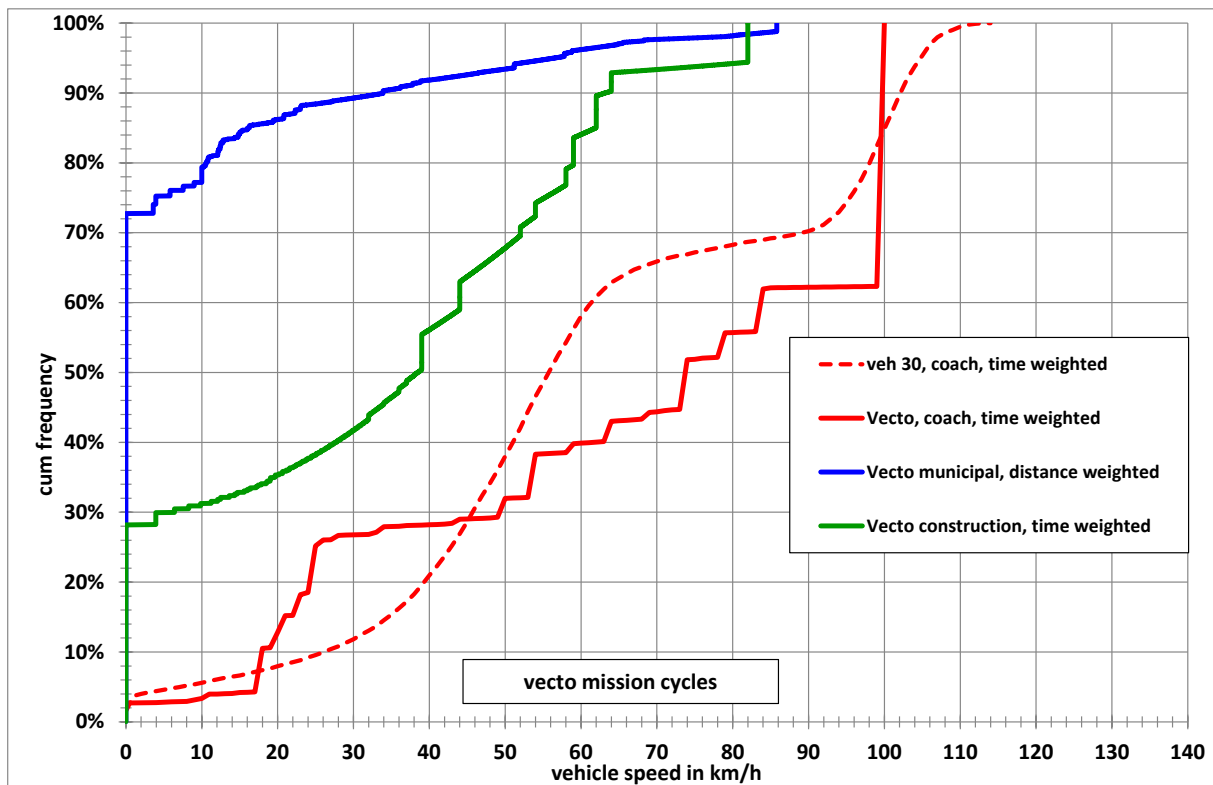
Figure 21: Cumulative vehicle speed frequency distributions for the Vecto missions municipal, construction and coach (WHDC coach for comparison), time weighted
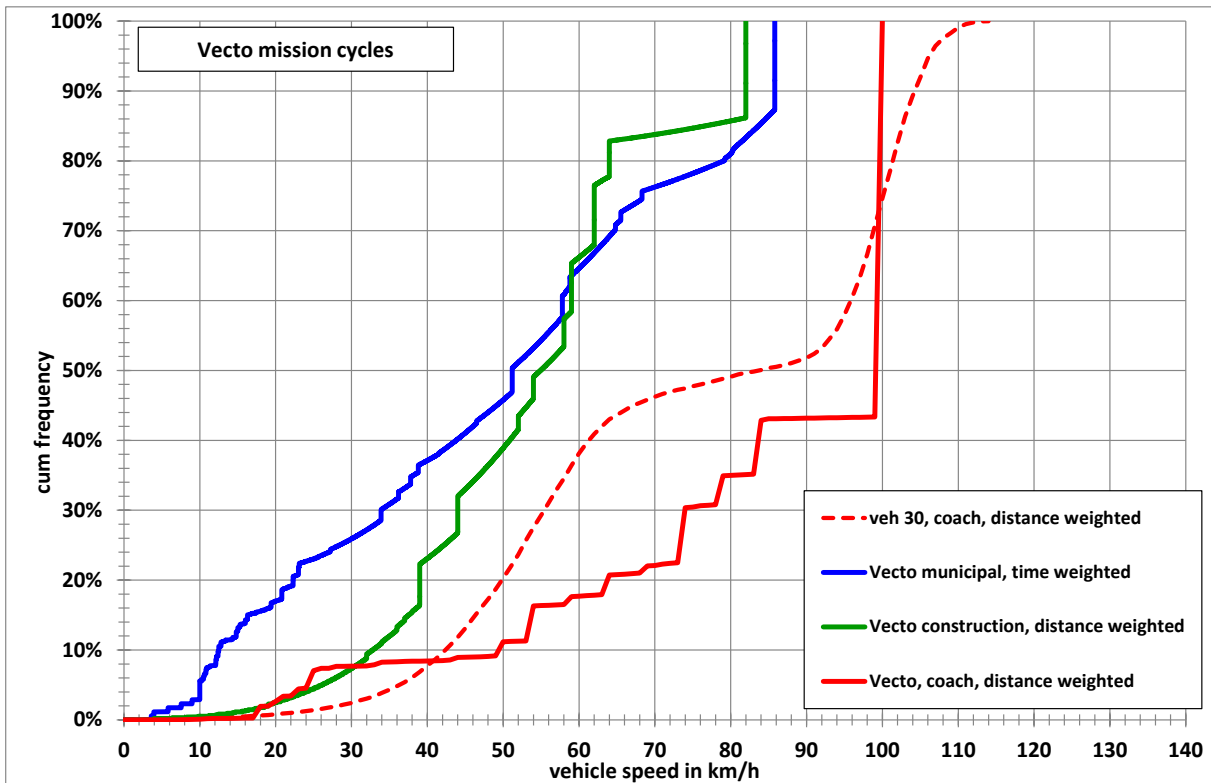
Figure 22: Cumulative vehicle speed frequency distributions for the Vecto missions municipal, construction and coach (WHDC coach for comparison), distance weighted

	Vecto cycles		
	coach	municipal utility	construction
v_05 in km	18.0	3.9	12.1
v_10 in km/h	20.0	5.8	20.1
v_15 in km/h	23.0	9.0	26.0
v_50 in km/h	74.0	20.8	45.5
v_85 in km/h	100.0	58.8	62.0
v_90 in km/h	100.0	65.9	64.0
v_95 in km/h	100.0	84.1	82.0
v_ave wo stop in km/h	68.2	30.0	46.3
v_ave w stop in km/h	66.4	8.2	33.2
p_stop	2.7%	72.8%	28.2%
# stops per km	0.04	5.8	1.1
time in h	4.1	1.2	0.6
distance in km	275.2	10.0	21.2
a_pos_ave in m/s²	0.57	0.42	0.42
p_acceleration	4.0%	34.5%	35.4%
p_cruise	94.0%	51.3%	47.0%
p_deceleration	2.0%	14.2%	17.6%

Table 17: Key parameter of the Vecto mission cycles for municipal, construction and coach (the results for one coach in the WHDC database for comparison)

4.4. Standard bodies and trailers for VECTO

In section 4.4.1, the method using standard bodies and trailers is briefly summarized. In section 4.4.2 an overview on the standard bodies and (semi-)trailers is given. Chapter 4.5 deals with alternative bodies and trailers. Full details are included in the technical annex. Chapter 4.4.3 describes the mass of tipper bodies. Chapter 4.4.4 then gives the results of the CFD computations performed on the standard bodies and trailers.

4.4.1. Identifying representative groups of standard bodies and trailers

The standard and alternative body configurations are dependent on the HDV vehicle class. The classification is currently based on the axle configuration and the maximum gross vehicle mass (GVM), as originally proposed by ACEA. Table 1 on page 10 shows the classification of trucks, their mission profile or type of use and identifies the standard bodies for each type of HDV class (see chapter 4.1). An overview of the reference standard bodies is given in Table 18.

Table 18 Overview of standard body types with formally defined dimensions (allocations to the HDV classes are defined in **Table 1** and **Table 3**.

Truck	Reference body type	Reference body
2 axle 4x2 rigid truck	hard shell box	B1 B2 B3 B4
2 axle 4x2 rigid truck	tipper for sand/cement	B5 [(2)]
3 axle 6x2 rigid truck	hard shell box	B6
3 axle 6x4, 6x6	tipper for sand/cement	B7 [(2)]
4 x axle 8x2 rigid truck	Construction	B8[(2)]
4 axle 8x4, 8x6	tipper for sand/cement	B9 [(2)]
Semi-trailer	hard shell box	S1
	tipper sand/cement	S2 [(2)]
Trailer	box body	T1
EMS	box body	Not defined yet

(2)…It is suggested not to demand CdxA tests for construction trucks since the bodies of such HDV vary a lot and are quite different to any "standard". In addition these vehicles hardly drive high velocities, thus their Cd value has only very limited influence on the resulting fuel consumption. Thus these vehicles may simply get a generic Cd-value and a generic mass of body and payload to save test efforts. This option is still under discussion.

4.4.2. Definition and dimensions of standard bodies and trailers

4.4.2.1. Reference standard Bodies

The dimensions of the standard (hard shell box) bodies for the 12 tons truck (B2) and the semi-trailer (ST1) were initially determined within in the LOT 2 project. In 2012 and 2013 in a VDA/CLCCR[13] project a range of reference standard bodies were defined (including an update of B2 and ST1). This included the bodies B1, B2, B3, B4, ST1 and T2. The main dimensions and mass of the reference standard bodies are presented in Table 19 below. In the technical annex all specifications are given [source VDA/CLCCR].

Table 19: Main specifications of reference Box bodies [source: VDA and CLCCR].

		Rigid truck					Semi-trialer	Trailer
Parameter	**Unit**	**B1**	**B2**	**B3**	**B4**	**B6**	**ST1**	**T2**
Body length	mm	6200	7400	7450	7450	7820	13685	7820
Width	mm				2550			
Height	mm	2680	2760	2880	2980	2980	2850	2730
# of pallets		15	18	18	18	19	34	19
Mass	kg	1600	1900	2000	2100	2200	7500*	5400*

* Total mass including chassis and axles

It has not been decided whether there should be standard tipper bodies: B7, B9 and ST2. This was investigated within the VDA/CLCCR project in which it was concluded, that the variations in practice are too large to define standard bodies. Two main categories were defined: the half-pipe (cross sectional) shape and the square shape bodies. Within the project it was decided to pursue CFD calculations with a typical body, based on a relative standard body of two large manufacturers. The CFD calculations will give more insight in the relative difference in air drag between the box body and the tipper body. After that, a way forward can be decided.

4.4.3. Mass of tipper bodies

A limited evaluation was done of the empty and laden masses of trucks with tipper bodies. This was done for both rigid trucks as well as tractor semi-trailers combinations.

The analysis was done by the evaluation of Weighing In Motion (WIM) data on about 10 locations on motorways in the Netherlands. With this type of measurements, the mass of individual axles of trucks are measured. As a result both the truck configuration can be identified (by the phase shift) as well as the total mass. The empty mass was collected by reading the licence plates of the passing trucks and collecting the empty mass data from the road authorities data base. The accuracy of the Weighing In Motion measurements is normally limited to

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[13] VDA: Verband der Automobilindustrie, CLCCR: International Association of the Body and Trailer Building Industry

about ± 500 kg. This is improved considerably by averaging the results of the 10 Weighing In Motion locations.

The results are presented in the tables below. In Table 20, the average mass of tractor tipper semi-trailers are presented. According to the table, the average cargo load is about 20 ton. The share of tipper semi-trailer trucks was 1.54% of the total passing trucks.

The results for the rigid tipper trucks are presented in Table 21. It can be seen, that statistically more tipper trucks with more axles are passing (so 4 axle more than 3 axle and 3 axle more than 2 axle trucks). 5 axle tipper trucks are not included in the table, but in the Netherlands they are more common than tipper trucks with fewer axles. The average cargo mass is as follows:

- 2 axle: ∼ 5.3 ton
- 3 axle: ∼ 8 ton
- 4 axle ∼ 7 ton.

The lower average cargo load of the 4 axle configuration than the 3 axle configuration is probably related to the different usage profile of the 4 axle configurations.

Table 20: Statistical data of average mass of tractors with tipper semi-trailers in the Netherlands (based on 10 Weighing In Motion measuring locations at motorways).

All axle semi-trailer tipper, including tractor	
Empty mass	15500 kg
Laden mass	35650 kg
# measurements	11394
Percentage of total measurements	1.54%

Table 21: Statistical data of average mass of tipper rigid trucks in The Netherlands (based on 10 Weighing In Motion measuring locations at motorways).

2 axle rigid tipper truck	
Empty mass	8600 kg
Laden mass	13900 kg
# measurements	152
Percentage of total measurements	0.02%

3 axle rigid tipper truck	
Empty mass	12450 kg
Laden mass	20600 kg
# measurements	624
Percentage of total measurements	0.08%

4 axle rigid tipper truck	
Empty mass	17500 kg
Laden mass	24600 kg
# measurements	860
Percentage of total measurements	0.12%

4.4.4.   Analysis of relevant construction details for standard trailers

While the main dimensions of the standards, which were taken from typical existing bodies and trailers, are rather similar for the same categories, details of the constructions are quite different (e.g. corner radius, wear plates, trailer box size and location, underfloor design,…).

For the definition of the standard bodies and trailers it thus was important to which extent these details could influence the resulting CdxA value for the HDV in the aerodynamic test procedure. Since rather small effects were expected, physical tests of HDV with (slightly) different body and trailer configurations was not a reasonable option. Thus CFD simulations have been performed. The simulation work was used for several tasks:

a) Analyse which construction details have reasonable influence on the CdxA results and thus need to be specified for the standard bodies and trailers

b) Compute the influence of the yaw angle of the inflowing air on the aerodynamic drag as input for the CdxA test procedure and for the corresponding VECTO simulation (which also considers yaw angle effects on the aerodynamic drag)[14]

c) Participate in the ACEA "round robin test" on CFD simulation runs to get experience in the repeatability of results when different CFD codes are used (thus the same HDV has been simulated as done in the ACEA group and also the ACEA standard settings have been used). This work is a first step towards an eventual application of CFD simulation to reduce the number of physical CdxA tests in the HDV-CO2 test procedure.

Estimation of aerodynamic drag using Computational Fluid Dynamics (CFD) is already successfully applied in development process in almost all companies; see e.g. (FAT, 237), (FAT, 241), (Islam, 2009), (Clasen, 2008), Singh, 2008), (Xinke, 2011). Usually, before a prototype is produced and tested, first tests are virtually done. Furthermore, the measurement process is quite expensive and in some cases, such as drag estimation of a semi-trailer truck, the wind tunnel size could be a limiting factor. Currently, there are several commercial and open-source CFD Software packages available, e.g. ANSYS Fluent and CFX, AVL-Fire, Star-CD, Power Flow, OpenFOAM, which are able to estimate aerodynamic drag coefficient C_d virtually. In presented work, commercial CFD code ANSYS Fluent has been used.

The results of the actual CFD simulations should offer an overview of the drag force coefficient variation dependents on different conditions (e.g. cross flow) and different vehicle/trailer design modifications. Starting with a basis vehicle/trailer variant, simulation settings and work flow is validated. The basis geometry is a generic semi-trailer truck provided by "Forschungvereinigung Automobiltechnik" (FAT). For this study a representative vehicle was generated using Computer Assisted Design (CAD) which includes important semi-trailer truck features of all in the project involved manufacturer, see (FAT, 241). The used computational mesh settings and boundary conditions follow the suggestions by the ACEA working group on CFD-simulations. This study also includes the influence of some design variations on the C_D value. The vehicle design modification includes the modification of mirrors, tool box, trailer wear-plate, case radius, and trailer under-flow. Three different yaw-angles were studied by cross-flow investigation. Variation of the drag force coefficients in relation to the basis simulation has been evaluated. Finally, the results are summarised and an overview on drag force coefficient variations in relation to investigated conditions and vehicle design modification is given.

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[14] To complete the data on generic yaw angle functions, more HDV will have to be simulated or tested under various ambient air directions and velocities

Input data and settings

The geometry of the generic semi-trailer truck is provided by FAT (further FAT-vehicle) in STL (Surface Tesselation Language) data format. As mentioned before, the FAT-vehicle is designed in such a way that it includes all important semi-trailer truck features of all in the project involved vehicle and trailer manufacturers. Figure 23 shows different views of the FAT-vehicle used in this work.
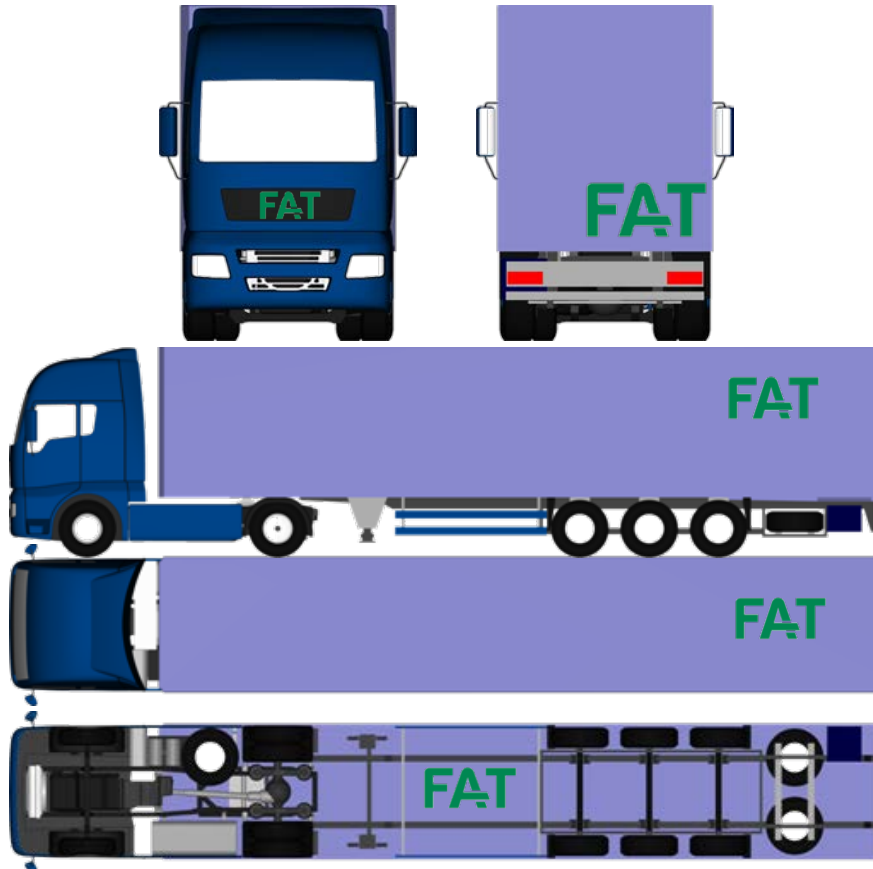

Figure 23: FAT-Geometry used in this work

The truck has a typical "cabover" configuration, where the driver sits next to the engine. Due to limitation of the maximum length of the combined vehicle, the combination is established in Europe. In the bottom view, it can be seen that the FAT-truck has two axles, engine in the middle of vehicle cabin, which is further coupled via a gear-box and a cardan-shaft to the transfer case differential on the rear axis. Typical truck components, such as mirrors, reflectors, fuel tank, air reservoir, spare wheel etc., are visible in FAT-truck design as well. The FAT-trailer is a conventional box trailer, which has three axles, two spare wheels, a tool box, and trailer legs. The components are attached to a typical trailer metal wearer. The wear-plate consists of two separated plate, which are not connected to each other.

Using above described geometry, computational mesh was generated taking into account suggestions provided by the ACEA working group on CFD-simulations. Figure 24 shows the refinements regions and corresponding cell size.
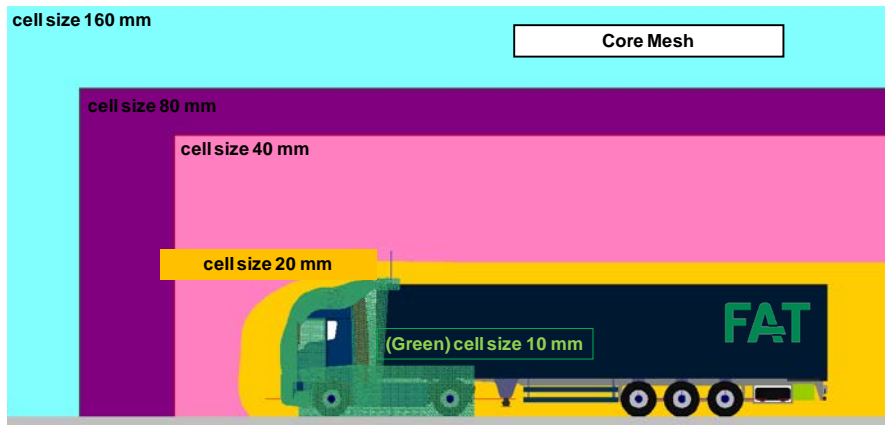
Figure 24: Refinements regions and cell size recommended by ACEA CFD working group
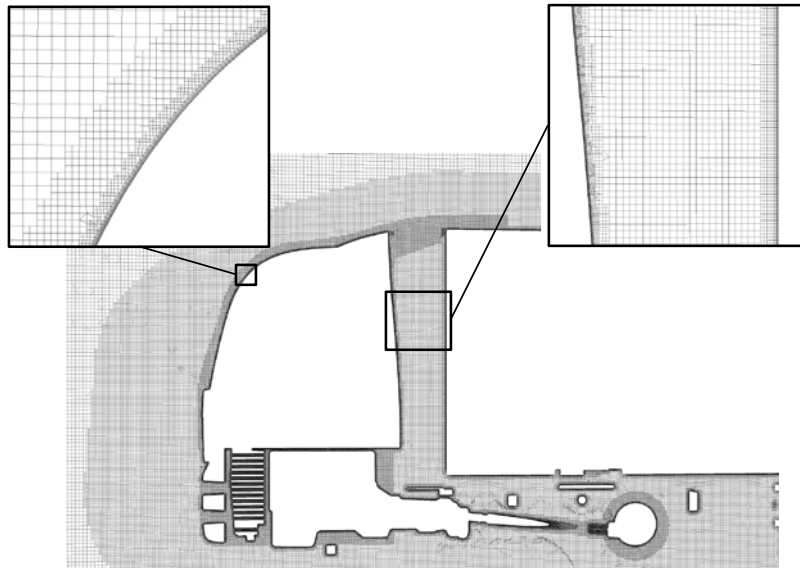

Figure 25: Symmetry cut through the used mesh in presented work

Meshing process begins with a definition of the box size (size of virtual wind tunnel) and the box cell size (in this case 160mm) of the core mesh. For each region/surface refinements additional refinement levels are defined separately and step wise, see Figure 24. Beginning with a core mesh size definition (160mm) each followed cell size is divided by factor of two. Applying the method, the finest surface resolution is 2.5mm, e.g. mirrors and some faces on the vehicle cabin. The maximal recommended surface cell size is 30mm. In order to capture all important effects close to the wall, 8 prism layers cells extrusion with a maximal high of 20mm have been generated. The prism layer starts with 1mm near wall cell size and there-with fulfils the wall-function requirements for Y+ value between 30 and 300. These settings results in a final mesh size of about 133 million cells. Figure 25 show a symmetry cut through the used mesh in presented work including two details of the boundary mesh close to the surface.

For the reference case, simulation settings as well as initial and boundary conditions are given by the ACEA working group on CFD-simulations and some of these data are presented in Table 22 and Table 23.

Table 22: Simulation settings data

Nr.	Description	Input data
1	Simulation type	Steady-state
2	Turbulence model	k-epsilon Realizable
3	Wall function	Non-Equilibrium WF
4		

Table 23: Initial and boundary conditions

Nr.	Description boundary condition (BC)	Input data
1	Inlet BC – velocity	90km/h
2	Outlet BC – pressure	101325Pa
3	Floor BC – sliding wall, Inlet/vehicle velocity	90km/h
4	Wheels BC – rotating walls, rotating velocity	calculated
5	Inlet Turbulence Degree	1%
6	Inlet Turbulence Char. Length Size	10mm
	Description material properties	
1	Density	$1,184 kg/m^3$
2	Viscosity	$1,49 \times 10^{-5} m^2/s$
	Description initial condition	
1	Initial pressure (only first simulation)	101325Pa
2	Initial velocity (only first simulation)	0m/s

At the beginning of the project a coarse mesh with about 5,5 million of cells is generated in order to get good initial field condition for all following simulations. The simulation with the coarse mesh is done using given data in Table 22 and Table 23. The results of the simulation are further used as field initial condition and are mapped to the fine mesh at the beginning of each following calculation. With this strategy the numerical problems usually caused by inappropriate/unknown values are avoided and the number of iterations until converge solution have been reduced.

Investigated variants

Presented work includes 9 variants in total, which are listed below:
1. Original FAT vehicle (reference calculation)
2. Truck mirror modification

3. Trailer tool box modification
4. Trailer wear-plate closed
5. Trailer box radius modification
6. Trailer under-floor
7. Cross flow beta=1,5°
8. Cross flow beta=3°
9. Cross flow beta=4,5°

First variant is calculated according to above mentioned FAT-specifications and boundary conditions and it is further used as reference simulation. The second investigated variant is the simulation where the truck mirrors are modified, see Figure 26.
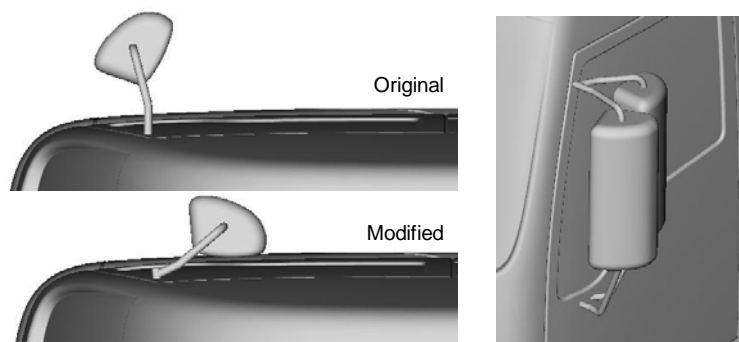
Figure 26: Alternative mirrors position

The mirrors and the holders are rotated about 90° about a point, which is very close to the window. In Figure 26 it can be seen that the new position of the mirrors are not aerodynami-cally efficient any more, due to plane front surface.
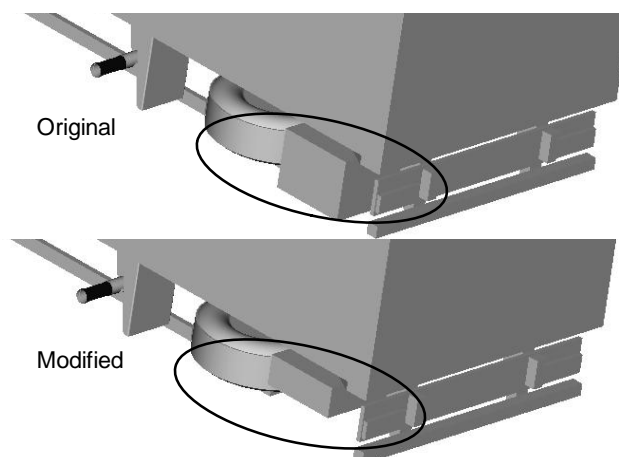
Figure 27: Modification of trailer tool box

Figure 27 shows the modification of the trailer tool box, in this case the high of the box was reduced by about 50%. Next modification is related to the trailer wear-plate. The original wear plate consists of two parts, which are not connected to each other. In the modified version, the two plates are connected to each other, see Figure 28.
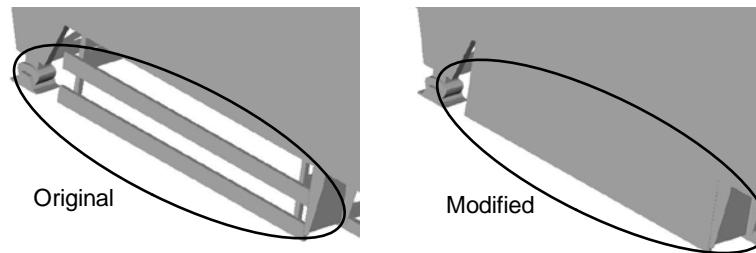
Figure 28: Modification of trailer wear-plate

In order to investigate influence of the trailer box radius on the drag force coefficient, the radius was modified from 50mm to about 80mm. The three top edges are modified as presented in Figure 29.
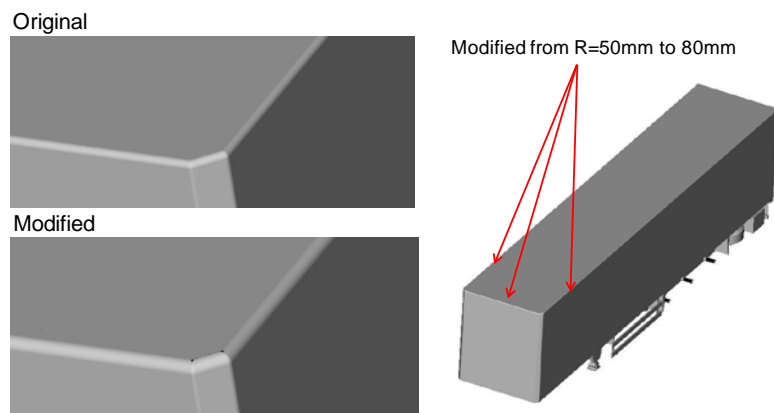
Figure 29: Radius modification of the trailer box body
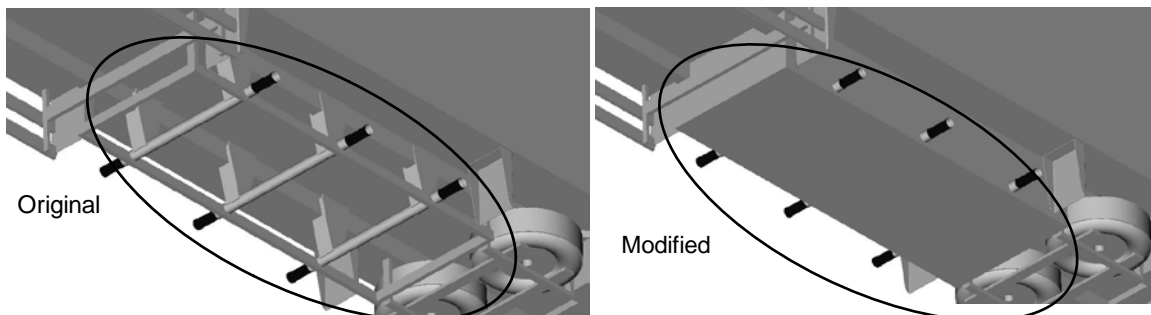
Figure 30: Closed trailer under floor

In the last geometry modification the trailer under floor is closed as presented in Figure 30.

Finally, the tree last variants are related to modifications on the flow conditions. For these variants, a cross wind flow with different yaw angles (1,5°, 3°, and 4°) was inserted. For these variations the original FAT vehicle geometry has been used. In all cases the vehicle velocity of 25 m/s is kept constant and the side velocity component is calculated according to the beta angle, see Table 24.

Table 24: Cross flow input data

Yaw-angle [°]	1,5	3,0	4,5
x-velocity [m/s]	25,0	25,0	25,0
y-velocity [m/s]	0,655	1,310	1,968
Velocity Mag. [m/s]	25,008	25,034	25,077

Results and discussion

As mentioned before, the aim of the presented work is to estimate the aerodynamic drag force coefficient under different above described geometry designs and flow conditions. The drag force coefficient is calculated applying following equation:

$$C_D = \frac{2F_D}{\rho v^2 A} \tag{1}$$

where, F_D is drag force, ρ is air density, v is free stream velocity, and A is reference area.
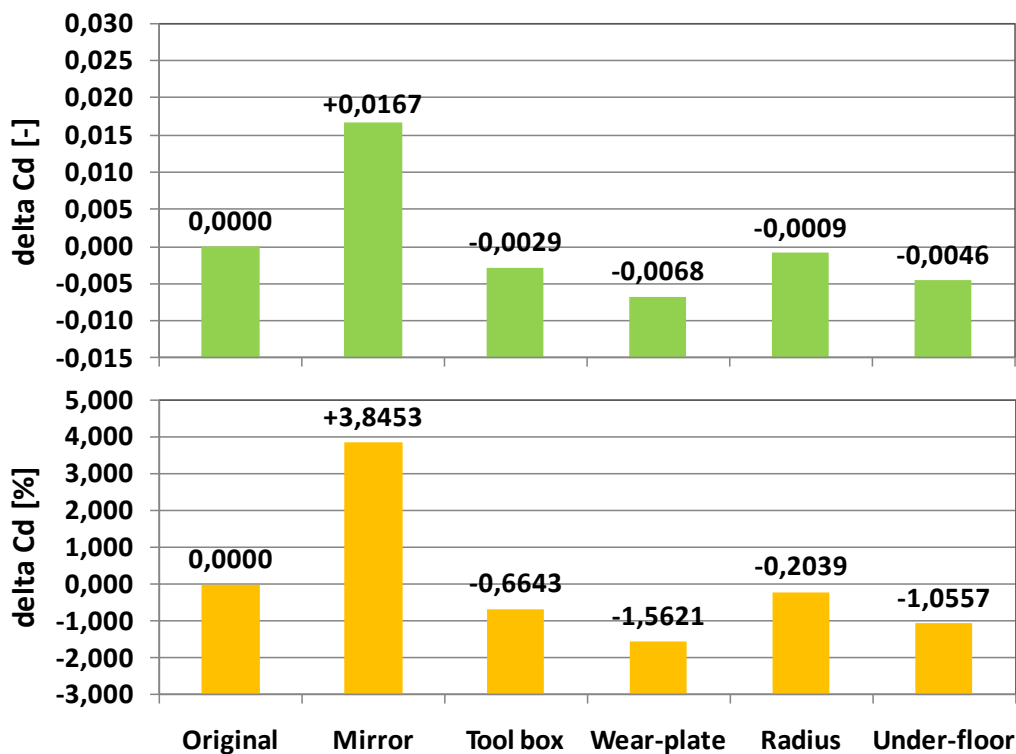
Figure 31: Drag force coefficient

Figure 31 presents the comparison of the drag force coefficient between original FAT geometry and above described vehicle design modifications. Presented results are normalised and the delta C_D is evaluated. In Figure 31 it is evident that the new mirror position causes an increase of drag force coefficient by +0,0167 (+3,84%). The increase can be explained by a non-aerodynamically efficient shape of the mirror, namely a plane front surface of mirror. Figure 32 shows a comparison of the original FAT design and the new mirror position,

whereas the vehicle surface is coloured by pressure and stream lines by the velocity. It is evident, that recirculation zone behind the mirror is clearly bigger, which explains the increase of the drag force coefficient.
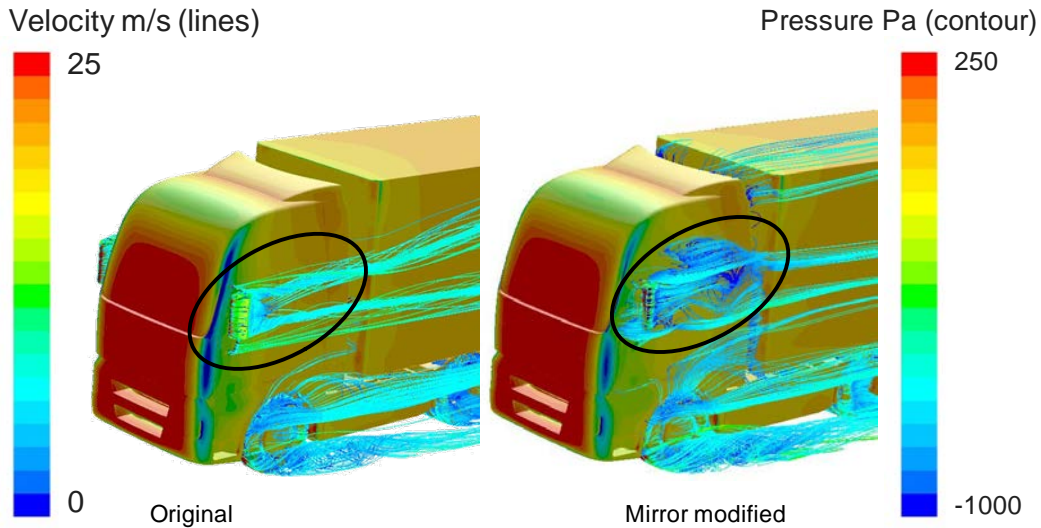
Figure 32: Pressure contours and velocity stream lines, original FAT design vs. new mirror position

The simulation results shows that a reduction of the tool box high by 50% drag force coefficient is reduced by -0,0029 (0,66%), which presents a non-negligible value. The wear-plate is closed as shown in Figure 6. Presented simulation result show that the drag force coefficient is reduced by -0,0068 (-1,56%) and that the modification has the biggest influence on the drag force coefficient reduction in comparison to all other modifications with exception of the mirror position. The radius modification has a small influence on the drag force coefficient. Closed trailer under-floor reduces the drag force coefficient by -0,0046 (-1,05%).
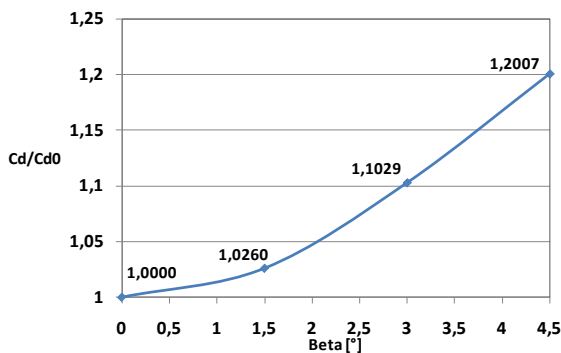
Figure 33: Cross flow drag force coeff. ratio
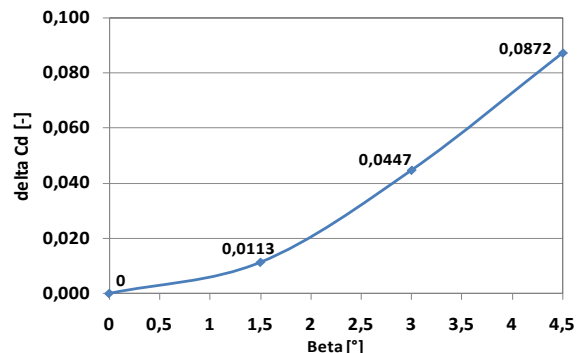
Figure 34: Cross flow drag force coeff. difference

Figure 33 and **Figure 34** show the results obtained by beta variation, where typical parabolic behaviour can be seen. By beta angle of 1,5° an increase of drag force coefficient by 2,6% is evident. By beta of 3° the drag force coefficient increases to about 10% and by beta of 4,5° about 20% can be seen.

Findings from the CFD simulation

The aim of CFD simulation was to estimate virtually the drag force coefficient C_d under different conditions and design variations of a semi-trailer truck. The results should offer an overview of the drag force coefficient variation dependents on different conditions (e.g. cross flow) and different vehicle/trailer design modifications. The vehicle design modification includes the modification of mirrors, tool box, trailer wear-plate, case radius, and trailer under-flow. Three different yaw-angles were studied by cross-flow investigation.

Truck mirror modification

A change in the mirror position can heavily influence the Cd value. For Cd x A tests certainly the original mirror position has to be demanded.

Trailer tool box modification

A reduction in the tool box high by 50lead to a reduction in the drag force coefficient -0,0029 (-0,66%). Therefore, it is recommended to precise the position and size of the tool box in order to keep the drag force value in a proper range. Due to the limited influence of the tool box it may be sufficient to define the position and the dimension (LxBxH) with e.g. 10 % tolerance allowed.

Closed trailer wear-plate

A closed tailer wear-plate reduces drag force coefficient by -0,0068 (-1,56%) and thus has the biggest influence on the drag force coefficient in comparison to all other modifications with exception of the mirror position. Thus it is recommended to define a closed wear-plate as standard for the norm trailer (easier to define "closed" that to define "open").

Radius modification

The radius of the box body was modified from 50 mm to 80 mm. The CFD-simulation shows that the modification has a minor influence on the drag force coefficient. Thus we assume that a definition of the radius of the box does not need to be specified in detail as long as it is in usual dimensions (< 80mm). Further evaluation may be undertaken with a radius of 20mm.

Under-floor

A reduction of the drag force coefficient by -0,0046 (-1,05%) was achieved in the CFD simulation by a closed trailer under-floor. Since a closed under-floor is not standard at trailers, we suggest that open under-floor is the standard for the norm-trailer. A detailed definition of the under-floor steel-frame seems not to be necessary due to limited effect of even complete closing.

Cross flow

Three different yaw angle configurations have been calculated using 1,5° steps up to 4,5° yaw angle. As expected the results shows a tremendous increase on the drag coefficient with increasing yaw angle, approx. 20 % increase of the C_d value compared to yaw angle 0°.

4.5. Assessment of effects from alternative bodies and trailers

In section 4.5 two types of reference standard bodies are described: the box body and the tipper for sand/cement. For both the semi-trailer as well as for the rigid truck the following alternative body types are distinguished:

- Swap body (including container)
- Dry bulk tanker
- Wet bulk tanker
- Other, such as flat bed

The main goal of this section is to identify the main alternative body groups and to compare the drag force coefficient (CdxA) of some of these alternative bodies with the box body (section 4.4.4, the FAT tractor-semi-trailer combination).

First, section 4.5.1 describes how a representative group of alternative bodies and/or trailers was identified. Subsequently typical dimensions of this group of semi-trailers, which turned out to be tanker semi-trailers, were collected (section 4.5.2). Section 4.5.3 describes how these dimensions were then used for CFD modelling and thus for the determination of the drag forces of the alternative semi-trailers.

4.5.1. Identifying a representative group of alternative bodies

The main goal is to identify a group of semi-trailers, other than with box-body, that represents a substantial number of tractor-trailer combinations present on the European roads. Additionally it should be a group for which drag resistance is quite relevant, so the vehicles should not primarily be used for local distribution or services. According to the CO_2 projection in the LOT 2 project, around 60% of the energy consumption is with tractor semi-trailer configurations. This 60% is on its turn dominated by 4x2 tractors (80%). The remaining 40% of the energy consumption is used by a large variety of truck (axle) configurations in a range of mission profiles. So it can be concluded that the most important alternative body groups will be found with the tractor semi-trailer configurations. Consequently the body types for semi-trailers are further investigated.

Figure 35 shows the new registrations of semi-trailers in the EU27 in 2008. As can be seen, curtain and box van trailers represent a large share of new trailer registration in the EU27.
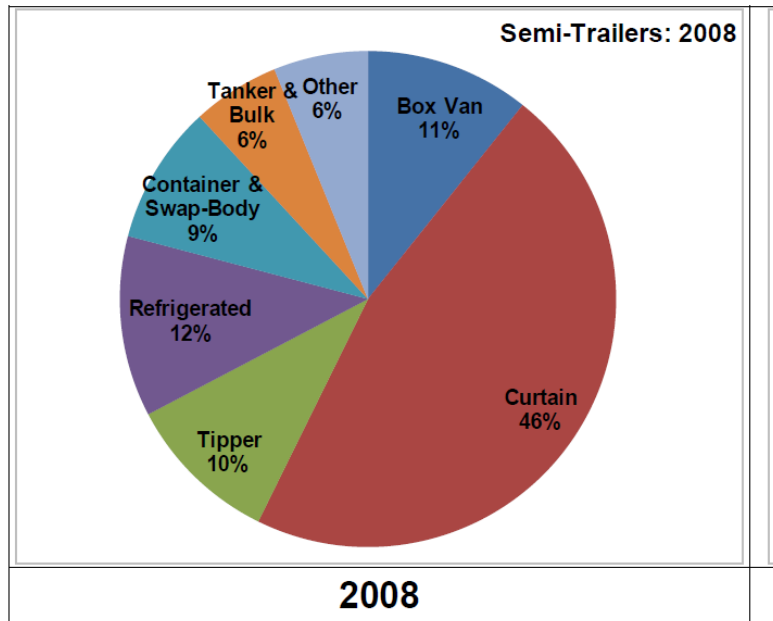
Source: CLEAR International Consulting (2010)

Figure 35: Comparison of new registrations of semi-trailers in EU27 in 2008 [source: VDA and CLCCR].

Refrigerated trailers and container and most swap-body semi-trailers have a similar geometry as the standard box body. Therefore, this type of trailers was not selected for a comparison of drag force coefficients. They are likely to not differ greatly. The 'tipper' is already included in the standard body category and 'other' category trailers comprise many different variants, for which a generic type cannot be defined. Therefore, in this study it was decided to look further into the drag force coefficients of both dry bulk and wet bulk tanker semi-trailers. This types of semi-trailers have a very different geometry compared to the standard box body type trailers.

4.5.2. Definition and dimensions of tanker semi-trailers

Within the tanker category commonly a differentiation is made between trailers used for transport of so-called wet bulk and of dry bulk material. Examples of wet bulk products are edibles like milk and vegetable oils, but also non-edible products like diesel, gasoline, Liquefied Natural Gas (LNG), etc. Dry bulk materials are for instance chemical bulk products such as fertilizer, plastic granulates, etc., but also so-called dry edibles (flour, peanuts, sugar, wheat, maize, rice, etc.).

In order to determine characteristic dimensions, a number of manufacturers of tanker semi-trailers, for dry as well as wet bulk, were contacted and interviewed. Also several large fleet owners with services across Europe were interviewed (among others: http://www.limpens-elsloo.nl/en). The selection of the characteristics of the 'standard' alternative configurations was focused on relatively optimised tractor semi-trailer configurations with a long haulage mission profile.

4.5.2.1. Mass of tanker semi-trailers

A limited evaluation of the empty and laden masses of tractors with tanker semi-trailers was done, by the evaluation of Weighing In Motion (WIM) data at about 10 locations on motorways in the Netherlands. For these analysis dry and wet bulk tankers cannot be separated. The laden mass was directly measures, while the empty mass was collected by reading the licence plates of the passing trucks and collecting the empty mass data from the road authorities data base.

The results are presented in Table 25 below. According to the table, the average cargo load is about 17 ton, while the empty mass is about 15.5 ton. The share of tanker semi-trailer trucks was 7.9% of the total passing trucks. This shows the relative large importance of this category.

Table 25: Statistical data of average mass of tractors with tanker semi-trailers in the Netherlands (based on 10 Weighing In Motion measuring locations at motorways).

All axle dry + wet tanker semi-trailer, including tractor	
Empty mass	15500 kg
Laden mass	32400 kg
# measurements	58403
Percentage of total measurements	7.90%

4.5.2.2. Dimensions of dry bulk tanker semi-trailer

One manufacturer kindly provided detailed drawings of their most representative 60m³ semi-trailer dry bulk tanker. This tanker is very typical for the chemical industry and the food industry and is one of the most popular models in Europe. A 3D representation is presented in Figure 36.
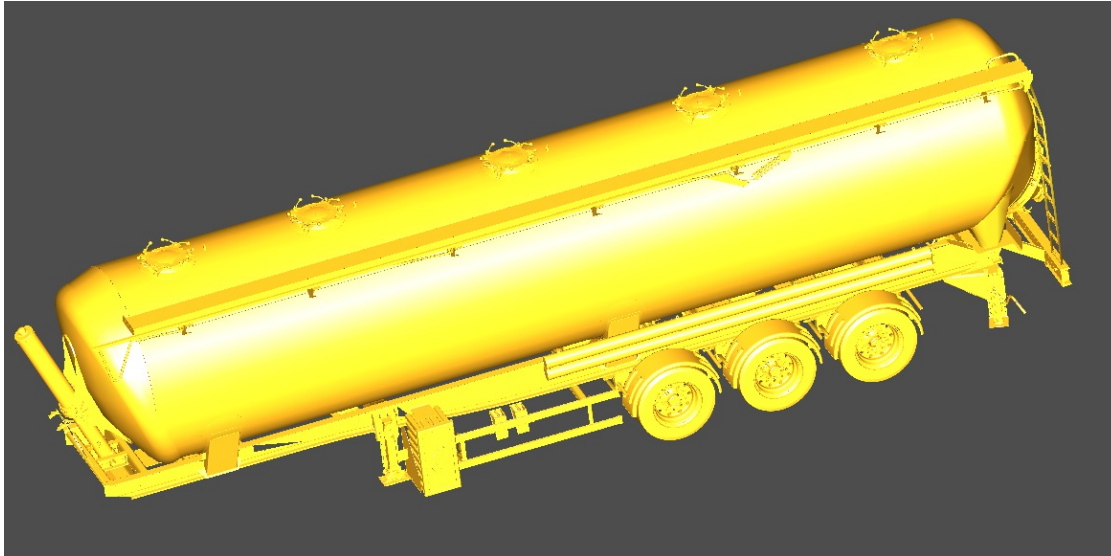
Figure 36: 3-d representation of dry bulk tanker semi-trailer used for CFD calculations.

The level of detail of the technical drawings was such that they could directly be shared with SES-Tec OG, who subsequently modelled the tanker semi-trailer and performed CFD calculations to obtain information on the drag force coefficients (section 4.5.3). The main dimensions, relevant for this study, are included in Table 26.

Table 26: Main dimensions of the dry bulk tanker trailer

Parameter	Unit	External
Length	mm	13,150
Vessel Diameter	mm	2,550
Height, unloaded	mm	3,990
5th wheel height, loaded	mm	1,150 to 1,200
Distance from mid-axle to semi-trailer end	mm	4,125
Axle distance	mm	1,310
Volume	m^3	60
GVM	kg	40,000
Axle load	kg	27,000
Empty mass	kg	±8000*

*Ranges between 5,700 and 10,000 kg according to Dutch tanker semi-trailer registrations.

Based on the drawings, SES-Tec prepared a model of the tanker suitable for performing CFD calculations. To get an CFD process able file, some details such as from the wheel hubs and the brake system were removed from the original files. The tanker semi-trailer was combined with the FAT tractor of the earlier calculations on the standard body of section 4.4.4, this way allowing for a good comparison between drag forces (CdxA) of the standard body and the alternative body.

The semi-trailer is set under an angle of ±1.2°, in practice, this angle often varies between 0,5 and 1,2°. Furthermore a distance of 230 mm is set between the rear end of tractor cabin and the front of the semi-trailer, this is a rather optimal situation applied by an interviewed large fleet owner. In practice this distance varies considerably.

4.5.2.3. Characteristics of the wet bulk tanker trailer

For the wet bulk tanker semi-trailer, the drawings were obtained from a popular tanker semi-trailer from one of the largest manufacturers. The 3D models for the CFD calculations were consequently made by adapting the models of the dry bulk carrier. The main differences are the length of the tank (shorter for the wet bulk), the number of man-holes on the top of the tank and the fact that the dry bulk tanker is a tipping semi-trailer with supporting legs behind the rear wheels and a heavier and higher (separate) frame is applied. The wet bulk semi-trailer also has a different tank shape at the front and rear. With respect to the combination of tractor and semi-trailers, we see with wet bulk a relative large gap of around 1 meter, between the rear of the cabin and the front of the tank. This is a consequence of the mass distribution and permissible axle loads. It is also somewhat dependent on the length of the tractor chassis and the configuration of the semi-trailer.

The main dimensions in Table 27 show the modelled combination of tractor and semi-trailer.

Table 27: Main dimensions of the wet bulk tanker trailer used for the CFD calculations.

Parameter	Unit	External
Length	mm	11,000
Vessel Diameter	mm	2,550
Height, unloaded	mm	3,800
5th wheel height, loaded	mm	1,150 to 1,200
Distance from mid-axle to semi-trailer end	mm	3,350
Axle distance	mm	1,310
Volume	Liter	38,000
GVM	kg	39,000
Axle load	kg	27,000
Payload	kg	±8000*

*Ranges between 5,700 and 10,000 kg according to Dutch tanker semi-trailer registrations.

The model of the wet bulk tanker again, was combined with the FAT tractor, allowing for a good comparison between drag force coefficients of the standard body and the wet bulk tanker, see section 4.5.3.

The semi-trailer tank is set under an angle of ±1.0°, in practice this angle often varies between 0.5° and 2.75°. Furthermore a distance of 1,000 mm is set between the rear end of

tractor cabin and the front of the semi-trailer, this situation is applied at several interviewed large fleet owners.

4.5.3. Drag force coefficients of tanker semi-trailers configurations

The aim of these CFD calculations is to estimate the drag force coefficient C_D and total drag $C_D.A$ for the typical dry and wet bulk tractor tanker semi-trailer configurations under different yaw-angles. The drag forces are determined relative to the drag forces of the FAT ("Forschungvereinigung Automobiltechnik") tractor with the standard box semi-trailer. The FAT tractor is also used for the tanker semi-trailers, to be sure that the changes in the drag coefficient are a result of the different trailer variants. The CFD calculations were done by SES-Tec OG.

The used computational mesh settings and boundary conditions follow the suggestions by the ACEA working group on CFD-simulations. The boundary conditions, the meshing strategy and the virtual workflow has been kept constant for all simulations, this has been done to ensure maximum comparability.

Three different yaw-angles were studied by cross-flow investigation. Variation of the drag force coefficients in relation to the basis simulation has been evaluated.

4.5.3.1. Input data and settings

The geometries of the two truck trailers which are used for the CFD calculations are created based on a model provided by "Spitzer Silo-Fahrzeugwerke GmbH". The geometry was modified in a way that it fits to the need of the current study. During the geometry preparation for the CFD simulations it was tried to keep as much details as possible. Figure 37 shows the main views of the trailer variant A, the dry bulk semi-trailer, and Figure 38 shows the main views of the trailer variant B, the wet bulk semi-trailer.
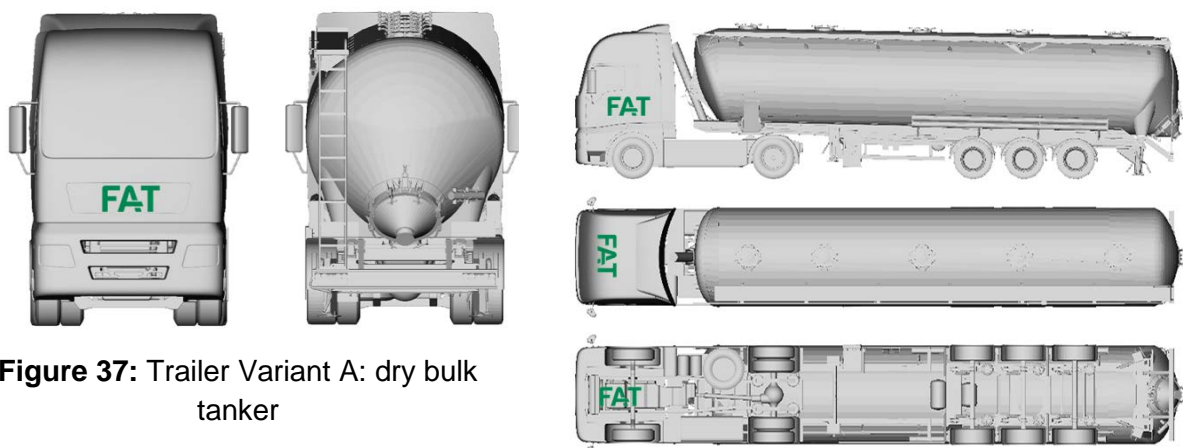
Figure 37: Trailer Variant A: dry bulk tanker
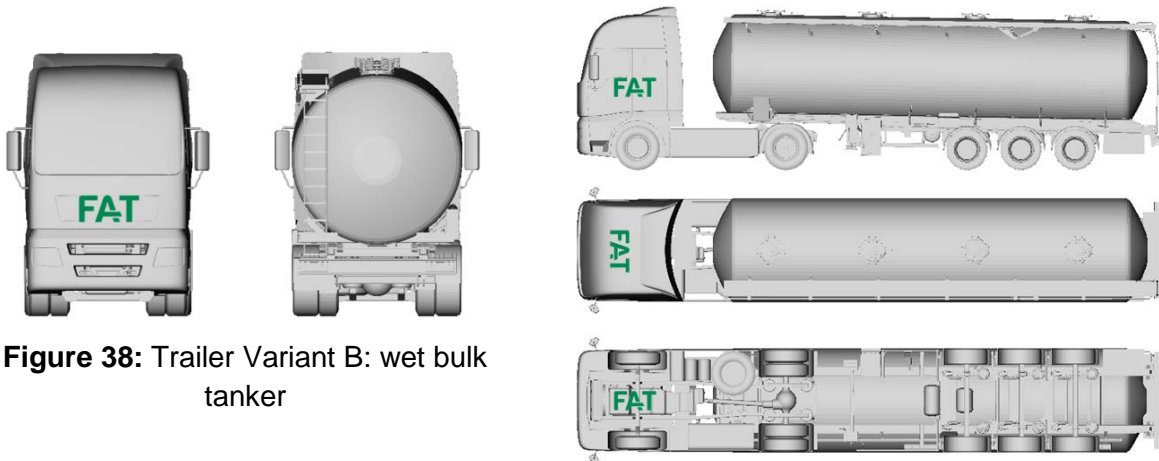
Figure 38: Trailer Variant B: wet bulk tanker

Using above described geometry, computational mesh was generated taking into account suggestions provided by the ACEA working group on CFD-simulations. Figure 39 shows the refinements regions for the Variant A and corresponding cell sizes. The mesh definition for Variant B has been done in the same way.
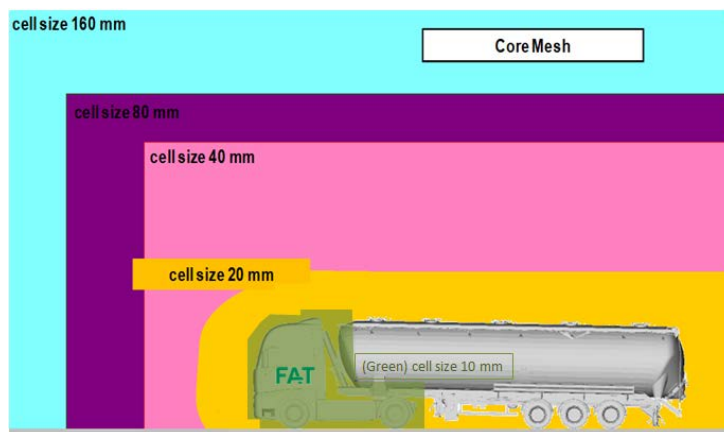
Figure 39: Refinements regions and cell size
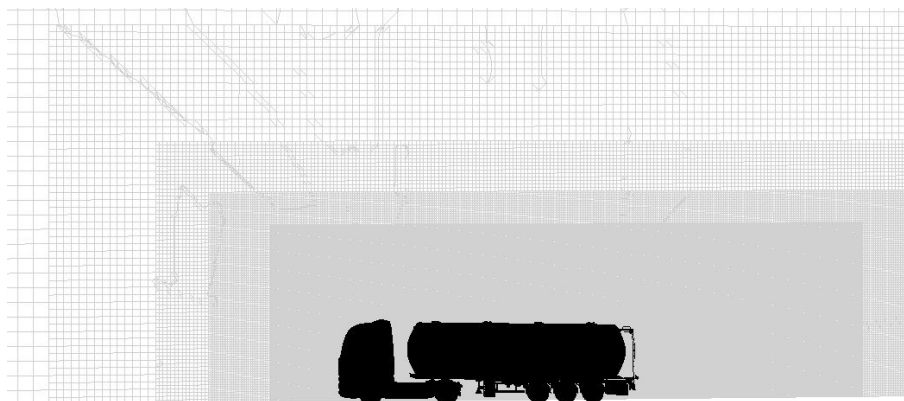
Figure 40: Symmetry cut through the used mesh in presented work

Meshing process begins with a definition of the box size (size of virtual wind tunnel) and the box cell size (in this case 160mm) of the core mesh. For each region/surface refinements

additional refinement levels are defined separately and step wise, see Figure 39. Beginning with a core mesh size definition (160mm) each followed cell size is divided by factor of two. Applying the method, the finest surface resolution is 2.5mm, e.g. mirrors and some faces on the vehicle cabin. The maximal recommended surface cell size is 30mm. In order to capture all important effects close to the wall, 8 prism layers cells extrusion with a maximal high of 20mm have been generated. The prism layer starts with 1mm near wall cell size and therewith fulfils the wall-function requirements for Y+ value between 30 and 300. These settings results in a final mesh size of about 133 million cells. Figure 40 show a symmetry cut through the used mesh in presented work including two details of the boundary mesh close to the surface.

For the reference case, simulation settings as well as initial and boundary conditions are given by the ACEA working group on CFD-simulations and some of these data are presented in Table 28 and Table 29.

Table 28: Simulation settings data

Nr.	Description	Input data
1	Simulation type	Steady-state
2	Turbulence model	k-epsilon Realizable
3	Wall function	Non-Equilibrium WF

Table 29: Initial and boundary conditions

Nr.	Description boundary condition (BC)	Input data
1	Inlet BC – velocity	90km/h
2	Outlet BC – pressure	101325Pa
3	Floor BC – sliding wall, Inlet/vehicle velocity	90km/h
4	Wheels BC – rotating walls, rotating velocity	calculated
5	Inlet Turbulence Degree	1%
6	Inlet Turbulence Char. Length Size	10mm
	Description material properties	
1	Density	1,184kg/m^3
2	Viscosity	1,49x10^{-5}m^2/s
	Description initial condition	
1	Initial pressure (only first simulation)	101325Pa
2	Initial velocity (only first simulation)	0m/s

At the beginning of the project a coarse mesh with about 5,5 million of cells is generated in order to get good initial field condition for all following simulations. The simulation with the

coarse mesh is done using given data in Table 28 and Table 29. The results of the simulation are further used as field initial condition and are mapped to the fine mesh at the beginning of each following calculation. With this strategy the numerical problems usually caused by inappropriate/unknown values are avoided and the number of iterations until converge solution have been reduced.

All simulation settings have been kept the same as for the report [6] therefore the comparability should be as good as it can be.

4.5.3.2.   Investigated variants

Presented work includes 6 variants in total, which are listed below:
1. Trailer A –> yaw angle = 0°
2. Trailer A –> yaw angle = 1.5°
3. Trailer A –> yaw angle = 3.0°
4. Trailer B –> yaw angle = 0°
5. Trailer B –> yaw angle = 1.5°
6. Trailer B –> yaw angle = 3.0°

As a reference case the results of the aerodynamic simulations of the FAT geometry, has been used [6]

The variant 1 – 3 are corresponding to the trailer variant A and representing the geometry at three different yaw-angles (0°, 1.5°, 3.0°). Variant 4 - 6 corresponds to trailer variant B using the same three yaw – angles. In all cases the vehicle velocity of 25 m/s is kept constant and the side velocity component is calculated according to the beta angle, see Table 30.

Table 30: Cross flow input data

Yaw-angle [°]	1,5	3,0
x-velocity [m/s]	25,0	25,0
y-velocity [m/s]	0,655	1,310
Velocity Mag. [m/s]	25,008	25,034

4.5.3.3.   Results and discussion

As mentioned before, the aim of the presented work is to estimate the aerodynamic drag force coefficient under different above described geometry designs and flow conditions. The drag force coefficient is calculated applying following equation:

$$C_D = \frac{2F_D}{\rho v^2 A} \tag{1}$$

where, F_D is drag force, ρ is air density, v is free stream velocity, and A is reference area.

Figure 41 and Figure 42 shows a comparison between trailer A and trailer B, respectively the dry and wet bulk configurations. The vehicle surface is collared by pressure.
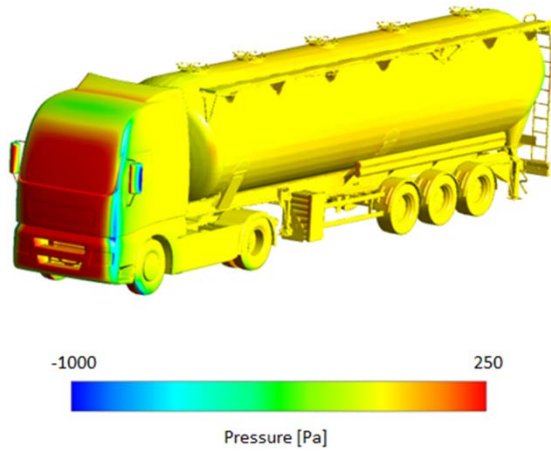
Figure 41: pressure on the vehicle surface trailer A: dry bulk tanker
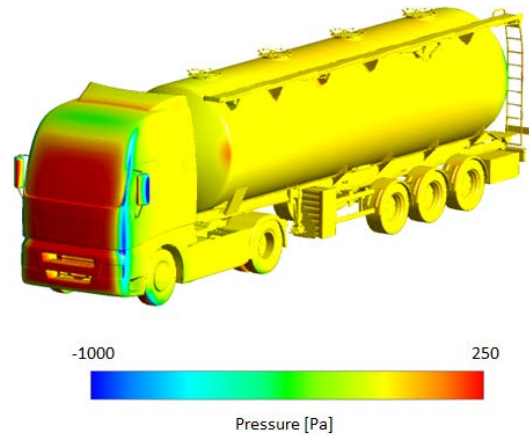
Figure 42: pressure on the vehicle surface trailer B: wet bulk tanker

Figure 43 and Figure 44 shows a cut through the simulation domain, and the velocity distribution on this cut. It can be seen that the distance between the tractor and the trailer variant B is much higher compared to the distance of tractor and the trailer variant A. This difference is the reason for the higher drag coefficient of variant trailer B.
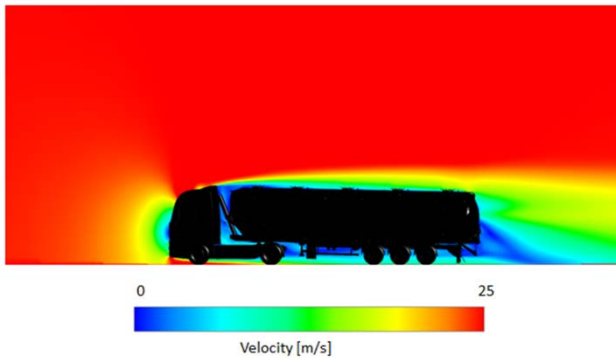
Figure 43: velocity contour - trailer A
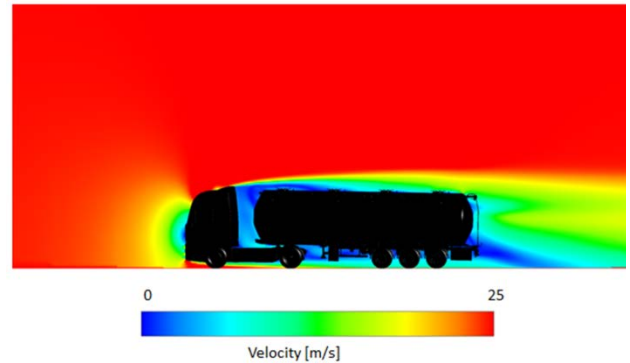
Figure 44: velocity contour - trailer B

Figure 45 and Figure 46 show the results obtained by the yaw angle variation for the C_D and $C_D * A$ values, respectively. The curves show the expected typical parabolic behaviour. The basis variant for the calculation has been the FAT semi-trailer with a cross flow yaw angle of 0°. All other results are relative to this variant. The ratio between standard box and the tanker trailers for $C_D * A$ is a bit smaller than the ratio for C_D, because the frontal area of the tanker semi-trailer is slightly smaller than the frontal area for the standard box semi-trailer..
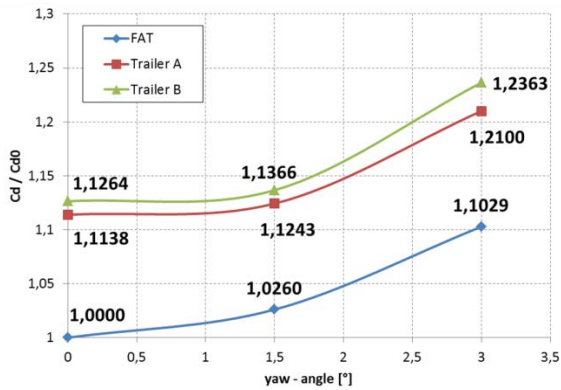
Figure 45: ratio of C_D from alternative trailer to standard trailer
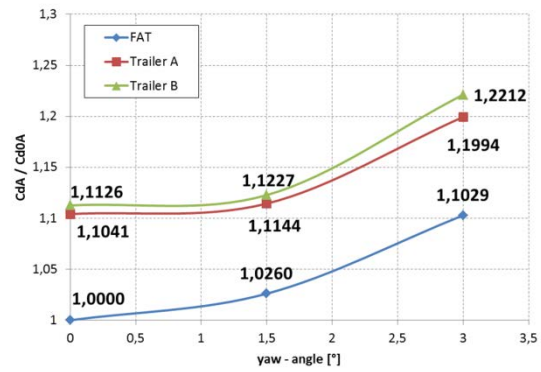
Figure 46: ratio of $C_D * A$ from alternative trailer to standard trailer

Tractor semi-trailer configurations: FAT=box semi-trailer, trailer A= dry bulk semi-trailer, Trailer B is wet bulk semi-trailer

4.5.3.4.   Conclusions: drag force coefficients of wet bulk and dry bulk tanker semi-trailer

Comparing the drag resistance (CdxA) of the tanker semi-trailers and the box semi-trailer configurations yields the following observations:

1. The drag force coefficients of the dry and wet bulk tanker configurations are approximately 11 to 13% higher than those of the standard box semi-trailer configuration.
2. The drag force coefficients of tractor-tanker-trailer combinations show the same parabolic behaviour with yaw angle as the tractor-standard-box-body configuration.
3. The higher drag resistance of the tank configurations is caused by a) the many brackets and accessories (box, hoses, manholes and railings) mounted on the semi-trailer which all contribute to the drag. And b) the relative large distance between the rear end of the cabin of the tractor and the front end of the tank.
4. The drag force coefficients of the wet bulk tanker and the dry bulk tanker are at a comparable level. The wet bulk trailer has a slightly higher drag force coefficient than the dry bulk ($\sim 1.3\%$), due to the larger distance between cabin and front of the tank.
5. The difference between tanker and box configuration is a bit smaller ($\sim$10%) at the highest yaw angle. This can be explained by the relative roundish shape of the front end of the tank compared to the square shape of the box. Some of the loss due to the larger gap between cabin and front of semi-trailer is recaptured at the larger yaw angle due to the roundish shape.
6. From the results a first set of 'default C_dxA values' can directly be derived (+12% compared to standard box semi-trailers). It is recommended to validate the results with different CFD codes and/or with driving resistance or fuel consumption measurements on the road for both the dry and wet bulk tanker semi-trailers if these default values are going to be implemented in legislator framework. In such a case it may be also relevant to check the standard dimensions and variation of the tanker

4.5.3.5. Integration of and further work on alternative bodies

The following further work is recommended:

- Discussions and decisions are necessary, how alternative bodies are treated in a future legislation for HDV CO_2 emission certification. A reasonable option would be:
  - Alternative bodies and trailers can optionally be tested in the aerodynamic drag test procedure as described in chapter 4.2.3. As alternative default values may be applied (to limit the effort for small body builders)
  - In the CdxA test for bodies and trailers any tractor or rigid truck can be used which has a sales number above xxx in last 3 years. The body builder can either test only his body or trailer if he gets the CdxA value for the same vehicle configuration but with the standard body or trailer by the vehicle manufacturer. If he has no access to the standard result he needs to test also the vehicle equipped with the standard body or trailer.
  - From the comparison of the alternative body or trailer with the result for the standard bodies or trailer configuration the percent change in CdxA shall be calculated.
  - A generic look-up table will be provided by VECTO simulation runs for all HDV-classes which gives the percent change in fuel consumption as function of the percent change in CdxA and of the percent mass change.
  - The result for alternative bodies and trailers is then the percent change in fuel consumption and CO_2 against the "standard" body or trailer.
  - The tests shall incentivize the production of more fuel efficient bodies and trailers by application of aerodynamic improvements and weight reduction.
- If this option is selected, draft CdxA values for different body and trailer types need to be elaborated either by testing or by CFD simulation especially for alternative body categories with a large CO_2 contribution. These are tractor semi-trailer configurations with swap-body and with flat-bed body. Certainly all VECTO simulations to set up the look-up table has to be done and several details of the test procedure would have to be defined.

4.6. Aggregated vehicle validation procedure

An option for an aggregated vehicle validation procedure was developed to allow a relatively simple check of the entire vehicle specific input data used for single vehicles for certification with VECTO.

Background of the development of the so called SiCo-test (simple constant speed test) and of the corresponding method of an "ex-post validation" is the demand for independent checks of the CO_2 results from VECTO for single vehicles. The basic certification approach of component tests with vehicle simulation demands for correct independent reconstruction of the test that each component is measured according to the defined component test procedures.

Then the data can be fed into VECTO and the results can be compared with the CO_2 value declared by the manufacturer. This certainly is extremely complex and we may not expect such activities by member states.

An attractive alternative is certainly to measure the entire vehicle on a test route and then to simulate the vehicle with VECTO for the measured speed trajectory with measured road gradients and wind conditions. This however would require the availability of all component test data necessary to run VECTO for independent labs. Since the component test data, such as engine fuel maps, is typically proprietary of the HDV manufacturer which is not commonly available, this option proofed to be technical attractive but not applicable due to data access limits.

As possible solution following option was developed:

- VECTO in the declaration mode simulates in parallel to the CO_2-test cycle also a very simple constant speed test for each HDV
- The constant speed levels and the according simulation results for the power demand at the wheels and for the fuel consumption are exported by VECTO.
- The HDV can then be tested in the reported constant speeds and results can be compared with the simulated power at the wheels and with the simulated fuel consumption provided by VECTO. Alternatively the constant speed tests may be driven also on a chassis dyno, if mainly the efficiency of the engine and transmission system shall be checked[15].

The options seems to be a viable way for checking test results without needing any proprietary VECTO input data. Variability in boundary conditions of the test could be considered by simulating the SiCo-cycle in VECTO for variable wind conditions, different air density and with small road gradients. The user can then interpolate the results for his specific test conditions.

The SiCo-cycle is in an early development phase yet. It was foreseen to apply the method in autumn 2013 on a bus but during the tests the wheel rim torque-meter was damaged. The tests have been repeated end of March 2014 but evaluation is still ongoing. The results of this first application of the SiCo-test most likely will lead to amendments and improvements of the corresponding test procedure. The updated procedure shall then be applied in a "proof of concept phase" by manufactures to find further need for improvements and to get sufficient data to develop reasonable thresholds for deviations between measured and simulated values.

In general the method is assumed to be applicable only to identify conspicuous deviations for single HDV. In these cases the type approval authority may request a verification of the component test data used to run VECTO for the vehicle[16].

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[15] Testing the entire CO2 test cycles on the chassis dynamometer would result for some cycles in very long tests and in addition the cycles with variable road gradients are hard to follow by drivers on the chassis dyno. Nevertheless this option may be analysed during the proof of concept phase too.

[16] Since deviations against test data can also result from the generic data VECTO is using and also from inaccuracies of the VECTO tool for single vehicles, deviations between measurement and VECTO result do not necessarily result from incorrect vehicle specific input data

The actual status of the SiCo test procedure is described in the following and shall be interpreted as basis for a "proof of concept phase" where more extensive tests are included than in a final certification method to be sure that sufficient information is available for further improvements of the method.

4.6.1.1.   Simulation of a simple speed test by VECTO

All input data for VECTO has to be the official data for the certification procedure[17].

Beside the standard CO_2 test cycles for each HDV class also the SiCo velocities are stored in the data base of VECTO for each HDV class. The SiCo are defined by target speed over distance containing the main target speeds of the corresponding CO_2 test cycle (Table 31). If a vehicle would not be able to reach the highest speed from Table 24 with the VECTO input data, VECTO should deliver the simulation results for the maximum speed.

Table 31: Constant speed phases for the SiCo for the corresponding CO_2 test cycles

	0	30	50	60	85	100
Long haul	x	x		x	x	
Reg Del	x	x		x	x	
Urb Del	x	x		x	x	
Municipal	x	x		x	x	
Construction	x	x		x	x	
City Bus	x	x	x	x		
Coach	x		x		x	x

(0)   In idling the auxiliaries have high impact on the measured fuel flow. Since auxiliaries are simulated based on generic data in VECTO, no reasonable accuracy can be expected in idling. The actual proposal still included idling since it may be an indicator on the [g/h] uncertainty added by auxiliaries (and other uncertainties) to the result at higher velocities

The SiCo strings the target speeds together, as shown in Figure 47. The main target speed is computed also for a positive road gradient which results in a typical engine load from the CO_2 test cycle *(all SiCo will be fixed constant speed test phases, more details can be drafted after the first tests and analysis)*. VECTO simulates the SiCo as target speed cycles similarly to the CO_2 test cycles.

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[17] As described in the "technical annex".
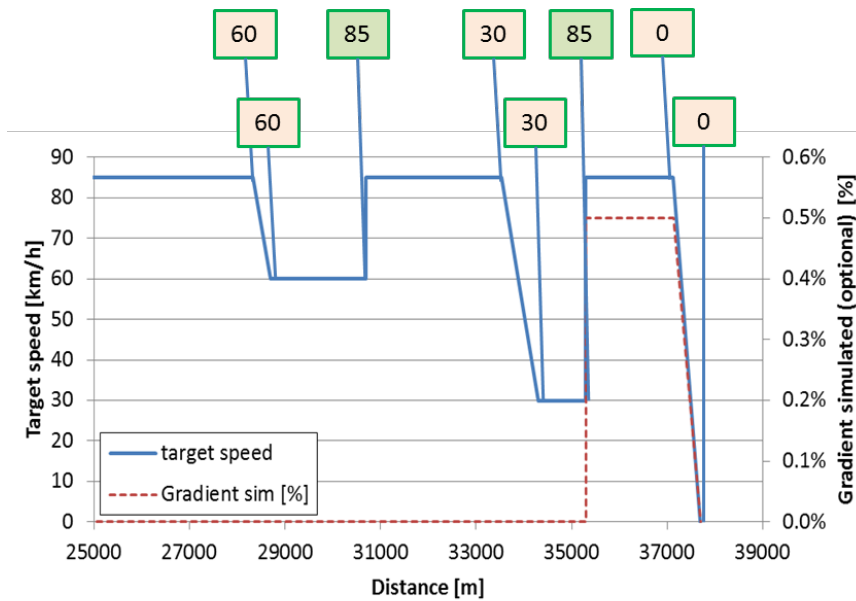
Figure 47: Schematic picture of a SiCo test to be computed by VECTO (*final test points open*) with the marks which shall be installed on the test track for driver information. Depending on the test track and on torque measurement equipment applied, the single constant speeds may be driven in separate tests without full load acceleration phases

The results for the SiCo are provided by VECTO in a separate SiCo file in addition to the official fuel consumption for the vehicle. The SiCo file contains the vehicle description and the fuel consumption computed for the single phases of the SiCo and for the entire SiCo as shown in Table 32.

The data shown in Table 32 may be gained in a later certification procedure also in 2 steps (step 1 testing and comparing only the fuel flow in [g/h], in case of too high deviations against VECTO results also the torque measurement at wheel hubs can be applied to better allocate the source of the deviation).

Table 32: Example table for the data to be provided by VECTO in the SSC file for each certified HDV

	Gear	P-wheel	FC[3]	FC	Time
		[kW]	[g/h]	[g/kWh]	[s]
Idling	0	0.0	1808.6		--
60 const	6	51.0	12413.6	243.4	--
85/0% const	8	101.5	22557.2	222.2	--
85/0.5% const	7	140.8	29802.2	211.7	--
accel 60-85 [1]	Start in 6	250.7	--		28
accel 30-85 [1]	Start in 3	251.2	--		53
Total [2]		41.8	15938.9	381.4	626

(1) Accelerations only included if test track and test equipment is sufficient. If acceleration phases can be used in final certification is questionable but it is suggested to include them in the proof of concept phase where possible)

(2) Higher accuracy is expected for the single constant speed phases than for the entire cycle result. Nevertheless in the proof of concept phase also the uncertainties related to a complete cycle should be analysed

(3) The overall fuel consumption value is influenced by RRC of the test tires and by wind and temperatures during the test and thus may be not accurate enough. The applicability of this value thus needs to be further evaluated.

4.6.2.   Measurement of the SiCo on a test track with the corresponding HDV

The measurements shall be performed on selected HDV under following conditions:
- The HDV has to be equipped with the components defined in the SiCo file (which auxiliary engagement should be simulated by VECTO for the SiCo needs further discussion)
- The HDV has to have a total mileage between aa and bb[18] km
- The tire profile depth shall be not less than 80% of the new tire, otherwise tires shall be changed
- No additional equipment shall be installed which influences the aerodynamic resistance

The manufacturer shall tests xx[19] HDV per family to report to the type approval authority.

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[18] The mileage values are just placeholders. A suitable roll-in procedure needs to be developed in course of the proof of concept phase which gives similar conditions as defined in the component test procedures.

Test set up:

The measurements of the SiCo shall follow exactly the specifications defined in chapter 4.2.3 *(Cd x A test procedure)* with following extensions and open questions:

- Conditioning similar to the aerodynamic drag test procedure *(to be discussed, depends also on findings on influences of preconditioning on RRC which are expected in 2014 from separate test campaigns)*
- Fuel consumption shall be measured on board with the accuracy defined in the technical annex[20]
- The distances where the target speed changes in the SiCo shall be marked clearly visible for the driver on the test track. At or near the mark the next target speed shall be installed readable for the driver as shown in Figure 47.[21]
- The driver shall perform full load acceleration to the next target speed level when he passes the mark (in case of increasing speed) or he shall perform normal braking (either -0.5 m/s² or -1 m/s²) to reach the next (lower) target speed at the next mark.
- Wind speed and road gradients have to be recorded and calibration of anemometer and velocity signal shall be in line with the aerodynamic drag test (see chapter 4.2.3 and technical annex).
- During the SiCo test the torque and speed at the wheel hub as well as the velocity have to be recorded in accordance with the aerodynamic drag test (see chapter 4.2.3 and technical annex).

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4.6.3. Evaluation of the SiCo test

The values in Table 33 shall be evaluated from the test results as follows:

P-wheel [kW] from following calculations:

M_d [Nm] = average over minimum 10 and maximum 60 seconds of the measured torque, starting averaging later than 15 seconds after reaching each target speed (in the proof of concept Phase also data from shorter test tracks with corresponding shorter stabilisation time will be highly welcome, minimum requirements for later certification procedure open yet)

Rotational speed [s^{-1}] = average in accordance with M_d.

P-wheel [kW] = Md x Rotational speed x 2 x Pi /1000

FC in [g/h] from following calculations:

FC [g/s] = average in accordance with M_d.

FC [g/h] = FC [g/s] x 3600

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[19] Placeholder: needs to be discussed if manufacturer has to do such tests or if this test is just relevant for eventual independent labs. Also "family" needs to be defined.

[20] Open yet. Fuel flow meters shall allow accuracies <1%, Carbon balance in case of PEMS equipment rather less accurate

[21] Defined distances per constant speed may be advantageous to have always defined preconditioning for each step. Evaluation is done later for the constant speed phases separately.

FC in [g/kWh] from following calculations:

FC [g/kWh] = FC [g/h] / P-wheel [kW]

Time [s] from following calculations:

Time stamp when new target speed is reached the first time with less than 2% deviation minus time stamp when the former target speed is left the first time with more than 2% deviation *(reasonable thresholds to be defined after first experience with tests)*.

Each result shall be computed per direction first. Then the average over the both directions shall be calculated.

The measured values shall not exceed the limits defined in Table 33.

Table 33: Tolerances allowed for the measured values against the ex-post results from VECTO *(all tolerances are just placeholders yet)*

	P-wheel	FC	FC	Time
	[kW]	[g/h]	[g/kWh]	[s]
Idling	-	-	-	--
60 const	7%	--	4%	--
85/0% const	7%	--	4%	--
85/0.5% const	7%	--	4%	--
accel 60-85	--	--	--	10%
accel 30-85	--	--	--	10%
Total	--	--	7%	--

If P-wheel is exceeded by more than the defined tolerances, a deviation in air resistance and/or rolling resistance against the VECTO data exists. The consequences are:
1) Re-check if same tires are mounted as defined in CO_2 certification
2) Check if wind conditions and road gradients are within the boundary conditions
3) Check if aerodynamic condition of the vehicle is as defined in CO_2 certification (body and trailer, additional accessories etc.).
4) If errors are found in 1) to 3), repeat the tests after elimination of the error source

If no error in the test is visible but still the tolerances are exceeded, the component tests for C_dxA and for the tire RRC values have to undergo a quality check.

If the FC in [g/kWh] exceeds the defined tolerances, a deviation in auxiliary power demand, in transmission efficiency or in engine efficiency against the VECTO data exists. The consequences are:
1) Check if correct gears have been used
2) Check auxiliary status, load battery and repeat the test

If exceeding of tolerances remains, the component tests for the gear box, for the axle and for the engine have to undergo a quality check by the type approval authority.

There are several issues which need to be considered in the proof of concept phase of the SiCo test:

- Speed dependent tire RRC shall be analyzed already for the aerodynamic drag test and shall be considered also in the SiCo test (related to proving ground/ tire make, tire pressure/ temp, ambient temp, other factors?)
- The proof of concept phase shall be designed to provide data to evaluate:
  - uncertainties for measurement equipment in vehicle (fuel flow meter, wheel torque sensors, anemometer)
  - production tolerances (engine, auxiliaries, transmission, axel)
  - deviations related to operating temperature (oil temperature)
  - necessary sensor equipment and possible correction algorithms for tolerance in tire rolling resistance

It is recommended to include further development work on the SiCo test into a follow up project from the Commission since such a test procedure seems to be important.

4.7. Sensitivity analysis for input data

A sensitivity analysis was performed where each set of input data was varied within reasonable ranges to show their influences on the resulting fuel consumption. This analysis was made for three vehicle classes since the share of the single components on the overall energy consumption as well as the test cycles are quite different between these classes.

The performed sensitivity analysis covers all vehicle specific input parameters:

- Air drag parameter
- Rolling resistance
- Engine fuel consumption map
- Transmission and axle loss maps

These parameters have been varied within the expected accuracy of the underlying measurement procedure to show the influence on the accuracy of the resulting HDV fuel consumption.

VECTO parameters for auxiliary operation have not been varied in the sensitivity analysis as these HDV components are in the current stage covered by generic approaches only. Further sensitivity analyses are recommended related to the VECTO prediction for the influence of driver assistance systems (eco-roll, engine stop-start systems) once the related function parameters have been agreed on by industry.

4.7.1. Reference vehicles

For the sensitivity analysis reference vehicles have been compiled for VECTO with typical vehicle specifications based on the data collected during LOT2 and LOT3. The vehicle models from the proof of concept phase however, are not available to LOT 3. Three different HDV configurations have been analysed:

Table 34: Reference vehicles for sensitivity analysis

Vehicle	Rated power [kW]	Total weight [t]	c_d x A [m²]	RRC [kg/kg]
4x2 Rigid Truck, 12t max. GVW	185	9.9	5.28	0.0094
4x2 Tractor & Semitrailer, 40t max GVW	350	33.9	6.30	0.0055
6x2 Coach, 24t max GVW	350	19.0	3.26	0.0064

The input data for these reference vehicles will also be distributed with the VECTO code. Any OEM-specific information has been made unrecognisable.

For all three vehicles the corresponding mission profiles were used:

- **4x2 Rigid Truck, 12t max. GVW**: Long Haul, Regional Delivery, Urban Delivery
- **4x2 Tractor & Semitrailer, 40t max GVW**: Long Haul, Regional Delivery
- **6x2 Coach, 24t max GVW**: Coach

4.7.2. Variation of input parameters

In the sensitivity analysis the main input parameters to be determined by the component test procedures have been varied in an order of magnitude which refers to the estimation for the accuracy (95% confidence interval) of the different measurement methods. Details are listed below.

4.7.2.1. Air drag parameter (C_dxA)

Based on the analysis on repeatability and reproducibility of the constant speed test procedure made in the proof of concept and the facts that

- the method has been improved in the meantime and
- in a real certification process OEMs will run the tests several times and select the best result

the relative accuracy of the C_dxA value was estimated with +/-3%, e.g. a baseline value of the reference vehicle of 6.30 [m²] was varied in a range of 6.11 and 6.49.

4.7.2.2. Rolling resistance

The rolling resistance coefficient was varied for each tire by an absolute value of +/- 0.3 [kg/t]. This magnitude was taken from the tolerance of the COP testing (EC) 1235/2011.

4.7.2.3. Fuel consumption map

Two different scenarios have been considered in the sensitivity analysis for the accuracy of the fuel consumption map:

a) *"Worst case" tolerance for measurement quantities according to the ECE R49.06 regulation*

As effective provisions for the EURO VI regulations the specifications in the R49 for linearity of measurement systems and for determination of fuel consumption have

been identified. If one assumes a completely linear measurement error of the measured signal compared to the reference value the "slope" in the linearity requirements is the main relevant provision.

The following "worst case" tolerances have been added to the baseline fuel map for generation of the "low FC" map:

- engine speed = 1.02*reference value

- engine torque = 1.02*reference value

- fuel flow = 0.98 * reference value or (reference value – 0.3% max. fuel flow) whichever is higher

The "high FC" map was generated in a similar way but with changed signs.

In the VECTO simulations the engine full-load torque and the drag curve have been adapted for the "low FC" and "high FC" version accordingly (i.e. the "low FC" engine has higher rated power etc.).

b) Tolerances according to the TUG test equipment standards

The following tolerances have been derived from the measurement standards used for TUG equipment for system approval:

- engine speed: tolerance neglected (signal from the rotation angle sensor)

- engine torque = 0.3% of full-scale

- fuel flow = 0.12% of full-scale

With these tolerances also a "low FC" and a "high FC" engine fuel map have been generated.

4.7.2.4. Transmission and axle loss maps

The loss maps for the transmission and the axle have been varied by +/- 0.3 [Nm]. This variation range has been taken from the accuracy demands as defined in the technical annex. In the sensitivity analysis transmission and axle loss maps have been varied in separate scenarios.

4.7.3. Results

This section presents the variation of overall fuel consumption for each input parameter, vehicle and mission profile.

4.7.3.1. Air drag parameter (C_dxA)

The following diagrams show the change in fuel consumption due to varying the air drag parameter by +/- 3%.
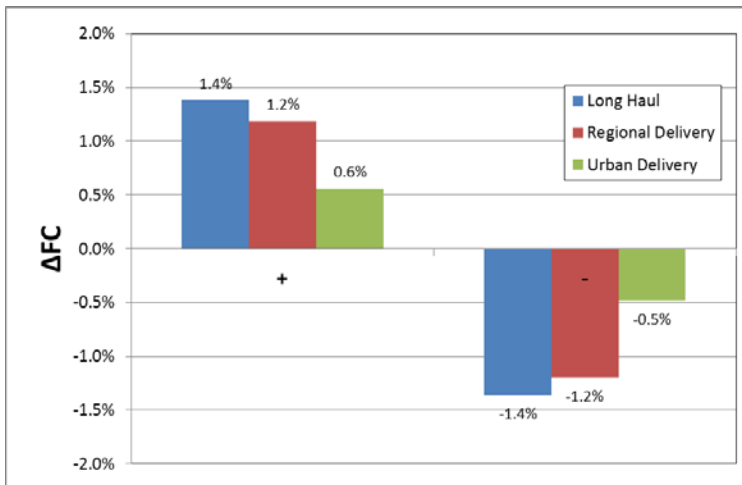
Figure 48: FC change for +/- 3% air drag results for 12t 4x2 Rigid Truck
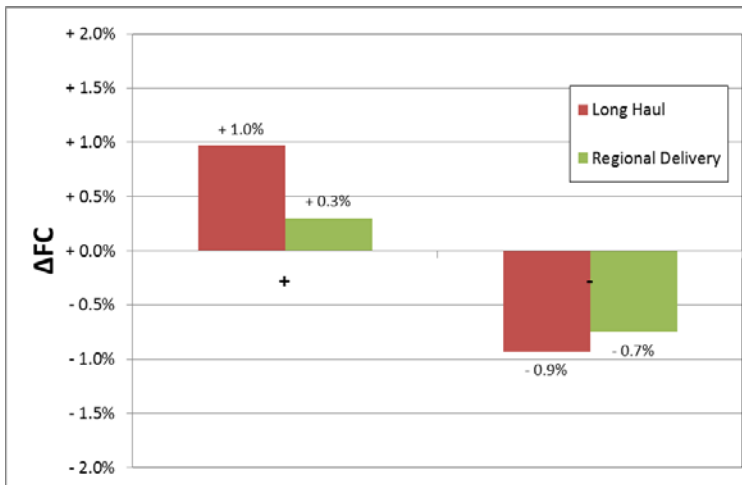
Figure 49: FC change for +/- 3% air drag results for 40t 4x2 Tractor & Semitrailer
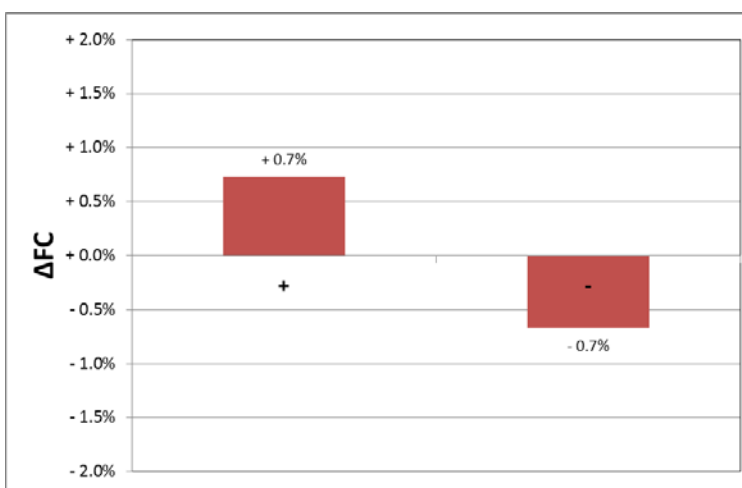
Figure 50: FC change for +/- 3% air drag results for 24t 6x2 Coach

The highest relative change in fuel consumption was found for the 12t rigid truck in the long haul mission profile with +/- 1.4%. The other cycles show less deviation because of lower speed and consequently lower air resistance in relation to the other resistances. The coach shows low influence -in spite of higher average high speed- resulting from the much lower base air drag coefficient and the higher baseline load from auxiliaries.

Note that the 40t Truck shows non-linear results in the Regional Delivery (+0.3%/-0.7%) which is due to changes in the gear shift behaviour. Every parameter change in the input files that affects engine power can naturally lead to changed gear shift behaviour.

4.7.3.2. Rolling resistance

The following diagrams show the change in fuel consumption due to varying the rolling resistance by +/- 0.3 [kg/t].
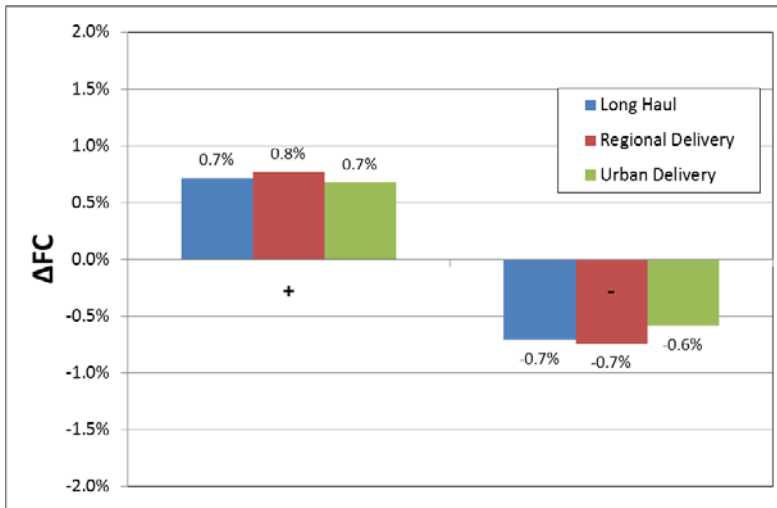
Figure 51: FC change for +/- 0.3 [kg/t] rolling resistance results for 12t 4x2 Rigid Truck
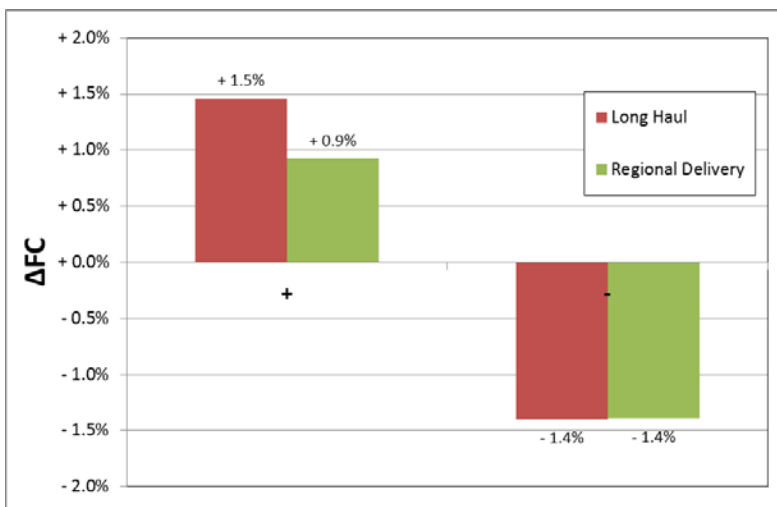
Figure 52: FC change for +/- 0.3 [kg/t] rolling resistance results for 40t 4x2 Tractor & Semi-trailer
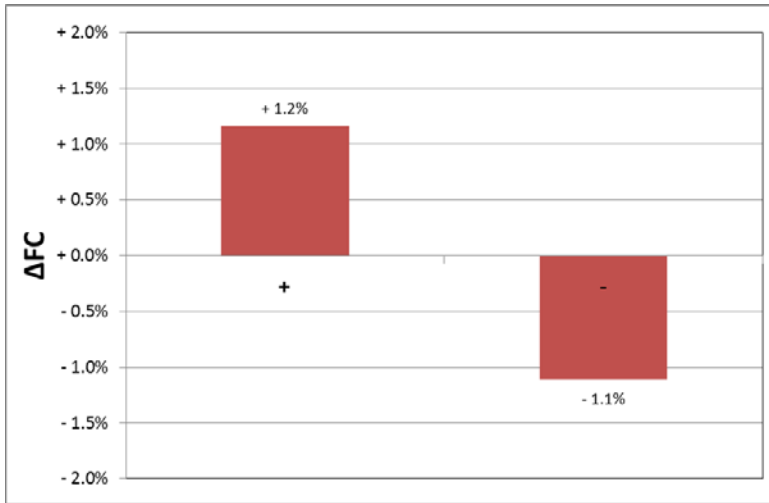
Figure 53: FC change for +/- 0.3 [kg/t] rolling resistance results for 24t 6x2 Coach

The highest influence on fuel consumption was found for the 40t Truck with 1.5%. The effects are lower for the other two vehicles where the rolling resistance has lower influence because of the lower weight.

The 40t Truck again shows non-linearity in the Regional Delivery cycle due to different gear-shift behaviour.

4.7.3.3.   Fuel consumption map

The following diagrams show the change in fuel consumption due to varying engine torque, speed and FC in the fuel consumption map. The analysis was only made for the 350kW engine used in the 40t truck and 24t coach reference vehicles. Additionally, for the 40t truck, two scenarios "Worst case" and "Equipment standards" were calculated as described before.

Figure 54 and Figure 55 show the results for the "test equipment tolerances" scenario.
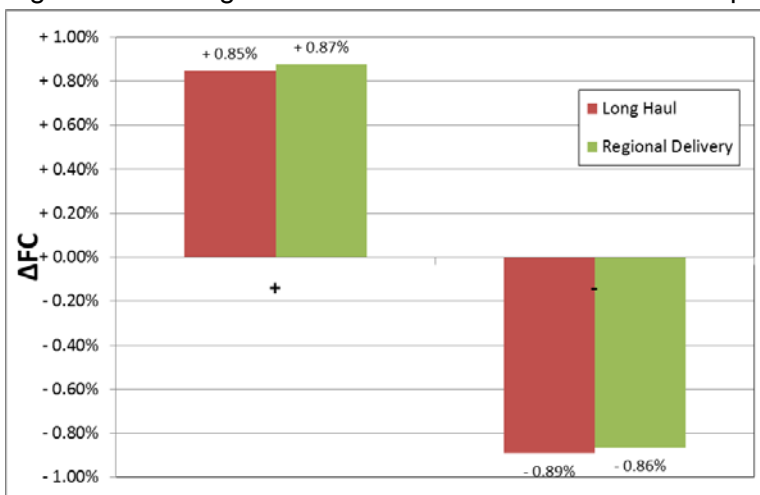
Figure 54: FC map variation "test equipment tolerances" scenario for 40t 4x2 Tractor & Semitrailer
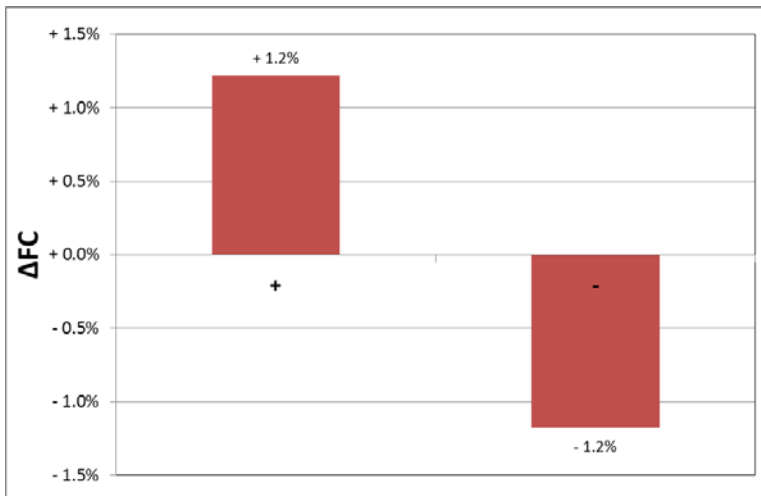
Figure 55: FC map variation "test equipment tolerances " scenario for 24t 6x2 Coach

In this scenario the variation in overall fuel consumption originating from the uncertainty in the engine fuel map is in the range of +/-1% with slightly higher values for the coach application (+/-1.2%) compared to the long haul truck (+/-0.8%). These different sensitivities for the two investigated vehicle classes can be explained by the different distribution of load points in the engine map.

Figure 56 compares the sensitivity for the 40t long haul truck in the two scenarios "ECE R49 Worst case" and the "test equipment tolerances". If the full range of tolerances as specified in the ECE R49 is utilised the overall fuel consumption can vary in a range of +/-4.5%. This is a significantly higher range of tolerance than the "state of the art" for this kind of test equipment. This high range of uncertainty is of course not appropriate for the HDV CO2 certification. Measures to elaborate more stringent provisions have been initiated and shall be based on an evaluation of possible accuracies in cooperation with ACEA.
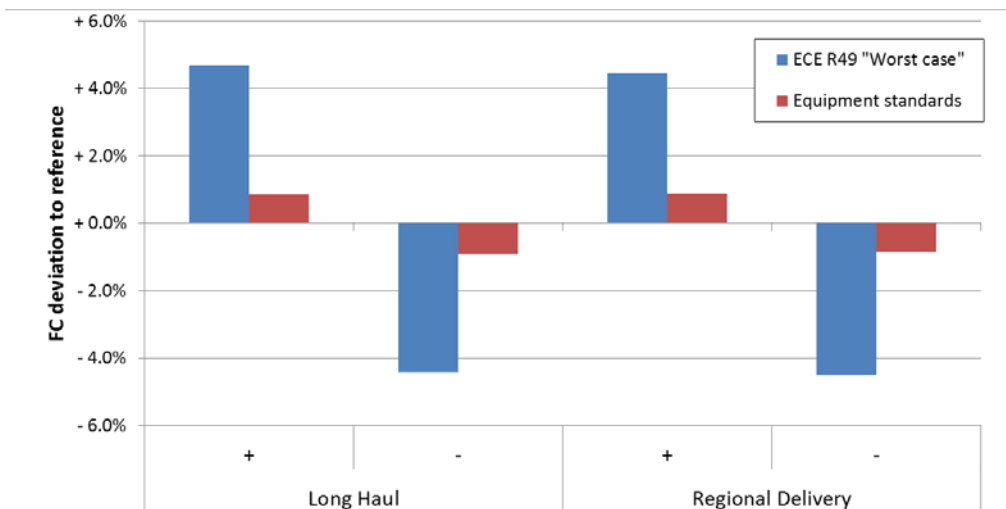
Figure 56: Comparison of the "ECE R49 worst case" and "test equipment tolerances" scenario for the 40t long haul truck

4.7.3.4. Transmission and axle loss maps

The following diagrams show the change in fuel consumption due to varying transmission and axle loss maps. The two maps were varied in a separate set of VECTO simulations. The impact of the tolerances as defined in the transmission and axle testing provisions on overall fuel consumption are nearly neglectable.
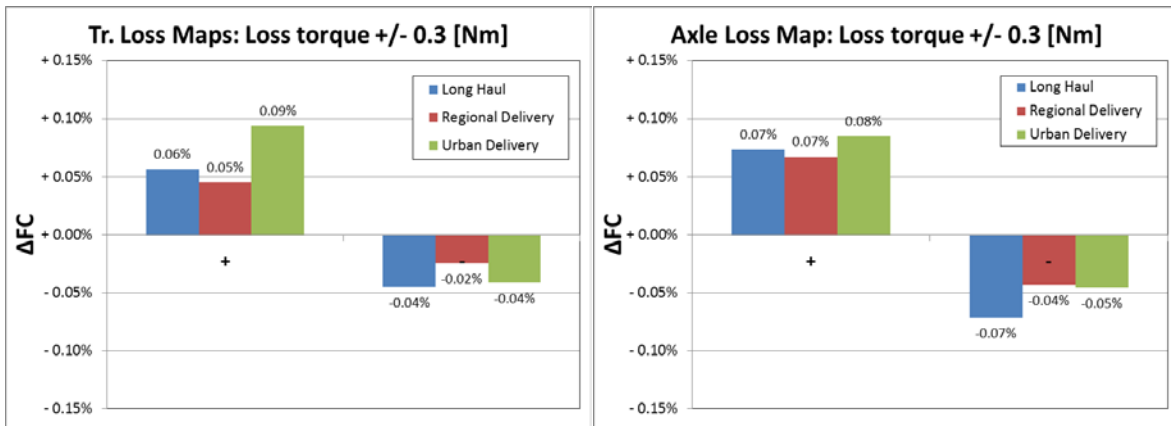
Figure 57: FC change for +/- 0.3 [Nm] transmission/axle loss torque for 12t 4x2 Rigid Truck
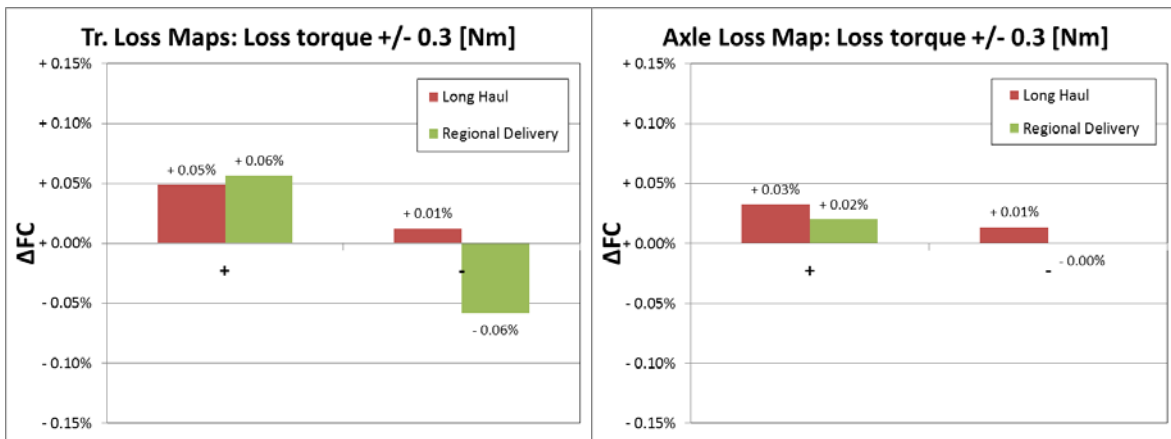
Figure 58: FC change for +/- 0.3 [Nm] transmission/axle loss torque for 40t 4x2 Tractor & Semitrailer
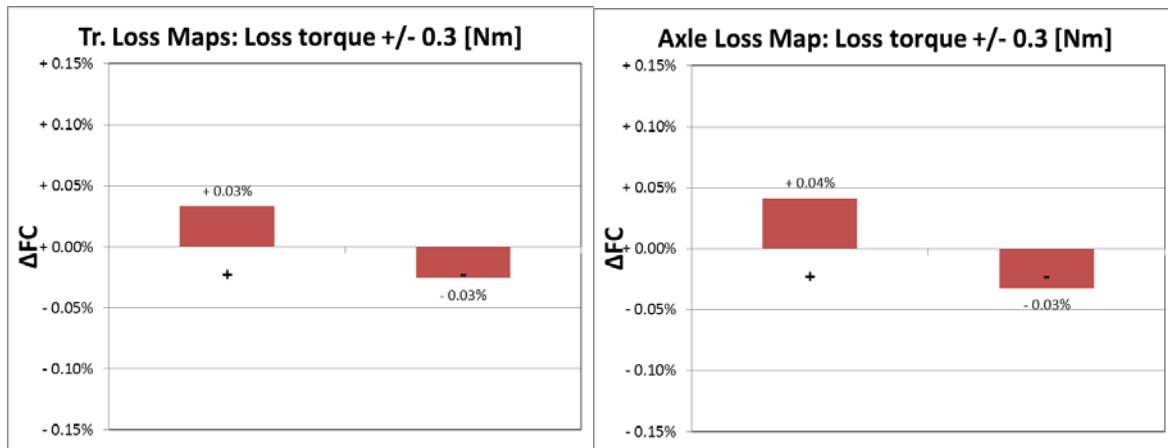
Figure 59: FC change for +/- 0.3 [Nm] transmission/axle loss torque for 24t 6x2 Coach

4.7.4. Conclusions from the sensitivity analysis

The main conclusion from the sensitivity analysis is that the current provisions of accuracy of engine speed, torque and fuel consumption from engine speed tests as specified in the ECE R49.06 regulation are not sufficient to be used as basis for the HDV CO_2 legislation. Recent standards for test equipment already fulfil much stricter limits. These broad tolerances might be misused by OEMs to cheat. This actual situation has already been communicated with ACEA CVD group. ACEA already indicated activities to come up with revised accuracy standards.

For the air drag test procedure the accuracy – which was assumed with +/-3% for the C_dxA value - is assessed to be sufficient for the overall FC result considering the complexity of the method. However, the accuracy as assumed here still has to be verified by ongoing measurements.

Rolling resistance: The influence of OEM-independent vehicle operation conditions is assumed to be much higher (road surface, rain, snow). It seems that the tolerances in the RRC test procedure of [0.3 kg/ton] have to be accepted at the time being. Nevertheless, the accuracy may be not sufficient to provide correct ranking between all tires (further discussion with ETRTA on tire specific data open).

Transmission / Axle: Nearly no influence of tolerances from the test procedures to the overall CO_2 value for the entire vehicle has been identified.

In 2014 ACEA announced a similar analysis of the sensitivity of the HDV CO2 test procedure related to the uncertainties in the component test procedures. First comments from industry indicate larger ranges of uncertainties than found in this study.

4.8. Proof of Concept

During LOT3 activities related to a "proof of concept" to validate the approach based on a combination of component testing and subsequent use of the VECTO tool for simulation of fuel consumption and CO_2 emissions from the entire vehicle have been undertaken. The activities comprised in total investigations on five vehicles:

1) A class 5 long-haul truck (40t GVW),

2) A class 4 rigid truck (18t GVW)

3) A class 2 rigid truck (12t GVW)

4) + 5) A coach and a citybus (analysis not finalised yet)

Investigations included execution of all relevant component tests, measurement of fuel consumption in constant speeds on the test track and on-road in real world driving conditions. Measurements on vehicles 1) and 2) have been performed in late 2012 and in early 2013 by OEMs and in a separate set of tests by DG JRC. These two vehicles have also been measured at the JRC HDV chassis dyno. The main findings of these investigations are summarised below. More details can be found in (Fontaras, 2014).

Comparison of VECTO results with measurements for constant speed tests driven on a test track:

- The wheel power was simulated by VECTO very accurately (deviations smaller than 1%) if the particular test conditions (wind situation, particular rolling resistance of the tires instead of test drum results) have been considered in the VECTO input data. If the particular test conditions were not provided to VECTO, the deviation of the simulated wheel power was in a range of (maximum) +/-5% compared to the values measured on the test track.

- Fuel consumption and CO_2 emissions from the constant speed tests have been simulated with VECTO in a range of +/-1% if the particular test conditions have been considered. In this case additionally the particular operation of the auxiliaries had to be specified in VECTO. An analysis of the deviation between measurement and VECTO result for fuel consumption and CO_2 emissions in constant speed conditions based on generic data only has not been performed at this stage as no generic auxiliary data was available at this time.

Comparison of VECTO results with measurements for real world on-road driving conditions

Vehicles 1) and 2) have been measured in rural and in motorway on-road conditions. The particular test routes (target vehicle speed, altitude profile) have then been imported into the VECTO "engineering mode". Recorded data have been compared with VECTO results for all modelled quantities. From the analysis of simulated vehicle speeds and gear selections requirements for amendments to the VECTO driver model have been identified (all these features have been implemented into VECTO in the meantime). If the VECTO results was corrected for this difference in driving behaviour the simulated fuel consumption for the on-road real world operation was calculated always within a +- 3% range from the real world measurement, and in several cases even closer than that (in the order of +-1.5%). Given the variability of the actual measurements (o=2%) and the fact that according to European legislation a +-3% margin is already considered acceptable for the passenger car CO_2 declaration (chassis dyno measurement), it was concluded that a future certification scheme can be based on the proposed approach.

Comparison of VECTO results with measurements on the chassis dynamometer

At the JRC HDV chassis dyno the WHVC and the FIGE cycle[22] as well as the draft HDC CO_2 regional delivery cycle have been measured. Scope of these tests was to investigate the quality of the simulations under highly controlled operating conditions (no uncertainties introduced due to varying wind, temperature, traffic or road load conditions) and to compare the uncertainty of a VECTO simulation run to that of a chassis dyno test. Measured fuel consumption was evaluated based the signal of a fuel meter installed on the vehicle.

For the complete WHVC and the FIGE cycle deviations between measured and simulated fuel consumption were found in the range of +/-3% (complete cycles) which lies within the uncertainty limits of the measurements. On a subcycle level for the WHVC and the FIGE the deviation between VECTO and measurement was found to be within +/-5%. A much lower correlation between fuel consumed according to measurement and simulation was determined for both vehicles in the draft HDC CO_2 regional delivery cycle (+/-10% deviation). Main uncertainties which influence this correlation were identified to be the exact wheel load conditions at the chassis dyno and the auxiliary operation at the vehicle.

For vehicle 3) first proof of concept results have been presented by the OEM in early 2014. The fuel consumption of this delivery truck was measured in urban real world on-road conditions and compared with the VECTO result for the particular driven route. Preliminary results show a slight underestimation of the measured value by VECTO by 5%.

For vehicles 4) and 5) no comparisons between measurements and simulation are available yet since the AT model in VECTO will be available not before June 2014 but is necessary for the simulation of the city bus and since also the bus auxiliary models would be needed, which are elaborated in a parallel project. Thus this data shall be seen as basis for further work on buses.

The proof of concept activities furthermore focused on a validation of the component test procedures, e.g. evaluation of the repeatability and reproducibility of the air drag test procedure, a comparison of rolling resistance measured on the test track with test drum results and a validation of the method of simulation of fuel consumptions in transient engine tests. These results are mentioned in this report in the sections related to the particular component test procedure.

4.9. Test program in LOT 3

Physical vehicle, engine and component tests within LOT 3 covered on-board tests for CdxA and fuel flow, chassis dyno tests to obtain data for auxiliary energy consumption and engine tests to develop and validate the engine component test and simulation routines. In total 20 days of measurements with on-board equipment on a test track and on dynamometers including the necessary personnel were included in the offer to LOT3 and have been used as described in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

---

[22] These cycles are the baseline vehicle speed profiles for the WHTC and the ETC transient engine test cycle.

Table 35: Tests performed by TUG within LOT 3

Test days	Test procedure	Tasks	Dates
8	On-board measurements	CdxA test procedure and SiCo test in cooperation with Daimler and EvoBus	28. to 30.11. 2013 (1st set of tests November 2ß13 was not useful due to a breakdown in the torquemeter) 31.3. to 4.4.2014 (valid tests)
4	Engine test procedure	Measure fuel flow map and WHTC on a EUO VI HDE	11. to 14.02.2013
2	Anemometer calibration	Test on chassis dyno set up to investigate options to calibrate on-board anemometer position	27. to 28.6.2013 (it proved that anemometer position cannot accurately be calibrated on the test stand)
6	Chassis dyno tests	Measure auxiliary engagement	16.1. to 18.1.2013 (vehicle was on test stand for emission factor tests from other project, auxiliary tests done as add on, data used for generic data base and for generic vehicle models)

It was foreseen in LOT 3 also to support JRC in organisation and evaluation of a pilot phase where the involvement of all stakeholder was foreseen which later are be involved in the CO2 certification. Since the responsibilities of OEMs, supply industry, technical services and type approval authorities have not finally been decided within LOT 3 this pilot phase was not started. Tests by LOT 3 have not been foreseen in the pilot phase, just support in elaborating the test matrix and in evaluating results. Remaining person days were used to further develop the generic AT model in VECTO (only a manufacturer specific option was offered in LOT3, see chapter 6.1.1.15).

5. Technical Annex

The technical annex is delivered as separate file to serve as document for future updates.

6. Software description

This chapter contains the documentation of the software tools as completed during LOT3:

1. The simulation tool for CO_2-emissions "VECTO"
2. The evaluation tool for constant speed tests "VECTO-CSE"

6.1. VECTO

In this chapter the simulation model VECTO (Vehicle Energy consumption Calculation Tool) is described. VECTO is the longitudinal dynamics model created to calculate fuel consumption and CO_2 for heavy duty vehicles.

Figure 60: VECTO application logo

The main characteristics of the model are:

- Backwards-calculating, quasi-stationary longitudinal dynamics model
- Driving model to consider real life driving behaviour, e.g. gear shifting, coasting and braking
- Constant time steps of 1 seconds (1Hz)
- Compatible with distance- and time-based driving cycles
- In- and output via textfiles (CSV and JSON)
- Implemented as Visual Basic .NET application
- Graphical user interface for calculation control and editing of the main input files, Figure 61.
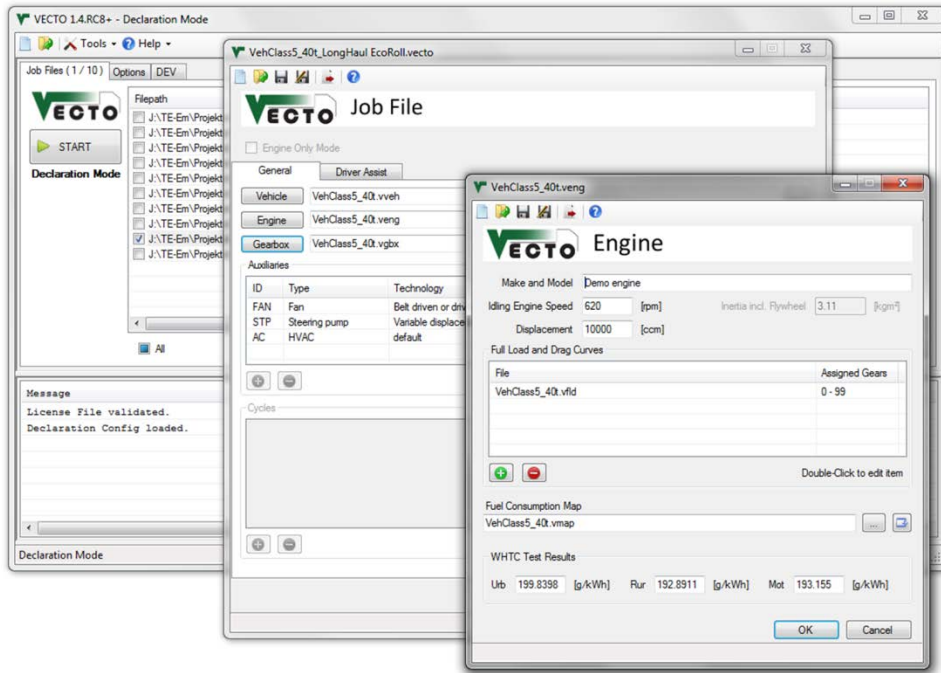
Figure 61: Example of the VECTO GUI

6.1.1. Model structure

The calculation is separated in four main modules as shown in Figure 62.
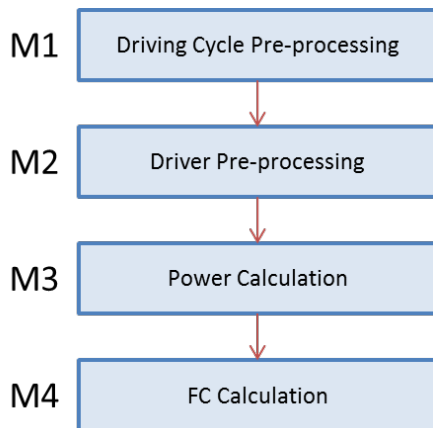
Figure 62: VECTO's main calculation modules

The tasks of the single modules are:

- In **Driving Cycle Pre-processing (M1)** the distance-based driving cycle (mission profile) is being converted to 1Hz. Time-based cycles are converted to 1Hz if necessary.
- **Driver Pre-processing (M2)** applies driver functions to the driving cycle which cannot be considered later in the backwards power calculation (M3) like Overspeed or Look-Ahead Coasting.

- **Power Calculation (M3)** is the core of the model. Here the engine operation points (engine torque and speed) are calculated for each time step considering driving resistances and powertrain losses and auxiliary power demands.
- Finally in **FC Calculation (M4)** the fuel consumption (FC) is being interpolated from the stationary FC map and the WHTC correction is applied.

The modules are described in detail below.

6.1.1.1.   Driving Cycle Pre-processing

The first main module **M1** converts the distance-based mission profile to the time-based 1Hz format needed for further processing. The mission profile as defined in the regulations only defines the target speed levels. Driving behaviour elements, which depend on the HDV configuration e.g. acceleration or deceleration behaviour have to be added by VECTO. In this module the target deceleration is added to the mission profile.

The target deceleration is defined as function over speed. It limits the deceleration during brake phases and is modelled to present average real life behaviour. The same approach is used for acceleration later. Figure 63 shows an example for both functions.
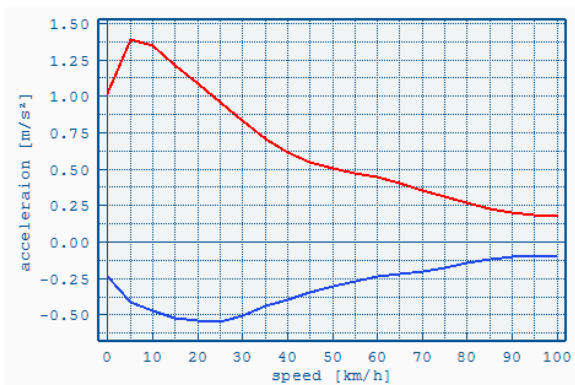
Figure 63: Example for speed-dependent target acceleration (red) and deceleration (blue)

For declaration these curves are predefined for each vehicle category. Apart from that the cycle remains target speed at this point, see Figure 64.

Figure 64: Cycle before (blue) and after pre-processing in M1

There are two different kinds of cycles supported by VECTO which require different pre-processing as shown in Figure 65:

- **Time-based cycles**: Vehicle speed is defined over time. Frequency may be higher or lower than 1Hz and even variable (e.g. CAN data). **M1.2** converts the cycle in 1Hz.
- **Distance-based cycles**: Here the vehicle speed is defined over distance (default for declaration mission profiles). **M1.1** converts these cycles to the 1Hz time-based format.
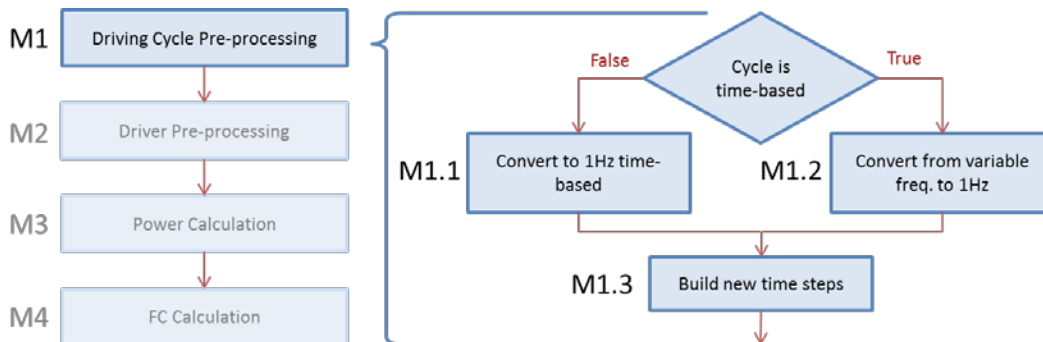
Figure 65: Driving Cycle Pre-processing (M1)

The driving cycle may contain additional parameters, beside the vehicle speed, like slope or gear input. Mission profiles used for declaration contain only these parameters:

- **Target speed** [km/h]
- **Slope** [%]
- **Stop time** [s] (when vehicle is standing)

Naturally, the stop time is only required for distance-based cycles.

In the part **M1.3** new time steps for the subsequent calculations are created. This is required in order to calculate the vehicle acceleration based on the speed. The acceleration is calcu-

lated as difference between the vehicle speed values of two *original* time steps and is allocated to the *new* time step between the old ones, see Figure 66.
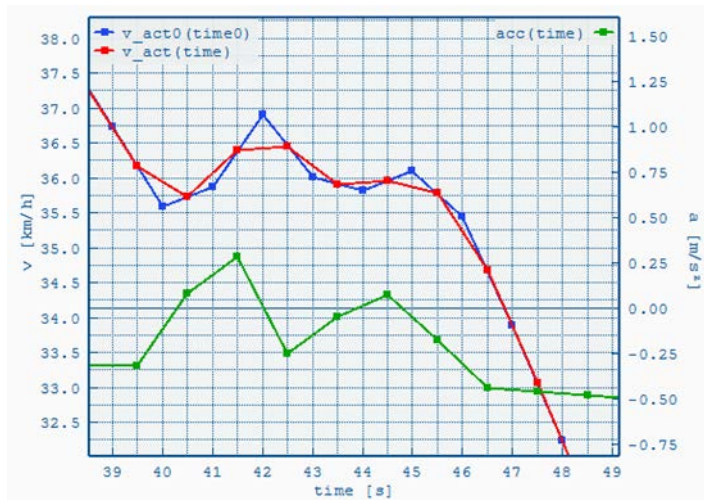
Figure 66: New time steps (red, green) created to calculate vehicle acceleration based on the original speed (blue)

All input parameters of the driving cycle (e.g. speed, slope) are interpolated for these new time steps.

6.1.1.2.   Driver Pre-processing

The second main module **M2** applies the following driver model functions in order to create a realistic and vehicle specific speed profile basted on the synthetic target speed mission profile:

- Overspeed
- Eco-Roll
- Look-Ahead Coasting

The reason why these functions are applied in a pre-processing step rather than being implemented directly in the main calculation loop **M3** is that they require rather complex modelling (e.g. nested forward-, backwards-loops) which made this approach more appropriate.

The module is separated in two sub-modules as shown in Figure 67.
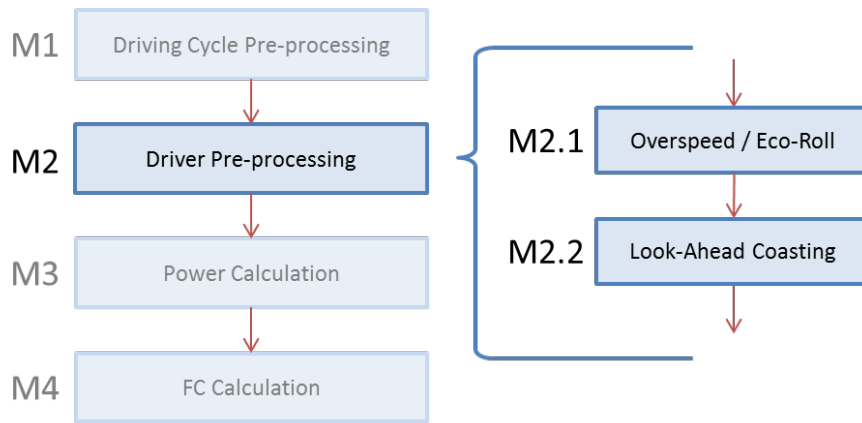
Figure 67: Driver Pre-processing (M2)

6.1.1.3. Overspeed / Eco-Roll

The first sub module **M2.1** applies either the Overspeed *or* the Eco-Roll function, depending on the vehicle configuration. Both functions control the vehicle's behaviour on uneven road sections (slope ≠ 0) and aim for lower fuel consumption by taking advantage of negative slopes and the vehicle's inertia. The core difference between the two functions is that Overspeed is designed to model an average driver's behaviour without the aid of driver assistance systems. Eco-Roll, on the other hand represents a driver assistance feature usually available as optional feature for modern trucks. For this reason vehicles without Eco-Roll always have the Overspeed function enabled for declaration.

6.1.1.4. Overspeed

The Overspeed function activates as soon as the total power demand at the wheels (P_{wheel}) falls below zero, i.e. the vehicle accelerates on a negative slope. The clutch remains closed, engine in motoring operation, and the vehicle accelerates beyond the cycle's target speed. When a certain speed limit (defined as relative difference to the target speed) is reached the mechanical brakes are engaged to prevent further acceleration. Figure 68 shows an example with target (purple) and actual speed (orange) on the top left axis, slope (brown) on the top right axis. The bottom graph shows engine power (blue), motoring curve (orange) and mechanical brake power (green). In this example Overspeed is allowed until the vehicle's speed exceeds target speed by 5 [km/h].
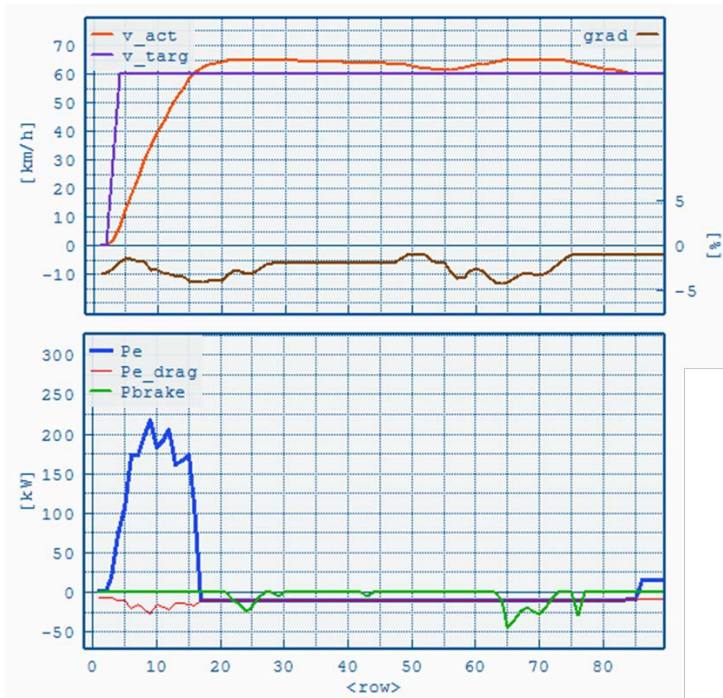
Figure 68: Overspeed example

6.1.1.5.   *Eco-Roll*

While Overspeed uses the engine drag power to cut off fuel consumption during downhill slopes Eco-Roll relies on a different approach. Here the target is using the vehicle's kinetic energy as much as possible by letting the vehicle roll freely whenever the conditions allow. Instead of using the engine brake (with no fuel consumption) Eco-Roll shifts to Neutral, engine idling, to minimize deceleration and maximize the vehicle's roll out distance. During this phase the engine has to overcome its own idling losses and the power demand from the auxiliaries. The engine is engaged again if the speed exceeds a certain threshold above or below target speed.

Figure 69 shows an example of Eco-Roll, same parameters and colours as in Figure 68. The engine is idling while the vehicle rolls freely and braking when the upper speed limit is reached.
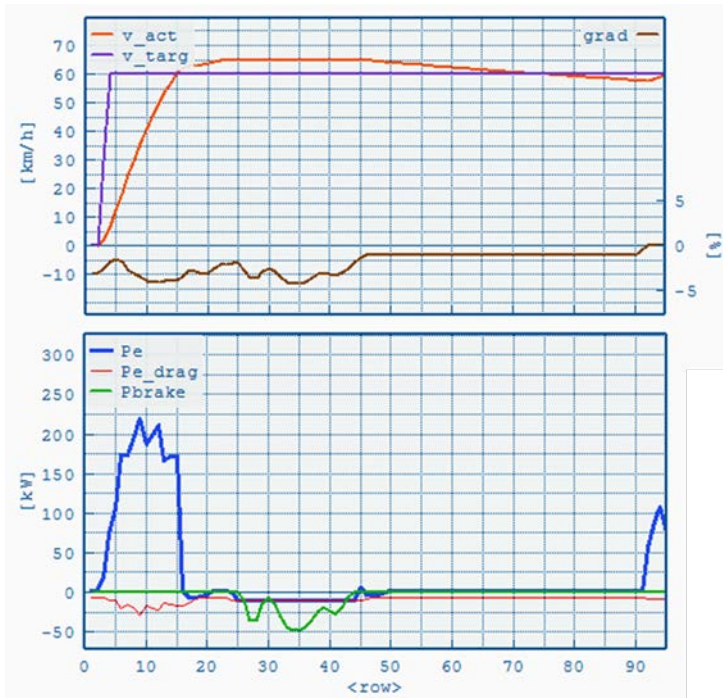
Figure 69: Eco-Roll example

6.1.1.6.   Look-Ahead Coasting

Like Overspeed, Look-Ahead Coasting is a function that aims on modelling real-life driver behaviour. It is a forward-looking function that detects forthcoming reductions in target speed in the mission profile (e.g. change of road type / speed limit, etc.) and induces an early, fuel efficient, deceleration making effective use of engine braking before applying mechanical brakes.

The implemented approach uses a predefined target deceleration ($a_{lookahead}$) to calculate the deceleration time for each particular target speed change as presented in Figure 70.
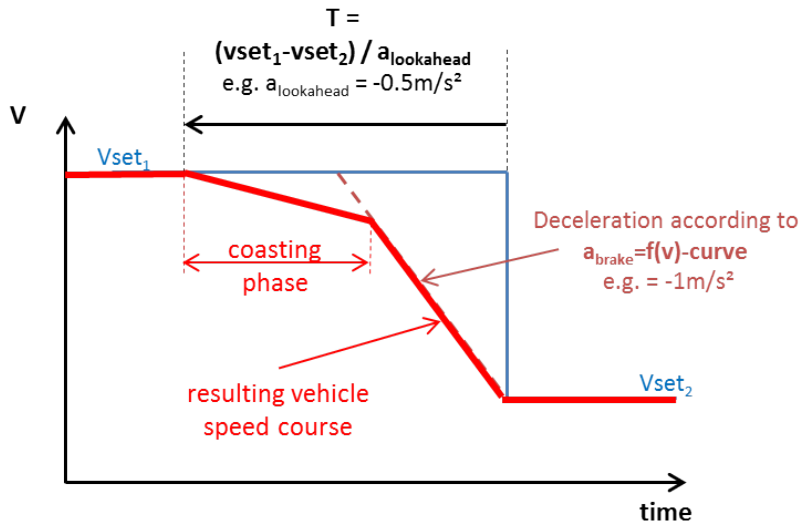
Figure 70: Calculation of deceleration time T [s] for Look-Ahead Coasting

At the resulting deceleration start point the model calculates the coasting trajectory until it meets the brake deceleration trajectory which was set in Driving Cycle Pre-processing (M1) as described in 6.1.1.1. The resulting deceleration consists of a coasting phase followed by combined mechanical braking and engine drag power.

6.1.1.7.   Power Calculation

The model's core module **M3** calculates the engine operation points for the entire cycle. Also, it applies two more driver model functions, the gear shift model and the acceleration limit.

The module consists of one loop running from the first to the last time step of the driving cycle. The following functions are applied for each single time step.
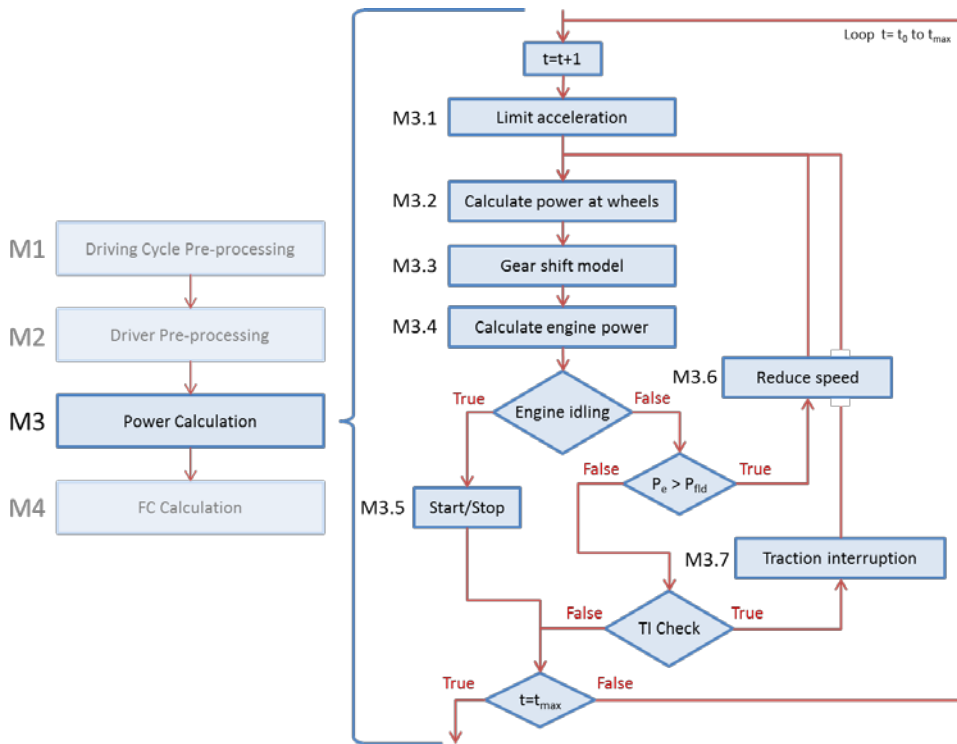
Figure 71: Power Calculation (M3)

6.1.1.8. Limit acceleration

The most important driver model functions were already applied in module **M2**. The first step for each time step is limiting the acceleration (**M3.1** in Figure 71) to the predefined speed-dependent target as shown in Figure 63. This way a plausible and realistic acceleration process should be ensured even for high-powered vehicles with low loading or on downhill roads.

6.1.1.9. Power at wheels calculation

In **M3.2** all driving resistances are calculated to determine the power demand at the wheels. The driving resistances consist of rolling-, air-, slope- and acceleration-resistance. Each component is described below.

6.1.1.10. Rolling resistance

The rolling resistance is calculated using a speed-independent rolling resistance coefficient, Equation 2.

$$F_{roll} = RRC.m.g.\cos(\alpha_S) \ [N]$$

Equation 2

where:

      RRC   = weighted mean of rolling resistance coefficient [-]
      m   = total vehicle mass [kg]
      g   = gravitational acceleration [m/s²]
      α_S = slope [rad]

In order to consider that the RRC is not completely independent from the vehicle weight it is modelled as a function of the total vehicle mass. Also, it has to be considered that not all axles are equipped with the same tyres (usually different tyres for steering-, powered- and trailer- axles). Equation 3 shows how the RRC is calculated in VECTO. The index *i* refers to each single vehicle axle (truck and trailer).

$$RRC = \sum_{i=1}^{n} s_{(i)} \cdot RRC_{ISO(i)} \cdot \left(\frac{s_{(i)} \cdot m \cdot g}{w_{(i)} \cdot F_{zISO(i)}} \right)^{\beta-1}$$
Equation 3

where:

$s_{(i)}$	= relative axle load [-]
$RRC_{ISO(i)}$	= tyre RRC according to ISO 28580 [-]
m	= vehicle mass plus loading [kg]
g	= earth gravity acceleration (constant = 9.81) [m/s²]
$w_{(i)}$	= number of tyres (4 if Twin Tyres, else 2) [-]
$FzISO_{(i)}$	= tyre test load acc. to ISO 28580 (85% of max. load) [N]
β	= constant parameter = 0.9 [-]

The function for load dependency was taken from literature (Michelin, XXX) and validated by data provided by ETRTO from the tire drum tests where the test load was varied.

6.1.1.11.   Air resistance

The air resistance is calculated using the drag coefficient, the frontal area and air density.

$$F_{air} = c_d \cdot A \cdot \rho \cdot \frac{v_{veh}^2}{2} \ [N]$$
Equation 4

where:

c_d	= drag coefficient [-]
A	= frontal area area [m²]
ρ	= air density [kg/m³]
v_{veh}	= vehicle speed [m/s]

Since this approach is only valid for windless conditions a correction factor is applied to the drag coefficient to consider average wind conditions, Equation 5.

$$c_d = c_{d(0)} \cdot f_{c_{d(v_{veh})}} \ [N]$$
Equation 5

where:

$c_{d(0)}$	= drag coefficient in windless conditions (yaw angle β=0) [-]
f_{cd}	= correction factor [-]

The factor is based on the vehicle speed since the relative influence declines with speed. Figure 72 shows the correction factor / speed function as it is applied in the model.
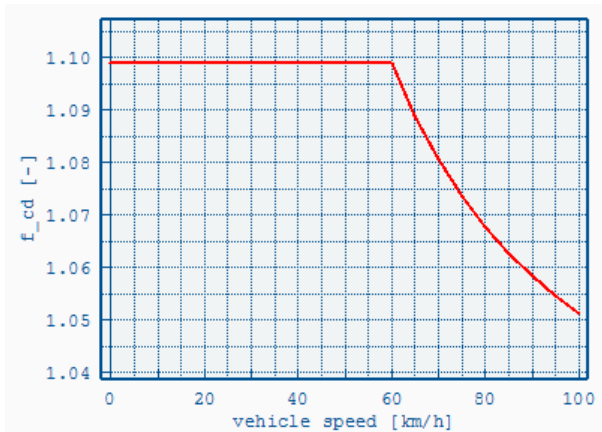
Figure 72: Drag coefficient scaling factor for cross wind correction

The scaling factor is derived from a generic yaw angle-dependent drag coefficient $C_d(\beta)$ which is based on measurements and CFD simulations. Figure 73 shows the relevant geometric correlations between air inflow (yaw) angle β between driving direction and relative air flow speed, which are used for derivation of the cross-wind correction factor f_{cd}.
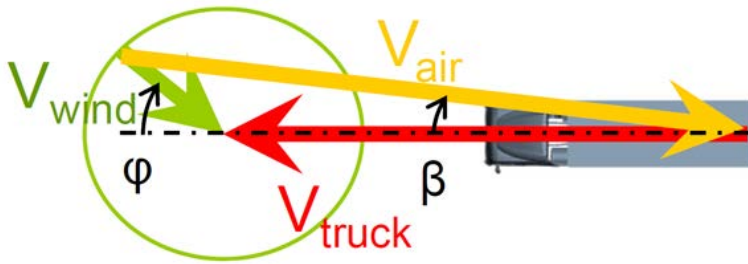
Figure 73: Wind components and angles

Using the yaw angle-dependent $C_d(\beta)$ value the total air resistance is calculated by integrating over the yaw angle:

$$F_{air} = \frac{1}{2} A . \rho . \frac{1}{2\pi} \int_0^{2\pi} c_{d(\beta)} . v^2_{air(v_{veh},\varphi)} \, d\varphi \ [N]$$

Equation 6

where:

A	= frontal area [m²]
ρ	= air density [kg/m³]
$c_{d(\beta)}$	= yaw angle-dependent drag coefficient [-]
$v_{air(vtr,\varphi)}$	= air inflow speed, function of $\mathbf{v_{veh}}$ and $\boldsymbol{\varphi}$ [m/s]
v_{veh}	= vehicle speed [m/s]
φ	= wind direction [rad]

The air inflow speed is calculated by:

$$v_{air(v_{veh},\varphi)} = \sqrt{(v_{wind} . \cos\varphi + v_{veh})^2 + (v_{wind} \sin\varphi)^2} \ [rad]$$

Equation 7

Merging Equation 4, Equation 5 and Equation 6 the cross-wind correction factor f_{cd} can be determined for a given vehicle speed, Equation 8.

$$f_{cd(v_{veh})} = \frac{1}{2\pi.v_{veh}^2} \int_0^{2\pi} \Delta c_{d(\beta)}.v_{air(v_{veh},\varphi)}^2 \, d\varphi \ \ [-]$$

<div align="right">Equation 8</div>

where:

$\Delta c_{d(\beta)}$ = generic function for relative change of c_d value with yaw angle [-]

For vehicle speeds speed below 60 km/h this factor is kept constant at the value of 60km/h (as shown in Figure 72). Reason is that at low vehicle speeds the cross-wind dependency of the air drag is uncertain due to high occurring yaw angles. However, the contribution of air drag on driving resistances at low vehicle speeds is minor anyway.

6.1.1.12. Slope resistance

The slope is considered by Equation 9.

$$F_s = m.g.\sin(\alpha_s) \ \ [N]$$

<div align="right">Equation 9</div>

where:

m = vehicle mass plus loading [kg]
g = earth gravity acceleration (constant = 9.81) [m/s²]
α_S = slope [rad]

6.1.1.13. Acceleration resistance

The acceleration resistance consists of the translational and rotational resistance and is calculated using Equation 10.

$$F_{acc} = \left(m + \frac{\Theta_{red}}{r_{dyn}^2} \right).a \ \ [N]$$

<div align="right">Equation 10</div>

where:

m = vehicle mass plus loading [kg]
Θ_{red} = reduced rotational inertia [kg.m²]
r_{dyn} = effective (dynamic) wheel radius [m]
a = vehicle acceleration [m/s²]

The reduced rotational inertia merges all single rotational inertias of the power train by reducing them to the drive axle with Equation 11.

$$\Theta_{red} = \sum_{j=1}^{n} \Theta_j.i_j^2 \ \ [kg.m^2]$$

<div align="right">Equation 11</div>

where:

Θ_j = inertia of a single component [kg.m²]
i_j = total transmission ratio from the component to the drive axle [-]

The acceleration resistance does not include the engine inertia. It is later added when calculating the engine power.

6.1.1.14. Total power resistance - Power at wheels

The sum of all driving resistances defines the total power required at the wheels for the actual driving condition, Equation 12.

$$P_{wheel} = v.(F_{roll} + F_{air} + F_s + F_{acc}) \ [W]$$

<div align="right">Equation 12</div>

where:

      v   = vehicle speed [m/s]

6.1.1.15.   Gear shift model

The shift model **M3.3** has been designed to represent average shifting behaviour of drivers with manual gearboxes and automated manual gearboxes[23]. It is based on shift curves that define the engine speed for up- and down- shifting as a function of engine torque. Figure 74 shows an example for shift curves.

Figure 74: Example of up- and down- shift curves for VECTO's gear shift model

As soon as the engine operation point passes one of the shift curves a gear change is initiated. When changing gears the model can skip gears as long as the resulting engine speed is inside the shift curves and the torque is below full load. Furthermore, in AMT mode, the shift model initiates an up-shift even if the engine speed is below the up-shift curve but if the same boundary conditions as explained above apply.

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[23] A beta version of a basic model for automatic transmission is included in VECTO and was tested by ZF, VOITH, Allison and EvoBus. It seems that from the input a generic AT model can be developed with support of the involved industry partners. This generic AT model will be finalised in June 2014 as additional work from LOT 3 and shall be released afterwards. The necessary resources at TUG are covered by person days not spent for supporting the pilot tests phase for the entire procedure (see chapter 2.9).

6.1.1.16. Start gear calculation

Another function of the gear shift model is the calculation of the start gear which is used when the vehicle is accelerating from stand-still. Trucks usually don't use the first gear(s) for starting at flat roads, especially with low loading. The model is required to select an adequate gear for all these cases. The shift curves cannot be used for selecting start gears in combination with target speed cycles because the abrupt speed changes would cause the model to always use the first gear.

To select an appropriate start gear independent of the (target) speed profile, while considering loading and slope, a fictional load case was defined. This load case is defined with the actual loading, auxiliary power consumption and slope but a predefined speed and acceleration, representing average real-life conditions at -or rather shortly after- vehicle start. Under these conditions the highest gear is chosen where the resulting engine speed/torque point is inside the shift curves and a certain torque reserve is ensured.

Figure 75 shows an example of how the start gear varies for different slopes but the same target speed cycle.
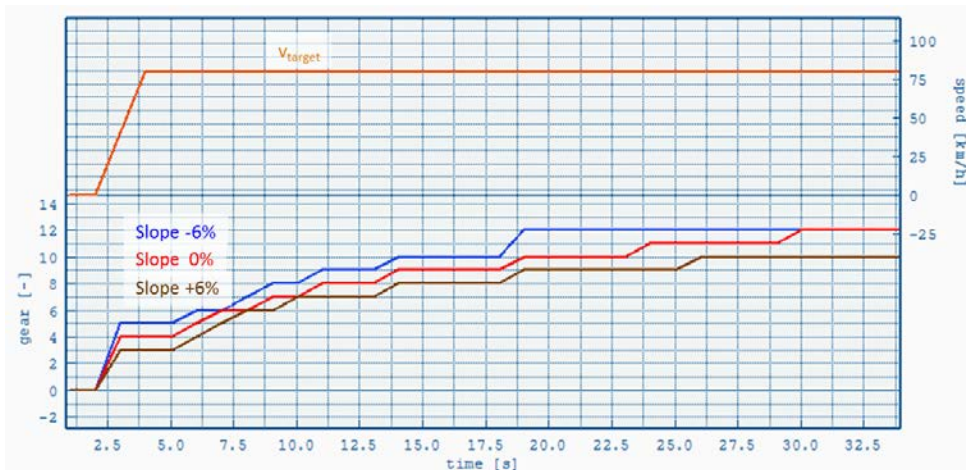
Figure 75: Example of different start gears for the same target speed but different slopes

6.1.1.17. Engine speed calculation

When the clutch is fully closed the engine speed is calculated using the vehicle speed and the total ratio from wheel to engine, Equation 13.

$$n = \frac{60}{2\pi} \cdot \frac{v}{r_{dyn}} \cdot i_{axle} \cdot i_{gear} \; [min^{-1}]$$

Equation 13

where:

n	= engine speed [min^{-1}]
v	= vehicle speed [m/s]
r_{dyn}	= effective (dynamic) wheel radius [m]
i_{axle}	= final drive ratio [-]
i_{gear}	= gear ratio of current gear [-]

The approach is not valid for vehicle start conditions when the clutch is partially opened and a slip is present between engine and gearbox. VECTO uses a clutch model to calculate the engine speed at low vehicle speeds until the speed is high enough for closing the clutch completely.

Figure 76 shows the resulting engine speed (blue) during acceleration form stand-still. n_{clutch} (red) is the engine speed with active clutch model and n (orange) the engine speed according to Equation 13 (orange).
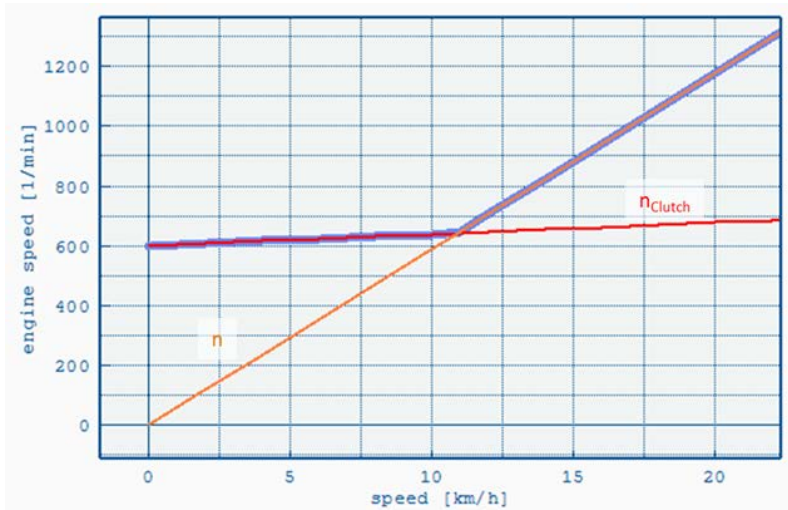
Figure 76: Engine speed during acceleration form still-stand

The clutch model considers the vehicle's engine speed range (idling to rated speed) hence being valid for different vehicle- and engine- sizes.

6.1.1.18.   Engine power calculation

After the driving resistances have been calculated and the gear is selected the engine power is calculated in **M3.4**. Between wheels and engine a number of additional losses are added:

- Powertrain losses (gearbox, differential).
- Hydraulic retarders cause idling losses that have to be considered.
- Power demand by auxiliaries.
- Rotational inertias in the power train

Equation 14 shows all losses considered in the engine power.

$$P_e = P_{wheel} + P_{lossAxle} + P_{lossRet} + P_{lossGB} + P_{auxSum} + P_{aEng} \ [kW]$$ Equation 14

where:
    P_{wheel} = Power at wheels, see Equation 12 [kW]
    $P_{lossAxle}$ = Differential losses [kW]
    P_{lossGB} = Gearbox losses [kW]
    $P_{lossRet}$ = Retarder idle losses [kW]
    P_{auxSum} = Power demand of auxiliaries [kW]
    P_{aEng} = Inertia losses of engine and flywheel [kW]

Gearbox and differential losses are defined by torque/speed maps based on measurements.

Retarder idle losses are modelled by a speed dependent (engine speed or drive axle speed - depending on type) torque loss.

In the determination of component losses the sequence of components is considered (e.g. the axle losses are included in the torque going through the gearbox etc.

6.1.1.19.   Auxiliaries

In VECTO a generic map-based approach was implemented to consider all types of auxiliaries. The main steps are:

1. The supply power demand for each single auxiliary is defined in the driving cycle. Hence a time/distance-dependent power demand can be defined.
2. Based on the supply power and a pre-defined efficiency map the auxiliary input power is calculated.
3. A constant efficiency determines the losses between auxiliary and engine.

Figure 77 and the following equations show how the mechanical power demand for each auxiliary is calculated.
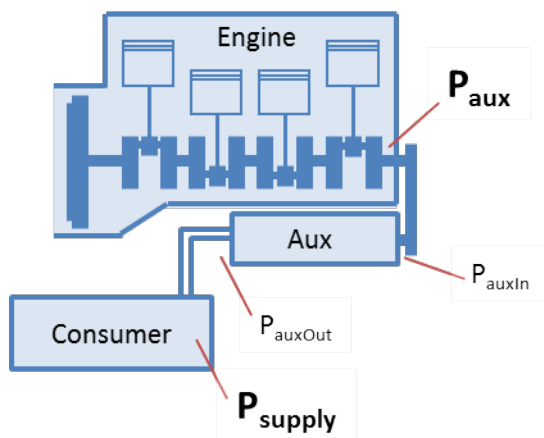
Figure 77: Generic auxiliary model

$$P_{auxOut} = \frac{P_{supply}}{\eta_{eff}} \ [\text{kW}]$$

Equation 15

$$P_{auxIn} = AuxMap(n_{aux}, P_{auxOut}) \ [kW]$$

Equation 16

$$P_{aux} = \frac{P_{auxIn}}{\eta_{mech}} \ [\text{kW}]$$

Equation 17

where:

P_{supply}	= Effective supply power demand [kW]
P_{auxOut}	= Auxiliary output power [kW]
η_{eff}	= Consumer efficiency [-]

n_{aux}	= Auxiliary speed (constant ratio to engine) [min^{-1}]
$AuxMap_{(n,P)}$	= Interpolation from auxiliary efficiency map [kW]
P_{auxIn}	= Auxiliary input power [kW]
η_{mech}	= Efficiency of auxiliary (belt/gear) drive [-]
P_{aux}	= Mechanical auxiliary power demand at the crank shaft [kW]

The mechanical power demand values of each auxiliary are accumulated and added to the total engine power (P_{auxSum}, Equation 14).

This approach is - for the VECTO version as released at the end of LOT3 - only available in the "engineering mode". For declaration pre-defined generic values for P_{aux} are specified for each auxiliary, depending on HDV class, mission profile and technology, as described in section 4.2.6 of this report.

6.1.1.20. Transient engine full load

In order to consider the transient full load torque build up a PT1 approach is used to lower the stationary full load tp transient conditions. Equation 18 shows how the transient full load is calculated.

$$P_{fld} = \frac{P_{fld\_stat} + t_{PT1} \cdot P_{e(t-1)}}{t_{PT1} + 1} \ [kW]$$

Equation 18

where:

P_{fld_stat}	= Stationary full load at the given engine speed [kW]
t_{PT1}	= PT1 time constant at the given engine speed [s]
$P_{e(t-1)}$	= Engine power at the preceding time step [kW]

The time constant is a function of engine speed to consider the lower torque build up time at higher engine speeds, Figure 78.
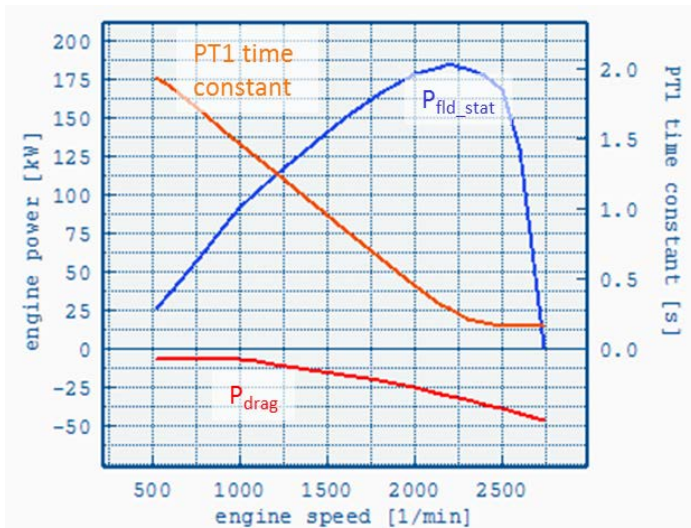
Figure 78: Exemplary stationary full load / motoring curve and PT1 time constant over engine speed

Figure 79 shows a comparison of a measured and a calculated full-load step.
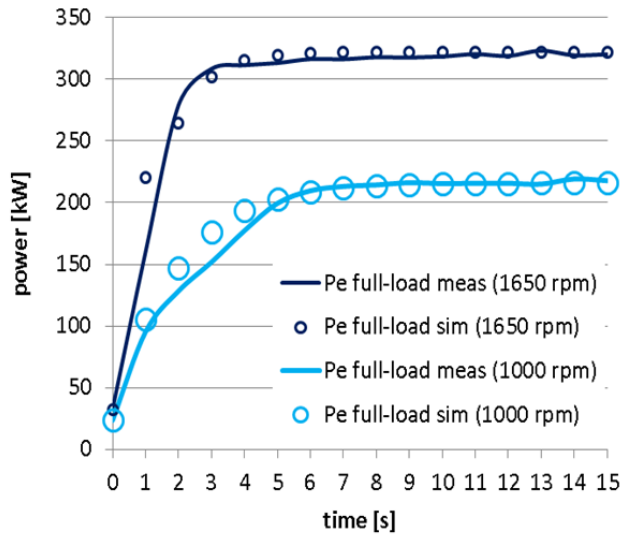
Figure 79: Example of a full-load step at two different engine speeds measured and calculated using the PT1 approach

6.1.1.21. Start/Stop

Start/Stop systems shut down the engine at vehicle stand-still to save fuel. This function is also implemented in VECTO.

During engine-stop the auxiliaries are not powered which would cause an invalid overall energy balance if not considered. At this point VECTO does not consider battery-charge control functions and auxiliaries are modelled with constant power demand. Therefore, when calculating vehicles with Start/Stop, VECTO corrects the overall fuel consumption using a linear regression between engine power and FC. This function is described in 6.1.1.25

Engine-stop is initiated after a predefined activation delay if the following three conditions apply:

1. $P_{wheel} <= 0$
2. Vehicle speed is below a certain threshold
3. Engine was running for a set minimum time

6.1.1.22. Speed Reduction

In some cases the vehicle might not be able to follow the target speed because the power demand is too high. This is especially the case for all rectangular target speed steps as defined by the mission profiles. If the calculated engine power is higher than the transient full load the vehicle speed is reduced and the time step is repeated starting from **M3.2** (Power at wheels calculation). This process repeats until the power demand can be provided by the engine. Figure 80 shows an example of an acceleration phase from zero to 45 [km/h] (left axis). Engine power (blue) and full load (brown) on the right axis.
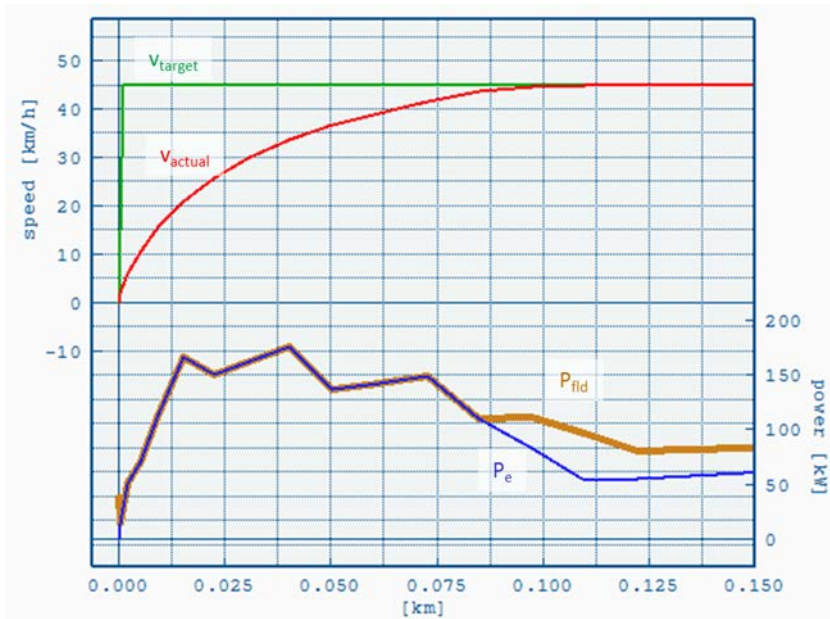
Figure 80: Full load acceleration

6.1.1.23. Distance Correction

In 6.1.1.1 it was described that the original distance-based mission profile is converted into a time-based form for further processing. For various reasons, e.g. Overspeed or Speed Reduction, the actual speed deviates from target speed and hence the actual distance does not match the target distance. To ensure that the vehicle travels the same distance as specified in the cycle a correction function was implemented that compares the actual distance with the theoretically travelled distance according to target speed. If the distance error is smaller if an additional time step is added (or skipped) the correction is applied by either duplicating the current time step (if actual distance is too low) or skipping the next one (if distance is too high).

Since the correction is independent of the Speed Reduction (discussed in the previous section) acceleration phases won't be affected by the correction. However there are cases when the correction adds time steps during coasting phases which unavoidably disturbs the coasting operation (i.e. short traction intervals). This effect is considered insignificant and won't affect comparability between different vehicles.

Figure 81 shows an example of a mission profile calculated with or without Distance Correction.
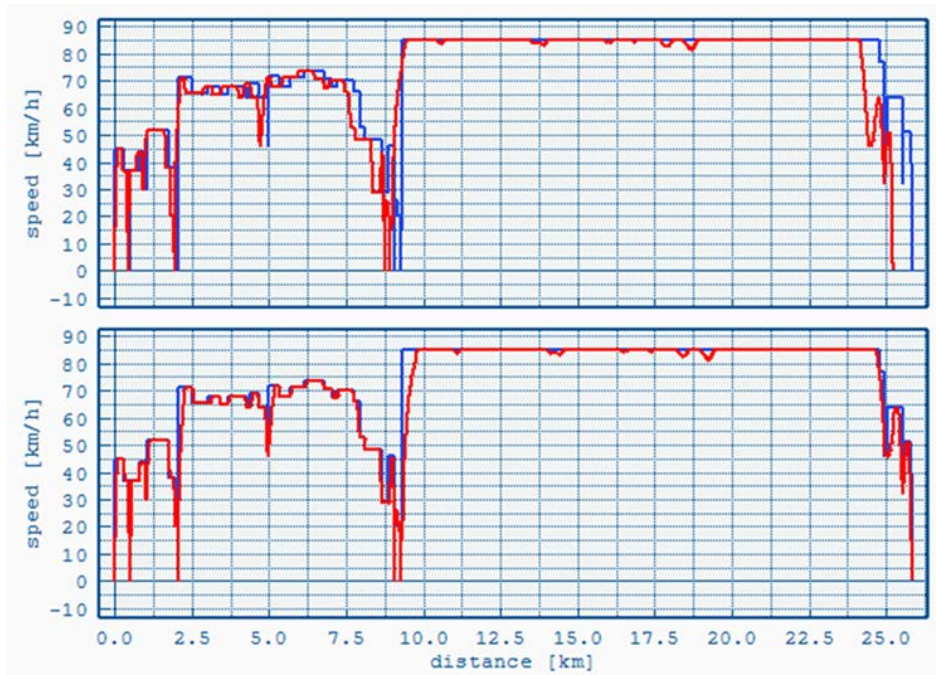
Figure 81: Mission profile with (bottom) and without (top) Distance Correction applied. Blue line: target speed, red line: simulated vehicle speed

A limitation of this function is that it causes short interruptions in coasting and roll-out phases whenever a correction is applied. The resulting error should be insignificant though.

6.1.1.24. Traction Interruption

When changing gears the powertrain of non-powershift transmissions is opened for a short time period in which the vehicle cannot accelerate and rolls out freely. The duration of this traction interruption (TI) depends on the gearbox type. Since VECTO is using a 1Hz resolution, TI durations other than full seconds are difficult to model. Therefore VECTO uses a simplified approach to consider the exact roll out time during traction interruption while still sticking to 1Hz time steps. This is realised by calculating the roll out time for the exact TI duration (even parts of seconds) and passing the resulting end-speed to the nearest rounded 1Hz time step.

Example: If the traction interruption is set to 2.3 s the vehicle speed loss is calculated for the exact time (i.e. 2.3 s) and this end speed is passed to the next closest time-step (i.e. 2 s).

While the described approach is able to represent acceleration times in a realistic order of magnitude the model doesn't provide the accuracy needed for a reliable ranking in fuel efficiency between transmissions with and without traction interruption.

The issue will be further analysed during the work on automatic transmissions after LOT3.

Currently it is advised to use full-second TI durations until the approach was revised. Suggested default values for declaration are listed below. Values in brackets are ACEA suggestions but should not be used until the required accuracy can be ensured.

- MT: 2 (2.2) seconds

- AMT: 1 (1.5) seconds
- DCT: 0 (0.8) seconds

6.1.1.25. Calculation of fuel consumption

After module **M3** the engine load points (engine torque and speed) are defined for the whole mission profile. In the final calculation module **M4** the fuel consumption is calculated in three steps, Figure 82.
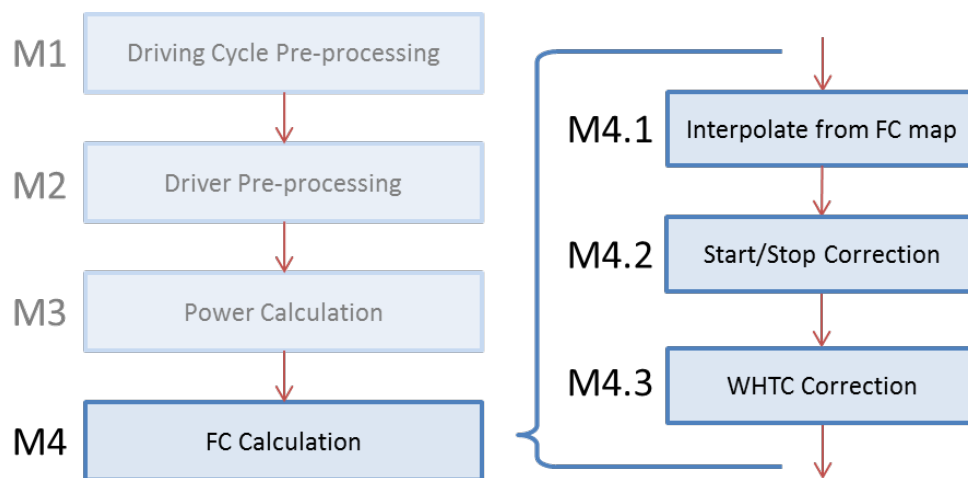
Figure 82: Fuel Calculation

6.1.1.26. Map interpolation

The base FC value is taken from a stationary FC map which defines the fuel consumption [g/h] over engine speed [1/min] and torque [Nm] as shown in Figure 83.
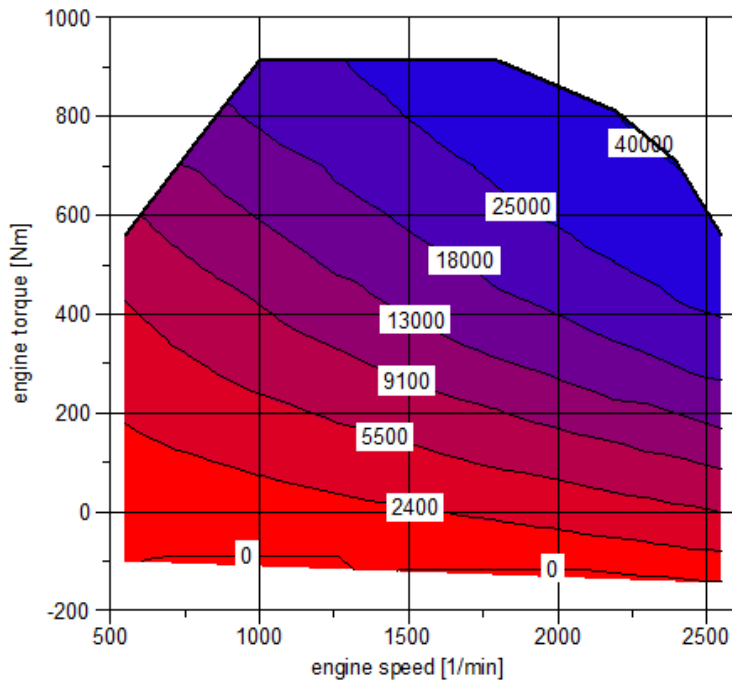
Figure 83: Fuel consumption map

For later interpolation the map is triangulated using the Delaunay method (Delaunay, 1934). The result is a set of triangles forming a surface that covers the whole FC map as shown in Figure 84.
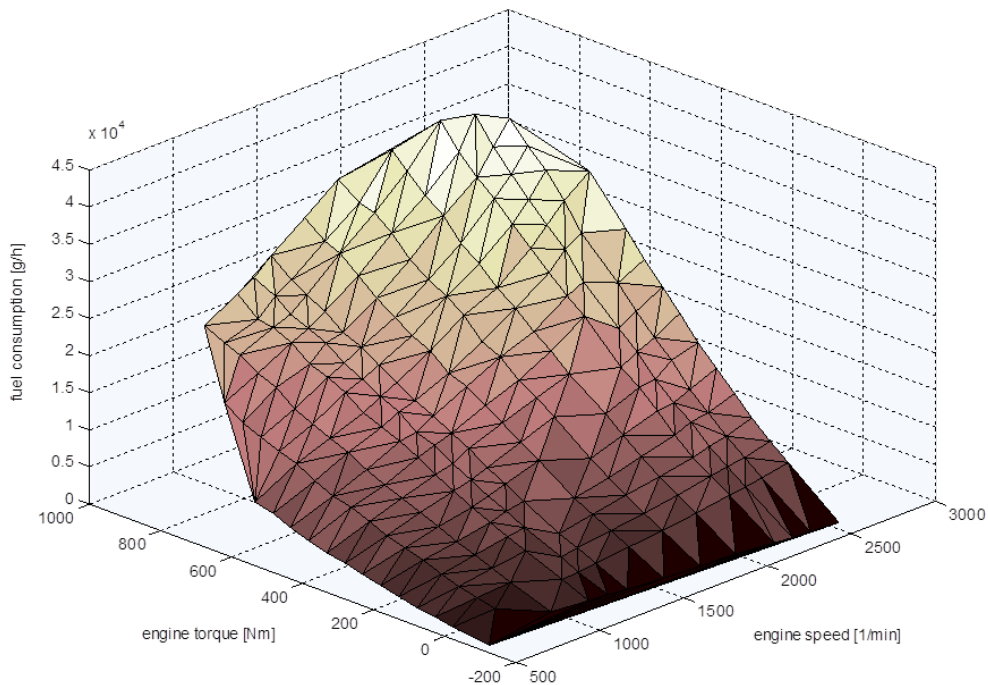
Figure 84: Triangulated FC map

The interpolation method returns the z-coordinate (fuel consumption) of a given load point (x/y = speed/torque) on this surface. Using this method the fuel consumption is determined for each time step of the mission profile.

6.1.1.27.   Start/Stop Correction

In 6.1.1.7 the Start/Stop function was already described. For vehicles with Start/Stop the fuel consumption needs to be corrected to consider the wrong auxiliary energy balance caused by engine stops because VECTO uses a constant power demand for auxiliaries for the whole mission profile. The correction consists of the following steps:

1. From all 1Hz data points of the VECTO simulation, a linear regression curve (y=k*x+d) for fuel consumption (unit: grams per hour) over engine power (unit: kilowatt) is calculated (see Figure 85).
2. From the difference between the energy consumed by the auxiliaries in the simulation with Start/Stop function and the target value (unit kilowatt-hours), a cycle average change in mechanical power "ΔPe" (unit kilowatt) of the internal combustion engine is calculated (using an average alternator efficiency and the cycle time with running engine).
3. The correction of the fuel consumption is performed for all 1Hz time steps using:

    ΔFC (unit: grams per hour) = ΔPe * k

    where: k… gradient in the regression from 1.

If the engine is running in motoring conditions ΔFC is set to zero.
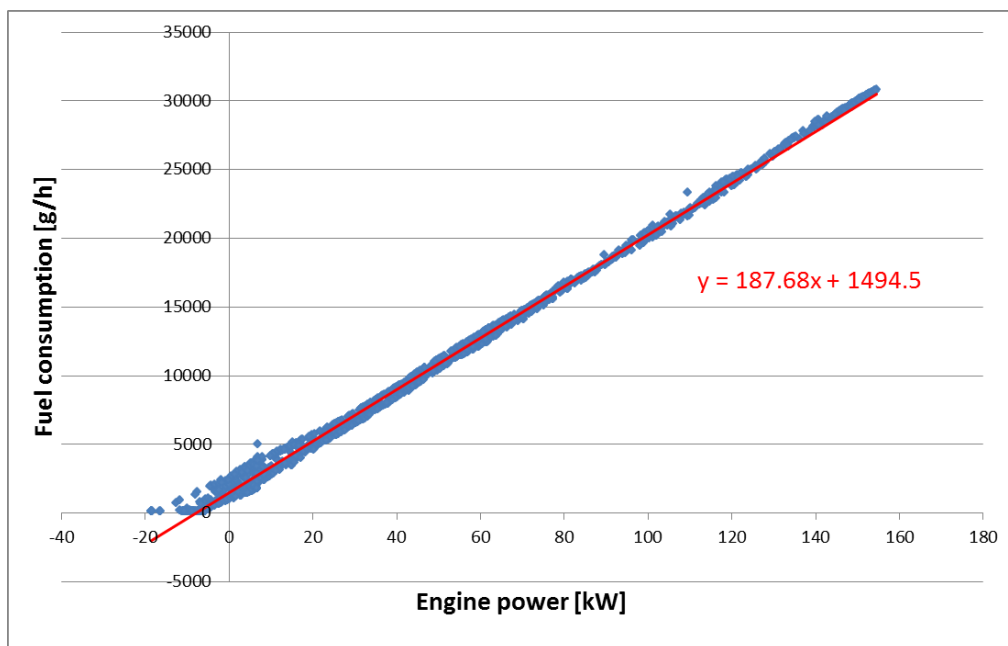
Figure 85: Example of a linear regression between engine power and fuel consumption

6.1.1.28.   WHTC Correction

The WHTC correction aims to counter the disadvantages of using a stationary FC map. Since the map is created using a stationary engine test, possible transient effects that may

be present for a certain engine are not considered. Detailed background on the WHTC correction factor method is given in section 4.2.1.2 of this report.

The following steps are applied IN VECTO for the WHTC correction method:

1. VECTO interpolates the fuel consumption for the WHTC load cycle from the engine fuel map based on the target speed and target torque as determined based the engine full-load curve. The results are FC values for the Urban, Rural and Motorway part.

2. The correction factor CF_{WHTC} is calculated using Equation 19 considering the current mission profile's weighting factors for each part.

3. The factor is multiplied to the FC values for each time step.

$$CF_{WHTC} = \sum_{i=1}^{3} f_i \cdot \frac{FC_{meas\_i}}{FC_{calc\_i}} \quad [-]$$

Equation 19

where:

CF_{WHTC}	= WHTC Correction Factor [-]
i	= index for each part (Urban, Rural, Motorway)
f_i	= Weighting factor per part [-]
FC_{meas_i}	= WHTC measurement result per part (input parameter) [g/kWh]
FC_{calc_i}	= Calculated FC per part [g/kWh]

The WHTC Correction is the final part of the VECTO calculation routine. The CO_2 result for the actual mission profile is directly derived from the fuel consumption using a gravimetric CO_2/FC factor.

6.1.2. User Manual

The VECTO user manual is provided in html format and can be accessed directly from the VECTO user interface.

6.1.3. Developer Guide

A VECTO software developer guide can be obtained together with the VECTO-software from the CITnet server.

6.2. VECTO-CSE for C_dxA evaluation

A first version of a tool for evaluation of constant speed tests has already been developed in 2012 by TUG in a project sponsored by DG JRC. This software was named "VECTO Constant Speed Evaluation tool" Version 1.0 or short "CSE 1.0" and was distributed to all members of the HDV CO_2 advisory group. CSE V1.0 was applied during the Proof of Concept phase of the LOT3 project in 2012 and 2013.

Caused by the further development of the aerodynamic drag test procedure a major update of the evaluation tool was required. This update is released with VECTO-CSE V2.01. This software tool is compatible with the latest version of the technical annex.

The main changes of VECTO-CSE 2.01 compared to VECTO-CSE 1.0 are:

- All kinds of test track layouts with any configuration of measurement sections[24] and driving directions are supported.

- As methods for identification whether the vehicle is inside a measurement section either:

    - a combination of opto-electronic barriers with a GPS device or

    - a high precision DGPS system

can be used.

- The foreseen calibration procedures for signals from the mobile anemometer and for vehicle speed are performed by the tool automatically.

- The algorithms are adapted to automatically evaluate the combination a "high speed test" and two "low speed tests" (one before and one after the high speed test) for each combination of measurement section and driving direction.

- All validity checks as specified in the technical annex which have to be passed to get approved results (e.g. for ambient conditions, stability criteria during constant speed phases) are considered in the test evaluation.

The tool as released in June 2014 is designed as an "engineering version", where still some parameters or settings used in the evaluation can be modified by the user. This software shall be used in the ongoing process of elaborating the final details of the constant speed test procedure in 2014. Once all details of the official test procedure have been defined, a VECTO-CSE "declaration version" shall be generated, where all evaluation parameters are fixed to the exactly as specified in the regulations.

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[24] Measurement sections (abbrev.: MS) define the part of the test track where the recorded signals are analysed in the evaluations.

6.2.1. Overview input data

Table 36 gives an overview on the required input files for VECTO-CSE.

Table 36: Overview input files

File type	Default extension	Explanation
vehicle	*.csveh	contains relevant information on the tested vehicle configuration (e.g. vehicle test mass, anemometer height)
ambient conditions	*.csamb	contains ambient conditions as measured by the stationary weather station
configuration file for measurement sections ("ms config")	*.csms	contains the configuration of the measurement sections (coordinates, driving directions etc.) on the test track. The measurement sections can be configured for the calibration run and the measurement runs separately.
measurement data	*.csdat	contains the measurement data recorded at the vehicle consolidated in 100Hz. Separate input files are required by CSE for: i.) the calibration run (during warm up of the vehicle) ii.) the first low speed run iii.) the high speed run iv.) the second low speed run Similar file formats are used for i.) to iv.)
altitude profile (optional)	*.csalt	contains the altitude profile on the measurement sections. This data is used for the correction of traction force for gradient influence in the evaluation if the related feature is activated in the VECTO-CSE GUI
job	*.csjob	contains all information for a test evaluation (evaluation settings, paths to input data). The job file is automatically created if VECTO-CSE is operated via the user interface but can also be generated or edited e.g. by means of a text editor. After a successful calculation VECTO-CSE also writes the main evaluation results into the job-file.
criteria (optional)		can be used to save or import a set of evaluation

File type	Default extension	Explanation
		parameters (e.g. validity criteria or settings for correction functions). For reasons of traceability for each calculation the used parameters are in any case also stored in the Jobfile.

Details on all input data to be specified in the input files and the according file formats are described in the User manual which is distributed together with the VECTO CSE software.

6.2.2. Evaluation algorithms

This section gives a documentation of the algorithms which are used to evaluate the input data.

6.2.2.1. Processing of data for vehicle position

In a first step VECTO-CSE converts the (D)GPS coordinates to UTM coordinates. The according results for UTM coordinates can be found in the results files (values: "Lat (UTM)" and "Long (UTM)"). For data inside of measurement sections also the theoretical position of the vehicle projected to the line defined by the start- and end-coordinates of the measurement section (result file values "Lat (root)" and "Long (root)") is calculated. This coordinate is the reference for the identification of the vehicle position inside the measurement sections and for the allocation of the altitude if the altitude correction is applied.

6.2.2.2. Assignment of measurement data to measurement sections

For assignment of recorded data to the measurement sections as specified in the *.csms-file two options can be chosen how the point in time is determined when the vehicle enters and exits the predefined measurement sections.

Option 1: Trigger signal

CSE identifies the entry or the exit of the vehicle if the criteria 1. to 3. are met:

1. The trigger signal shows a change in integer value

2. The position of the vehicle is inside a square around a start point or an end-point of a MS as defined in the *.csms-file. The square is defined by the (+/-)-range from the parameters "delta_x_max" and "delta_y_max" (unit: [m]).

3. The heading of the vehicle is in a (+/-)-range as defined by the parameter "delta_head_max" (unit: [°])

Option 2: DGPS signal

CSE identifies the entry or the exit of the vehicle if both criteria 1. and 2. are met:

1. An imaginary line perpendicular to a measurement section going through the start point or the end-point is crossed within the (+/-)-range of the parameter "delta_y_max" (unit: [m]) to the start point or to the end-point

2. The heading of the vehicle is in a (+/-)-range as defined by the parameter "delta_head_max" (unit: [°])

Important remarks:

- If a measurement section is specified in the *.csms-file only in a single driving direction, the data recorded on this section during driving in the <u>opposite</u> direction is <u>not</u> evaluated in VECTO-CSE.

- If the end point of a MS is identical with the start point of the next MS the events for "exit" of the first MS and "entry" into the next MS happen at the same point in time.

- The validity of the allocated data is furthermore checked by comparison of driven distance (determined via the calibrated vehicle speed) inside the measurement section with the distance as specified as in the *.csms-file. If the absolute difference is greater than the parameter "leng_crit" (pre-set to 3m)[25], the particular data is not considered valid.

- DGPS use: According to the technical annex it is only valid to use "option 2" as explained above in connection with use of high accuracy DGPS systems. This factum cannot be verified within VECTO-CSE.

- For all above mentioned parameters default values are pre-set in VECTO-CSE 2.01 as determined based on the experience with the available test data. An adaption of these parameters might be necessary for some cases in order to gain an appropriate assignment of measurement data to measurement sections.

6.2.2.3. <u>Evaluation of the calibration test</u>

According to the technical annex the signals for:

- vehicle speed

- air speed and

- yaw angle (beta)

shall be calibrated based on measurement data recorded at high speed driving during the warm-up phase. This evaluation is done in VECTO-CSE automatically in a pre-processing step.

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[25] Final value of parameter to be decided

Step 1: Calibration of vehicle speed

In VECTO-CSE the vehicle speed "v_veh" is determined based on the CAN (front axle) vehicle speed signal "v_veh_can" multiplied by the calibration factor "fv_veh".

The calibration factor "fv_veh" is determined by the average ratio of a reference vehicle speed ("v_ref") to the CAN (front axle) vehicle speed signal "v_veh_can" for all "datasets" [26] recorded during the calibration run. The reference vehicle speed is determined depending on the method of assignment of measurement sections as described below:

Option 1: Trigger signal

The reference vehicle speed is calculated by division of the length of the measurement section as specified in the *.csms-file by the driving time in the measurement section as determined based on the trigger signal.

Option 2: DGPS signal

For the DGPS option the vehicle reference speed is determined by two methods:

- by directly using the DGPS vehicle speed

- by division of the length of the measurement section as specified in the *.csms-file by the driving time in the measurement section as determined based on the DGPS coordinates.

Position and velocity are determined by (D)GPS devices by different physical principles. Currently it is not known which of the two methods a) and b) result in higher accuracy. Test data as available during VECTO-CSE development showed only very small deviations of the vehicle speed as determined by methods a) and b). A general selection of the method to be used shall be made after further use of VECTO-CSE in 2014. In the current VECTO-CSE version method a) is used for further processing. Calibration factors determined by both methods are shown in the result file.

Step 2: Calibration of air speed and yaw angle

For calibration of air speed and yaw angle CSE determines the calibration factors "f_{vpe}" (position error of measured air speed) and "β_{ame}" (misalignment factor for measured yaw angle) as specified in the technical annex. The evaluation steps are done as specified below:

1. The signals for air speed and yaw angle as recorded by the mobile anemometer are corrected for the instrument error (y=fx+d; where: x = original signal; y=corrected signal; f,d instrument correction factors). f and d have to be determined by an external procedure (anemometer laboratory calibration) and can be specified in VECTO-CSE in the user interface or via the job file.

2. In a first evaluation step it is assumed that all datasets have been recorded in valid wind conditions assigning the label "valid=1".

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[26] A „dataset" refers to the data recorded within a measurement section.

3. VECTO-CSE checks if a minimum of five valid datasets per measurement section and driving direction are available.[27] If uneven numbers of datasets for the two driving directions are available, VECTO discards the last dataset from the driving direction with the higher number of available valid datasets. Such datasets and invalid datasets (according to the wind criteria) are labelled with "used=0". The labels "valid" and "used" assigned to each dataset are also shown in the VECTO-CSE output file.

4. Based on all "used=1" datasets the calibration factors "f_{vpe}" and "β_{ame}" are determined using the formulas as specified in the technical annex in section 5.1.2.8. For the yaw angle the correction factor f_{ape} (position error) is taken from generic data.

5. With these correction factors the undisturbed air flow (air speed, yaw angle and wind at the anemometer position) and the boundary layer correction as specified in the technical annex in section 5.1.2.8 is calculated resulting in the reference values for air speed, wind speed and yaw angle.

6. Based on the values calculated in 5. the validity of the wind criteria for the single datasets as specified in the technical annex in section 5.1.2.2.3 is checked. If the validity of single datasets has been modified, the evaluation process is started again with point 3. If not, the calibration factors "f_{vpe}" and "β_{ame}" determined in point 3. are considered final.

Important remarks related to the evaluation of the calibration test:

- In the evaluation of the calibration test data recorded in both driving directions on a particular measurement section has to be available. This is checked by the software during read in.

- In VECTO-CSE more than one measurement section can be configured to be evaluated in the calibration test. The overall calibration factors are determined by averaging the results determined in a first step for each specified measurement section. If for a particular measurement section not enough valid datasets are available, the data for this section are completely discarded in the evaluations.

- In "step 1: calibration of vehicle speed" datasets are included in the analysis independent of the wind conditions.

6.2.2.4.   Evaluation of the constant speed tests

This section describes the evaluation steps performed for the measurement data recorded in the first low speed – high speed – second low speed test sequence.

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[27] The number of required valid datasets can be modified in the „options" tab, see 4.2.5.4.

Step 1: Calculation of air speed, yaw angle and wind speed

VECTO-CSE calculates the values for air speed, yaw angle and wind speed as laid down in the technical annex. This is done in the 100Hz time basis.

Step 2: Calculation of forces from driving resistances

VECTO-CSE determines the forces which apply to the vehicle from the driving resistances in the 100Hz time resolution according to the steps i. to iv.:

i. <u>Calculation of total traction force:</u>

The total traction force is calculated as specified below:

$$F_{trac} = \frac{(T_L + T_R) \cdot \dfrac{n_{eng} \cdot \pi}{30 \cdot i_{gear} \cdot i_{axle}}}{v_{veh}}$$

where:

F_{trac}	=	total traction force [N]
T_L, T_R	=	corrected torque for left and right wheel [Nm]
n_{eng}	=	engine speed [rpm]
i_{gear}	=	transmission ratio of engaged gear [-]
i_{axle}	=	axle transmission ratio [-]
v_{veh}	=	vehicle speed [m/s]

ii. <u>Correction for forces from road gradient and accelerations</u>

From the total traction force the forces from road gradient and accelerations are subtracted gaining the driving resistance force caused by air drag and rolling resistance. This is correction is only done if enabled in the VECTO-CSE evaluation settings:

$$F_{res} = F_{trac} - F_{grd} \cdot s_{grd} - F_{acc} \cdot s_{acc}$$

where:

F_{trac}	=	driving resistances force (air drag and rolling resistance) [N]
F_{res}	=	total traction force [N]
F_{grd}	=	gradient force [N]
s_{grd}	=	parameter for gradient correction (1=enabled, 0 =disabled) [-]
F_{acc}	=	acceleration force [N]
s_{acc}	=	parameter for acceleration correction (1=enabled, 0 =disabled) [-]

The gradient force is calculated from:

$$F_{grd} = m_{veh} \cdot g \cdot \sin\left(\frac{\Delta alt}{\Delta dist}\right)$$

where:

m_{veh}	=	vehicle mass as specified in *.csveh-file [kg]
g	=	earth gravitational acceleration (9.81) [m/s²]
Δalt	=	altitude difference from next to previous timestep
Δdist	=	difference of driven distance from next to previous timestep

The acceleration force is calculated from:

$$F_{acc} = m_{veh} \cdot a_{avg} + \cdot \frac{I_{wh} \cdot \dot{\omega} \cdot \omega}{v_{veh}}$$

where:

m_{veh}	=	vehicle mass as specified in *.csveh-file [kg]
a_{avg}	=	vehicle acceleration calculated from the moving averaged vehicle speed signal [m/s²]
I_{wh}	=	wheels rotational inertia [kgm²]
$\dot{\omega}$	=	wheels angular acceleration [rad/s²]
ω	=	wheels angular speed [rad/s]
v_{veh}	=	vehicle speed [m/s]

The averaging period for the signals of vehicle speed and engine speed as used for calculation of vehicle acceleration and wheel speed acceleration is defined by the parameter *acc_corr_avg* (unit: [s]).

In VECTO-CSE V2.01 in the default evaluation settings both corrections are disabled. The reasons are:

Gradient correction:

The influence of road gradient does not affect the C$_d$xA test result due to the general VEC-TO-CSE evaluation principle. So no precise altitude profile is required for baseline air drag evaluations. However, the determined values for rolling resistance on single combinations of measurement sections and driving directions are biased by road gradient forces. If a precise altitude profile is available, this influence can be eliminated.

Acceleration correction:

During the constant speed phases the vehicle speed cannot be kept totally constant due to small oscillations resulting from vehicle control. To limit these oscillations strict boundary

conditions for the stability of vehicle speed have been defined based on industry experience (+/- 0.15km/h for the low speed test, +/-0.3 km/h for the high speed test). However, due to the high vehicle masses even within these tight limits a variation of the vehicle speed can significantly influence the measured traction force.[28]

A correction of the measured traction force for acceleration effects has to take the quality of the vehicle speed signal into consideration. E.g. background noise or even small inaccuracies in the vehicle speed signal can significantly falsify the calculated accelerations and driving resistance forces. Based on the very few measurement data available to TUG in LOT3 (comprising no CAN vehicle speed signal) no setting for averaging of vehicle speed signal were identified which lead to improvement of calculated forces by the acceleration correction. This issue shall be further investigated in 2014.

iii. Normalisation of driving resistance forces to reference air density

$$F_{res,ref} = F_{res} \cdot \frac{\rho_{air,ref}}{\rho_{air}}$$

where:

$F_{res,ref}$	=	driving resistance force at reference air density [N]
F_{res}	=	driving resistance force at measurement conditions [N]
$\rho_{air,ref}$	=	air density at reference conditions 1.188 [kg/m³]
ρ_{air}	=	air density at measurement conditions [kg/m³]

ρ_{air} is calculated from the air temperature measured on the vehicle and the air pressure and relative humidity as measured at the stationary weather station based on the following equations:

$$p_{v,H2O} = 611 \cdot \frac{RH_{stat}}{100} \cdot 10^{\frac{7.5 \cdot t_{amb,stat}}{(237 + t_{amb,stat})}}$$

$$\rho_{air} = \frac{p_{amb,stat} - p_{v,H2O}}{287.1 \cdot (t_{amb,veh} + 273.15)} + \frac{p_{v,H2O}}{461.9 \cdot (t_{amb,veh} + 273.15)}$$

where:

$p_{v,H2O}$	=	H_2O vapour pressure [Pa]
RH_{stat}	=	relative humidity measured by stationary weather station [%]

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[28] E.g. a worst case calculation (assuming the maximum allowable drop of vehicle speed between the beginning and the end of a measurement section) for a standard loaded class 5 tractor semitrailer combination results in an average acceleration force of 550 [N], which is about 25% of the related air drag force. If the truck is tested in empty loading conditions, the acceleration force is reduced in this worst case example to about 250 [N].

$t_{amb,stat}$ =   ambient temperature measured by stationary weather station [°C]

$t_{amb,stat}$ =   ambient temperature measured on the vehicle [°C]

$p_{amb,stat}$ =   ambient pressure measured by stationary weather station [Pa]

iv. Correction of driving resistance force for the low speed tests

The driving resistance forces for the low speed tests are furthermore corrected by the factor $f_{roll,corr}$ as read in from the main VECTO-CSE GUI.

$$F_{res,ref} = F_{res,ref} \cdot f_{roll,corr}$$

This feature aims for correction of a systematic change of rolling resistance in the low speed tests compared to the high speed tests as driven in the test sequence.

Example: If the rolling resistance in the low speed tests is known to be at 85% from the rolling resistance in the high speed tests a correction factor of 1/0.85 = 1.176 has to be specified in VECTO-CSE.

Default setting for $f_{roll,corr}$ is 1 (i.e. no correction).

Step 2: Check of validity criteria for datasets to be included in the analysis

VECTO-CSE identifies the data recorded inside the measurement sections ("datasets") with the methods as described before. Datasets will be automatically excluded by VECTO-CSE from further evaluations in case of:

- invalid wind speed conditions (calibration test, low speed test, high speed test)
- invalid yaw angle conditions (calibration test, high speed test)
- stability criteria for vehicle speed not met (low speed test, high speed test)
- stability criteria for vehicle torque not met (low speed test, high speed test)
- unequal number of datasets per vehicle heading direction (high speed test)
- unequal number of datasets for a particular combination of measurement section and driving direction for the first and the second low speed test

For the pilot phase VECTO-CSE executes the evaluations but gives warnings in case of:

- valid range of ambient conditions exceeded
- maximum deviation of average tire pressure in low speed and high speed exceeded
- maximum deviation of RRC between first and second low speed test exceeded

VECTO-CSE aborts evaluations in case of

- test track requirements not met (max. 20° direction deviations (from +/-180°) between measurement sections)
- not sufficient number of datasets available (calibration test, low speed test, high speed test)

All validity criteria can be edited in the VECTO-CSE GUI in the "Criteria"-tab. The default settings for parameters as laid down in the technical annex can be restored via the "Reset Criteria"-button. The compliance of the single datasets with the single validity criteria is documented in the VECTO-CSE "ms"-outputfile". This file can be used to identify which criteria were not met by the data. Datasets which fulfil all validity criteria are labelled in VECTO CSE with "valid = 1" (invalid datasets: "valid = 0"). In cases where unequal numbers of valid datasets e.g. for the two driving directions are available, VECTO-CSE excludes also the last dataset surplus dataset of the other driving direction from further evaluations by setting the parameters "used" to 0. In the further evaluation steps only the "used=1" datasets are considered. More details are described in the VECTO-CSE User Manual.

Step 4: Calculation of $C_d x A_{fr}$ values for all combination of measurement sections and driving directions

For all applicable combinations of measurement sections and driving directions the following analysis is performed:

- Setup of a linear regression for all used=1 datasets from the high speed tests and the two low speed tests for $F_{res,ref}$ as a function of squared air speed (v_{air}^2) achieving an regression coefficient F_2 (unit: [Ns²/m²]) and a constant term F_0 (unit [N]). In the regression weighting factors are applied so that the cumulative weighting of all high speed datasets is 50%.

- The average absolute yaw angle β_{avrg} is calculated from all high speed datasets

- The value for $C_d(\beta_{avrg}) \cdot A_{fr}$ [m²] is calculated from

$$C_d(\beta_{avrg}) \cdot A_{fr} = 2 \cdot \frac{F_2}{\rho_{air,ref}}$$

- The rolling resistance coefficient (RRC, unit [kg/t]) is calculated from

$$RRC = \frac{1000 \cdot F_0}{m_{veh} \cdot g}$$

Step 5: Determination of overall test result

The result for overall "$C_d(\beta_{avrg}) \cdot A_{fr}$" and overall "$\beta_{avrg}$" is calculated from the results for all applicable combinations of measurement sections and driving directions by arithmetical averaging.

The final result for $C_d \cdot A_{fr}$ [m²] for zero cross-wind conditions is then achieved performing the yaw angle correction as specified below:

$$C_d \cdot A_{fr} = C_d(\beta_{avrg}) \cdot A_{fr} - \Delta C_d \cdot A_{fr}(\beta_{avrg})$$

where:

$C_d(\beta_{avrg}) \cdot A_{fr}$ = average result for product of air drag coefficient and frontal area from constant speed tests comprising an average absolute yaw angle of β_{avrg}

$\Delta C_d \cdot A_{fr}(\beta_{avrg})$ =   yaw angle correction applying the generic curve for $\Delta C_d \cdot A_{fr}$ as a function yaw angle for the value of β_{avrg}. In this correction the applicable generic curve for the particular vehicle class and vehicle configuration (rigid or with trailer) is used.

During the pilot phase also an alternative method for yaw angle correction will be calculated by VECTO-CSE (yaw angle correction performed for each combination of measurement section and driving direction before averaging of final result).The according results can be identified in the result files labelled with "Option 2".

6.2.3.   User Manual and Developers Guide

The User Manual of VECTO-CSE including a detailed description of input files, result files and instructions how to operate the GUI is distributed together with the software package via the CITnet. This document includes also a chapter with information targeted to developers who are working with the VECTO-CSE source code.

7. Overview on work performed

Table 37 gives an overview on the tasks planned at beginning of LOT 3 and of the work done. Also overview on open work from the tasks of LOT3 is given here. A complete list of open tasks identified during LOT3 is given in Table 39.

Table 37: Overview on the main tasks of LOT 3 (different task numbers compared to the tender)

Task 1:	Develop software tools to evaluate component tests and to simulate the CO_2 emissions for the entire HDV. The software tools have to be adapted to further developments in LOT 3 and especially to the progress made in the proof of concept phase (see task 2) and to the experience in the pilot phase (see task 3)
Status	VECTO tool with "declaration mode" and "engineering mode" delivered. VECTO-CSE tool in engineering version delivered
Main open work	The tools shall be applied by industry, feedback shall be collected and eventual bugs shall be fixed. Main open tasks, which were not foreseen in LOT 3, concern auxiliaries of buses and automatic transmission (AT) systems. The AT model has been developed already towards a high level of detail with support from Daimler, EvoBus, ZF, VOITH and Allison within LOT 3. TUG has agreed to finalise a first AT model release within VECTO for further testing by industry before summer 2014.
Task 2:	Start a "proof of concept phase" with a limited number of vehicles to be tested, where the already in LOT 2 defined component test procedures are applied. In addition test procedures will be developed for those components, for which no final method was suggested by LOT 2
Status	Tests with two vehicles have been performed by Daimler and by DAF supported by JRC and TUG where the agreed test procedures have been applied. Tests on-going include a city bus (Evobus) and a 12 t delivery truck (Iveco). A sensitivity analysis for the input data for three generic HDV categories was performed. Open issues detected during the test phases have been solved to a large extent.
Main open work	* For a final definition of the C_d*A test procedure on the test track the option to calibrate the on-board anemometer and the influence of tire RRC (possible drop when speed goes down from 88 to 15 km/h) may need to be amended after gaining further experience in application of the suggested test procedure. Options to minimise the influence of variations in tire RRC on the C_dxA value shall be tested in a separate measurement campaign. * Generic data and default values as well as simulation methods for auxiliaries have been elaborated but may need some amendments after a future test phase: • Gear shift characteristic curves for all gear box types • Alternator • Air compressor

	* Methodologies which still need to be developed and/or tested: o A "quality management procedure" to validate if the resulting CO_2 value for a HDV is correct as possible instrument in the certification for (draft "ex post" procedure exists but need to be tested and further developed) o The simulation approach for important auxiliaries from buses (HVAC, air compressor, alternator) is not included in VECTO yet. AEA Ricardo is leading a consortium which shall elaborate corresponding methods based on work already done by ACEA. o For the C_dxA tests TUG and ACEA also run CFD simulations which basically show good results. It needs to be decided if and to which extend CFD simulation can be integrated in the HDV CO_2 certification. Actual application would be the calculation of the "generic side wind correction", which gives the increase of C_dxA as function of the yaw angle for all the vehicle classes (examples are given in the report but yet no decision is made how to complete the generic yaw angle function for all HDV classes). Future application could be to use CFD simulation to assess the changes in C_dxA by small amendments against a measured "parent truck" (an assumed measurement uncertainty of +/- 2% would not suggest to measure aerodynamic effects smaller than 3%, there simulation could help).
Task 3:	Support JRC to organise and steer a "Pilot Phase" in which the final draft text on the HDV-CO_2 test procedure together with the software tools will be applied to perform the complete CO_2 test procedure on several HDV. The pilot phase shall mainly serve to make stakeholders, type approval authorities and manufacturers familiar with the procedure and to test the applicability of the organisational course of actions during such a CO_2 test of a vehicle. Certainly remaining small bugs will be eliminated during this project phase.
Status	Discussions on design of the pilot phase, expectations and participants ongoing. Within LOT 3 no tests which included also type approval authorities have been performed. Instead TUG performed vehicle tests in cooperation with Daimler and EvoBus as described in this report.
Main open work	To involve the type approval authorities and technical services in the pilot phase correctly, the responsibilities of each organisation in the later certification process have to be described in detail. The options are still under investigation in a separate process.
Task 4:	Writing the final draft text for the CO_2 test procedure / methodology and finalising the HDV-CO_2 simulation tools
Status	Draft text available
Main open work	Collect feedback after LOT 3, discuss and implement suggestions for improvement.

In the following the single tasks are described in more detail

The actions listed in the proposal and their status are listed in Table 38 per task.

Table 38: Overview on the actions

Task	Topic	Status	Comments
1.1	**Design of a user-friendly standalone pilot HDV CO2 Simulation tool**		
1.1.1	Evaluation tool for constant speed tests (VECTO CSE; Constant Speed Evaluator)	Version 2.0 delivered s	Shall be validated by external partners after LOT 3
1.1.2	Evaluation tool for coast down tests	Version 1 finalised. No need for update.	-
1.1.3	Tool calculating the "WHTC correction factor"	Simulation routine included in the actual VECTO release	Accuracy for engine tests needs further discussion. EU VI regulation may be insufficient for CO2
1.1.4	Prototype of the "HDV CO_2 simulation tool"	VECTO version with declaration mode finalised.	Shall be validated by external partners after LOT 3
	Interface for OEM specific simulation results	Gear position or engine speed, power demand from each auxiliary and vehicle velocity can be defined optional by the user in the VECTO engineering mode.	Finalised
	Routine for standardised validation of input data	A set of 3 generic HDV has been established which can be used to test further amendments in the software	Details on validation method open (part of Ricardo-AEA project?)
	Documentation of the software	Documentation is included in VECTO (Help function) and in the final report.	Documentation of source code shall be updated in May 2014 within LOT3 budget
2	**Development of additional default input data for the simulation tool**		
2.1	Evaluation of approaches to elaborate default input data for the simulation tool	Models for auxiliaries based on literature reviews and on ACEA white book established. Gear shift and driver model implemented in VECTO.	Further work after feedback on LOT3 reports may be necessary

Task	Topic	Status	Comments
		Yaw angle correction does not distinguish between HDV-classes.	
		Default data for losses in drivetrain implemented according to ACEA white book	
2.2	Establishment of full default input data sets for the simulation tool	Models from 2.1 were applied. Three generic vehicle models elaborated as collection of generic data. Main input on default values came from ACEA with support from LOT 3.	To be tested and validated by external users after LOT 3
2.3	Sensitivity analysis of input parameters and impact on simulation quality	Finalised	
2.4	Developing test procedures for the input data not covered by existing test standards or default values	Component tests for vehicle specific input data defined.	Auxiliaries are yet based on generic values. For some of them also component test procedures may be important
2.5	Definition of test cycles for mission profiles	Draft cycle available for each mission profile.	ACEA announced to add more test data for long haulage cycle
2.6	Definition of standard bodies and standard trailers	Bodies and trailers defined in cooperation with CLCCR[29] and VDA.	
3	**Consultation with stakeholders:** see list of meetings at the end of this table		
4	**Development of verification procedure**		
	Develop a viable method to validate the result of the CO2 certification on entire HDV	Draft developed and tested on one HDV	Application in more physical tests necessary before further development is possible
5	**Take part and giving assistance during the validation exercise**		

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[29] C L C C R. Comité de Liaison de la Construction de. Carrosseries et de Remorques; trailer and body building Industry.

Task	Topic	Status	Comments
	Data analysis	Parts of data from proof of concept phase analysed to support JRC. Data from ex-post test cycle and further tests from one bus analysed	
	Vehicle tests	2 test campaigns with Daimler and Evobus. The first was aborted due to failures in the torque meter rim equipment	
	Auxiliary tests	On 2 HDV the power consumption of auxiliaries was measured on the chassis dyno to validate the generic functions developed by ACEA	
	Engine tests	On one EURO VI engine the fuel map and the WHTC was measured to elaborate the WHTC correction algorithm.	
	Follow at least one test run per component during the proof of concept phase	Not executed due to limited admission	
	Giving support to JRC in workshops	Workshop on proof of concept phase supported. Advisory board meetings supported.	
6	**Draft CO2 emissions certification procedure based on the measurements using the simulation tool:** draft finalised		
	Provide draft technical annex	Draft for technical annex based on discussions, LOT3 results and ACEA white book exists	Needs regular updates in future projects

Overview on consultations with stakeholders

Task 3 follows the request from the Commission in the tender. Stakeholder consultations cover especially:

- ACEA and other OEMs (all tasks)
- Component suppliers with focus on gear boxes and auxiliaries (component test procedures and methods for simulation)
- Body builders and trailer manufacturers (discussion of responsibilities, standard bodies, default values,…)

- Type approval authorities and technical services (discussion of responsibilities, application flows, legal boundary conditions,…)

Beside face to face meetings several video and phone conferences have been made since project start. The meetings and video/phone conferences yet held are listed below:

2014.03.31	Audioweb with ACEA and tire manufacturers
2014.03.27	Meeting with DG Move to discuss test methods available for CdxA
2014.03.14	Audioweb participation at the bus auxiliary project meeting
2014.03.07	Audioweb with ACEA on VECTO-CSE
2014.03.06	Certification meeting TÜV, DG CLIMA, DG ENTR
2014.02.25	Meeting in Graz on automatic transmission model
2014.02.11	Audioweb with ACEA on options to include hybrid HDV
2014.01.29	Advisory Board meeting in Brussels
2014.01.24	Certification Telco TÜV, DG CLIMA, DG ENTR in Brussels
2014.01.21	Certification Meeting TÜV, DG CLIMA, DG ENTR in Brussels
2013.12.16	Audioweb with Allison on automatic transmission model
2013.12.02	Meeting Tyre manufacturers, TÜV, DG CLIMA in Brussels
2013.11.14	Workshop Transmission with TÜV and ACEA in Brussels
2013.10.30	Advisory Board meeting in Brussels
2013.09.25	Telco-Behr to auxiliary cooling fan
2013.09.12	Stakeholder Meeting, Brussels (certification procedure, CoP, ISC, timeline,..)
2013.09.03	Workshop in Brussels, TÜV, TUG, ACEA on Air Drag Tests
2013.07.30	Telco TUG and ZF on auxiliary steering pump
2013.07.24	Meeting Brussels with Tire Manufacturers (ETRTO)
2013.07.09	Telco with DG Clima
2013.07.03	Telco with Volvo on validation tests for Heavy Duty Hybrids CO2 test procedure
2013.06.20	Meeting in Graz with FTG on auxiliary steering pump
2013.06.14	Meeting in Brussels (Planning of pilot phase and further 2013 activities)
2013.05.30	Policy makers meeting, Varese
2013.05.07	Telco with Daimler on torque converter simulation for AT
2013.04.25	Meeting in Brussels with Tire Manufacturers (ETRTO)
2013.04.24	Meeting in Brussels on VECTO, Proof of Concept phase
2013.03.26	Telco on Proof of Concept for VECTO

2013.03.14	Telco with Allison Transmissions on AT simulation approach
2013.03.11	Meeting in Brussels on Heavy Duty Hybrids CO2 test procedure
2013.02.25	Meeting in Bad Homburg with ixetic on auxiliaries steering pump
2013.02.18	Visitation JRC-Balocco test site
2013.02.14	Meeting in Graz with VDA on CFD simulation for Cd x A
2013.02.04	Telco with VOITH, ZF, Daimler on AT simulation
2013.01.23	Meeting in Brussels with ACEA on Auxiliaries
2013.01.17	Telco with Bosch on auxiliaries alternator
2012.12.07	Meeting in Brussels with DG Clima and ACEA (TUG via video conference)
2012.10.25	Meeting in Brussels with ACEA, supply industry and stakeholders
2012.09.27	Meeting in Brussels (Kick-Off for LOT 3)
2012.09.11	Telco with Daimler on wheel hub torque measurement experiences

Following issues listed in LOT 2 and in the proposal for LOT 3 for the tests in a follow up project are not solved yet:

- Definition of minimum required number of valid measurement intervals in each direction for constant speed tests: close to decision
- Definition of a max. range for ambient conditions (temperature, pressure, wind): close to decision
- Definition of standard anemometer position at vehicle, mounting frame, calibration procedure. Suggestion for position available, proposal for calibration available.
- Design of a generic crosswind correction factor for C_d (C_d measured without crosswind): design clarified but generic values need to be produced for all HDV classes
- Test differences in engine fuel maps for different engine family definitions.
- Test of the model for automatic transmission in VECTO: on-going
- Elaboration of a HDV family concept; decision which basic variants in terms of cabin size, aero kits and drivetrain configuration shall be measured.
- Perform questionnaire for hauliers and fleet operators to test if the proposed CO_2-metrics and HDV segmentation is useful for them.

Open

- Further analysis of the multi-stage type approval approach with respect to its nonrestrictive applicability to the heavy-duty vehicles classes as defined in Lot 2. Address, where necessary, additions or restrictions.
- Consideration of the extension approach for adoption on technical progress.
- List all vehicles / vehicle combinations, which shall not be considered in general.

International co-operation

The consortium follows the development of HDV related CO_2 regulations in US, Japan, China and other parts of the world. Contacts with EPA and JARI are established and options are discussed in meetings. Discussions on the options to include hybrid trucks and buses into a CO2 test procedure are performed mainly in the HDH expert group for the GTR on HDH test procedures for conventional pollutants. International harmonisation was also a main topic in a workshop organised by JRC at 29th and 30th May 2013 in Varese. Beside the European stakeholders, following international contacts have been established:

Michael Olechiw; U.S. Environmental Protection Agency

Cleophas Jackson; U.S. Environmental Protection Agency

Mr. Osaki; JASIC, Japan

Mr. Morita; JASIC, Japan

Francisco Nigro; University of Sao Paulo; (Brazil)

Morgan Andreae; CUMMINS, USA

Ben Sharpe; ICCT
The discussions with the persons listed above were dealing with the options how to consider HDH in the CO2 certification (all listed persons in meetings, phone calls and e-mails) and with discussion on the procedure for conventional HDV (EPA, Brazil, Cummins, ICCT), also in meetings, in phone calls and in e-mails.

8. Main open work for follow up activities after LOT 3

This chapter shall support the Commission in planning the next steps after of LOT 3 is finalised.

We assume that LOT 3 will successfully provide (almost) complete descriptions of the HDV CO2 test procedure together with the corresponding software for all conventional truck classes. This includes: description of the methods, of the organisational and legal conditions and of the details of each component tests as well as the necessary simulation tool (VECTO) with user manual and description. Single tasks which may not be solved completely are listed below. Coaches should also be covered by LOT 3 but there the final solution for HVAC simulation may remain open since the actual proposal from ACEA seems to be too complex to be applied in type approval.

Thus LOT 3 shall cover most sources of HDV CO_2 emissions in terms of vehicle classes and mission profiles. In terms of registration numbers the trucks below 7.5t and also bodies and trailers are important products not covered by LOT 3 results.

In addition CO_2 emission values for special vehicles may be of importance for stakeholders due to the need of public calls for tenders when such vehicles are bought (e.g. city buses, garbage trucks, road sweepers, etc.). For these not yet covered vehicles and bodies the effort to reach a high accuracy for the CO_2 values can be quite high since often complex components are added to the "base HDV". So the additional effort to include additional tons of CO2 emissions accurately in the test procedure is expected to increase towards the last remaining topics.

In these situations decisions have to be made if the HDV categories shall be considered at all. If yes, which additional effort shall be made to consider special equipment etc. of the new classes and finally the timeline needs to be drafted until when the procedure shall be finalised. When these decisions are taken, the elaboration of the corresponding test procedures and amendments in VECTO can be launched.

From today's point of view, the following main components and vehicle classes are not covered by LOT 3 and need further decisions:

Table 39: List of open topics after LOT 3

Task	Description	Actions necessary
All HDV		
Cd x A test procedure	Final validation of the changes of rolling resistance when velocity drops from 88 to 15 km/h in the test procedure will not be possible within LOT 3 (test facilities under development). Eventually an adaptation of the evaluation method will be necessary and the prescription of tires with drum test data on their behaviour at these velocity change may be neces-	Funding for RRC tests needed in 2014. Detailed description of ongoing activities given in section 4.2.3.3.

Task	Description	Actions necessary
	sary. Cd x A test evaluation is established for "generic" RRC drop from 88 to 15 km/h. On demand the generic value can be exchanged by tire specific values if this proves to be relevant later in 2014. The CSE-Tool for evaluation has the RRC change as explicit input variable.	
Cd x A test procedure	Details of calibration and evaluation parameters (e.g. criteria for stability of torque signal or for required number of measurement sections) still need to be verified based on more measurement data.	A series of air drag tests was announced by industry for 2014. Support will be required (from TUG) related to the use of the standardised evaluation tool (VECTO-CSE).
Cd x A test procedure	CFD might be suitable method for determination of relative differences in air drag for certain HDV or trailer design variants. CFD was also used in LOT 3 to compute standard tractors in a comparison exercise with ACEA (chapter 2.4). Before CFD can be introduced for certification purposes it seems that more details of the code and of the settings need to be harmonised but the approach is promising. Within ACEA activities are ongoing to clarify the suitability of such an approach as part of the HDV CO_2 certification and its necessary boundary conditions.	Decision if CFD simulation shall be followed either for 2017 or for a 2nd phase of HDV-CO2 legislation. If yes, cooperation between ACEA, Commission and possibly a consultant is suggested to define the method in detail.
CdxA test application	For some HDV classes generic Cd values are under discussion and for EMS and for truck trailer combinations it is open if the entire combination has to be tested.	Discuss and agree with ACEA, eventually define standard trailers and bodies for these HDV classes
Engine map	The accuracy demanded for torque, rpm and fuel flow in the EURO VI directive is not sufficient for the HDV-CO2 certification.	Possible accuracies are outlined in the sensitivity analysis. To be decided if an amendment in the EURO VI engine test procedure or an extra paragraph in the technical annex is a proper solution to fix higher accuracy in

Task	Description	Actions necessary
		the legislative framework
Engine map	The specific Carbon content and the energy density of the test fuel influence the test results. A correction towards "reference values" per fuel type seems to be possible.	We suggest that the regulation for HDV shall follow the LDV regulation, which is under discussion with the implementation of the WLTP. Adaptation of VECTO would not be much effort.
Transmission testing	The remaining open issues in the description of the test procedure for transmission losses are accuracy of torque sensors and the definition of error analysis concept. Maybe also an oil family concept should be elaborated.	Ongoing related activities at industry. Review of final method.
Axle testing	Remaining open issues: • Verification of the generic standard table values • Definition of a reference test cycle to find the worst case oil (necessary for application of the family concept for different oils) • Handling of design changes during production cycle of an axle type to reduce test effort	Ongoing related activities at industry. Review of final method.
Auxiliaries (trucks)	Basic solution for trucks established in VECTO. For some combinations of auxiliary types and technologies data tables in VECTO are not finalised, i.e.: • pneumatic system (update available in ACEA WB April version) • steering pump (some technologies missing) • alternator (alternator technologies missing, list of power saving technologies and additional power consumers to be completed) .Details on these tasks are given in section 4.2.6.	Ongoing activities in ACEA. Review of final numbers.
Auxiliaries (trucks)	Review of options to consider component specific behaviour also for trucks to harmonise the procedure.	Involvement of component supply industry. Decide after project on "auxiliaries for

Task	Description	Actions necessary
		buses" is finalised.
RRC from tires	The tolerances (demanded accuracy) for the RRC values need to be defined together with responsibilities and eventual CoP procedures.	
All component test procedures	Elaboration of family concepts to reduce test burden	Draft concepts have already been elaborated by ACEA and suppliers for air drag, transmission and axle testing.
All-wheel drive	Open, if all wheel driven trucks shall be validated by vehicle tests (just an additional transmission compared to conventional trucks) and if ACEA may perform such validation tests.	Decide with ACEA on relevance and thus on need for validation
Pilot Phase including TAA and TS	Within LOT 3 it was planned to perform tests within a pilot phase which include also Type Approval Authorities (TAA) and Technical Services (TS) to simulate the entire process. It is foreseen to perform such pilot tests as soon as remaining legal uncertainties in the allocation of responsibilities between OEM and supply industry are eliminated in the draft technical annex. Such testing also needs a lot of support from OEM and needs to be planned as further activity.	Organise Pilot Phase
SiCo test	The simple constant speed test approach for ex-post validation of the component data used as input for certification needs further development and testing on test track and/or on chassis dynamometer	Further development needs budget within ACEA and most likely budget from COM for involvement independent consultants
VECTO tool	Remaining open issues related to the actual generation of the VECTO tool are: a) Update of parameters for crosswind influence (new data published in April version of ACEA WB) b) Fine tuning and agreement on model parameters for the driver model after testing of all functions by industry c) Definition of test cases to be used as reference in further model development d) Bus related topics (see extra	Perform updates, support industry in VECTO tests. Review of final parameters and model behaviour.

Task	Description	Actions necessary
	points)	
Driver assistance systems (Eco-Roll, Engine Stop-Start System, Acceleration Management). *This task overlaps with task "Predictive systems" below*	Functionalities already implemented in code of VECTO2.0 based on ACEA system description. Open: • Final testing of system behaviour (OEM comparison with company data) • Definition of criteria when such a feature can be claimed in the declaration (technical description, eventually a verification procedure, check if the feature can be deactivated by the driver etc.) • Decision whether generic function parameters (e.g. over- and under-speed in the Eco-roll function) or OEM specific values shall be used (rather unlikely). Latter would require testing standards to determine these parameters • Sensitivity analysis for the influence of driver assistance systems based on generic vehicles	Discussions with industry and decision on methods. Final development of VECTO functions and if applicable testing standards
VECTO mid-/long term strategy	Decision on general strategy: • Scope 2017: More professional software design, versioning, user support • Scope 2020 (or earlier?): shift to forward simulation (?).HILS option to be investigated for hybrids and also for smart controllers in conventional HDV	Decision on general strategy necessary (could be a focus early in LOT4). This might require e.g. a feasibility study on the efforts to switch to forward simulation. Activities started at ACEA.
HDV classes with small sales numbers		
General approach	Decision how to handle HDV classes with small sales numbers (e.g. all wheel drive vehicles or multi-axle rigid trucks): Options are: (a) Apply simplified approach (specific values only for weights, transmission ratios and engine) (b) Exclude from CO_2 certification	Discussion with industry, elaboration of default data if decision on simplified method
Buses and coaches		
Automatic transmission with torque converter	Basic model available. Update with feedback from manufacturers foreseen in June 2014.	Validation with measurements on buses open

Task	Description	Actions necessary
HVAC, air compressor and electric system	Apply ACEA tools to identify which parameters are relevant for bus-model specific different energy consumption. Simplification of the complex approach to the relevant parameters. Analyse if other relevant parameters need to be considered which are not in the ACEA tool yet.	Study ongoing at AEA-Ricardo
Validation	Bus tests are available (Volvo, EvoBus) but not clear, if all necessary data to apply the selected auxiliary methods will be available for the already tested buses	Bus validation seems to be extra work (LOT4) where automatic transmission and auxiliaries are validated by existing and – if necessary - new tests.
Trucks <7.5 tons **(**Not included in LOT 3)		
Check HDV framework for applicability	Analyse which parts of the HDV methods from LOT 3 may not fit for the small trucks	Decide, if to be included in HDV test framework. If yes, timeline and budget
Complement LOT 3 methods for <7.5t	Make relevant amendments for test procedures (e.g. engine vs. vehicle test may be relevant at smallest category) and for legal context and responsibilities	Many decisions may be necessary during project with OEMs and parties involved in multistage production
Validation	Method will have to be applied in proof of concept phase and pilot phase as for HDV >7.5t	
Special vehicles **(**Not included in LOT 3)		
Definition of additional HDV categories	Special HDV categories may be of interest although the extra fuel consumption due to extra equipment they have is small related to EU27 fuel consumption from HDV. These vehicles are e.g. garbage trucks, municipal utility (road sweepers,..), etc. where a decision is necessary if the power demand at PTO for these vehicles shall be considered (not yet included).	Decide which categories shall be covered
Develop component test procedures and test cycles, imple-	The fuel consumption and CO2 emissions of the "base vehicle" can be determined by the LOT 3 methods for conventional HDV. Test procedures for the	Timeline and budget per category

Task	Description	Actions necessary
mentation in VECTO, validation	additional power consumers (garbage presser, road sweeper, crane, …) and representative test cycles for the VECTO simulation need to be developed, tested and implemented in VECTO	
Bodies and trailers		
Test procedure for bodies and trailers	The actual test procedure foresees to test each HDV with defined "standard-bodies" or "standard -trailers". Thus no incentive is given for body and trailer manufacturers from the certification to improve aerodynamics and weight and also no information is given to customers on "non- standard" bodies and trailers.	Shall bodies and trailers be considered? If yes: optional or mandatory (see chapter 4.5.3.5) Ensure harmonisation with procedure for standard HDV
Develop and validate test procedure	The test procedure for "standard bodies" can be applied for any alternative body too. New element is: how to compare results with standard bodies, which trucks are allowed for trailer and body tests, how is sensitive data handled (vehicle model from OEM would be sensitive, generic data would have to be elaborated). An option is to define look-up tables which give change in fuel consumption as function of change in CdxA and mass against standard body or trailer.	Timeline and budgets
Advanced technologies **(**Not included in LOT 3)		
Waste heat recovery, hybrids, demand controlled auxiliaries,	Several technologies which may enter the market in future cannot be treated correctly with the actual methodology (i.e. the technology is not reflected in the efficiency map of the actually measured components or in the power demand simulation from driving resistances and auxiliary energy demand). A method seems to be necessary which defines in future if, how, when, under which responsibility, new technologies can be added to the test procedure	Decide responsibilities, timeline, general method to implement new components and technologies in VECTO

Task	Description	Actions necessary
"Quick-Innovation"	It is unlikely that new technologies can be integrated in the CO_2 test procedure quickly on demand (develop component test procedure, integrate simulation in VECTO, test and validate results). Thus a method may be necessary, which allows a quick assessment of the CO_2 benefit of new technologies. The method may e.g. be based on vehicle testing and a measured ratio with/without new technology or via interfaces in VECTO where values could be adapted (such as power demand from alternator if waste heat recovery produces electric energy)	Decision if necessary If yes: timeline, budget for development
Hybrids	In the actual VECTO approach heavy duty hybrid (HDH) vehicles are not foreseen. Since the outcome of the HDH-HILS Gtr. Is now clearer, options have been outlined in cooperation with the GTR HDH group: i) Coupling of VECTO with the HDH-Hils model ii) Integration of a generic HDH model in VECTO iii) Definition of look up tables for FC reduction rates as function of normalised battery capacity and normalised electric motor power. iv) Others not identified yet	Since the HDH HILS method proofed to be quite complex, several HDH may not use the HILS approach for type approval if they use a standard combustion engine which has already EURO VI type approval. Thus option i) may not be applicable to all future HDH models and the alternative options need to be further elaborated towards a certification procedure. This work may be part of a LOT 4.
Predictive systems	Predictive systems may decide different operation modes for components depending on the future route characteristics anticipated by actual GPS position and defined destination. It is open if such systems could be considered without a HILS approach. Maybe also the curvature of the CO2-test cycles needs to be defined for such systems.	Discussion with industry if relevant. If yes, solutions have to be elaborated.

9. Summary

The project started in September 2012 and had the goal to further develop a test procedure for CO_2 emissions from HDV up to a complete demonstration version. The base methodology was elaborated already in the project "Reduction and testing of Greenhouse Gas Emissions from Heavy duty vehicles", LOT 2 (call for tender ENV.C.3/SER/2009/0038). LOT 2 and the actual project ("LOT 3") were performed in close and very efficient cooperation with industry.

The HDV-CO_2 test procedure is based on:

- physical testing of the components of the vehicle relevant for the fuel efficiency and for CO_2 emissions
- a standardised simulation method to compute the fuel consumption from the measured component data.

The standardised simulation tool (VECTO) uses the measured component data and for the simulation of the energy consumption of the vehicle in standardised, virtual test cycles. The simulation tool is based on physical approaches well known from vehicle longitudinal dynamics to compute the engine power demand over the test cycles. Engine speed is calculated from the tire dimensions and from the transmission ratios using a driver model for triggering gear shift manoeuvres. The driver model supports manual transmission, automated transmission and automatic transmission and uses generic gear shift strategies. The driver model is also responsible to manage how the vehicle follows the standard test cycles.

The test cycles are "target speed cycles" which define the target speed for the driver as well as the altitude profile of the route and the stop durations over distance. The driver model considers typical maximum acceleration and deceleration wishes, look ahead braking, over-speed and under-speed and as option also Eco-Roll. At full load acceleration by the driver certainly the maximum engine torque at actual engine speeds limit the acceleration. The engine model considers time delays in the dynamic torque build-up of the engines.

For trucks generic auxiliary models are included for the alternator, the air compressor, the steering pump, the engine cooling fan and for the HVAC system. For some of these components vehicle specific technology selections can be made. In a later stage also component specific test results for the auxiliaries may be used but as basis standardised test methods need to be agreed. For bus auxiliaries a separate project is ongoing which shall be linked to the actual approach later in 2014.

The methods for the physical component tests are defined almost completely in the actual deliverables for the engine, the gear box, the axle, the tyre rolling resistance, for the air drag and certainly for the mass of the vehicle.

The average loading conditions and the relevant CO_2 test cycle(s) are allocated from VECTO depending on the vehicle class. The vehicle class is defined by the axle configuration, the vehicle type (rigid, tractor, bus) and the maximum gross vehicle weight. Separate CO_2-test cycles are available for HGV for long-haul, regional delivery, urban delivery, municipal utility and for construction missions. For buses the cycles cover heavy urban, urban, suburban, interurban and coach missions. Also several generic values are allocated to the vehicles as function of the vehicle class and the test cycle (mission profile).

The fuel consumption is then interpolated from a detailed engine map in 1Hz time steps and integrated over the cycle. The result is then corrected for transient effects by the "WHTC-correction function" which also prohibits specific optimisation of the engine efficiency in relevant steady state conditions in the engine map.

The results are provided for the empty vehicle, for average load and for the fully loaded vehicle in g/ton-km and in g/km; for buses g/passenger-km are used instead of g/ton-km.

For a standardised simulation the software VECTO was developed which offers a declaration mode where all generic data as well as the test cycle are allocated automatically as soon as the vehicle class is defined. In addition an engineering mode is offered, where the user can select and change all input data to allow recalculation of test data e.g. for model validation.

The methods and the software have been tested 2013 in a proof of concept phase which showed sufficient accuracies. Several tasks were identified in the test phase which needed further improvements. Most of the issues are solved now. Still open topics are listed in a separate chapter and shall be considered in the next step of the development process.

For the later implementation of the CO_2 test procedure into a legal framework several options have been elaborated and discussed but no decision was made yet on details of the legal framework.

The deliverables of LOT 3 are

- A "draft technical annex" describing the test procedure step by step as input into a future regulatory text.
- The software "VECTO" to calculate the HDV CO_2 emissions from the component test data.
- The software "VECTO-CSE" for the evaluation of the aerodynamic drag test data.
- A "draft certification report" which describes roughly how the process of the certification may look like.
- The actual report giving background information.

It is suggested to use the deliverables for a next test campaign from industry to identify eventual gaps and demands for improvement within the next months. Implementing findings from this test phase and considering the open issues listed already in the actual report shall be done in a next project phase. When the open technical issues are solved, the software should go through a revision including extensive testing to eliminate eventual bugs and to introduce a standardised software quality management. In this phase also additional functionalities for more user comfort, data security etc. should be added to the software. When also the regulatory details of the implementation are fixed, the test procedure is assumed to be ready for testing CO_2 emissions from HDV in a very accurate and efficient way. Nevertheless it has to be clear that the test procedure will have to be regularly updated in future to properly cover more advanced technologies which are assumed to penetrate the marked in future. Under these boundary conditions the test procedure described in the report shall be in the position to set strong incentives for development and finally for market penetration of fuel saving technologies.

10. Literature

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11. ANNEX: Declaration Data

This Annex gives a documentation of the generic input parameters included in VECTO for Declaration Mode (status 25th of June, 2014). The parameters are assigned according to HDV class and mission profile. Fields marked with "N/A" are yet to be defined.

At the moment generic data are complete for the vehicle classes as shown in Table 40. In the actual VECTO version only these HDV vehicle classes can be simulated in the Declaration Mode.

Table 40: Supported HDV classes in declaration mode (status 25th of June, 2014)

Chassis configuration	Axles	Axle configuration	Maximum GVW [t]	Vehice class
Rigid			7.5 - 10	**1**
Rigid			10 - 12	**2**
Rigid	2	4x2	12 - 16	**3**
Rigid			>16	**4**
Tractor			>16	**5**
Rigid	3	6x2/2-4	all weights	**9**
Tractor			all weights	**10**

The tables below give a full description of all generic parameters. Table 42 show the logics how the vehicle class is automatically selected in VECTO according to vehicle category, axle configuration and range of maximum gross vehicle weight (GVW).

Table 41: HDV Class Selection

Vehicle Category	Axle Config	GVW Min	GVW Max	HDV Class
RigidTruck	4x2	0	7.5	0
RigidTruck	4x2	7.5	10	1
RigidTruck	4x2	10	12	2
RigidTruck	4x2	12	16	3
RigidTruck	4x2	16	99	4
Tractor	4x2	16	99	5
RigidTruck	4x4	7.5	16	6
RigidTruck	4x4	16	99	7
Tractor	4x4	16	99	8
RigidTruck	6x2	0	99	9
Tractor	6x2	0	99	10
RigidTruck	6x4	0	99	11
Tractor	6x4	0	99	12
RigidTruck	6x6	0	99	13
Tractor	6x6	0	99	14
RigidTruck	8x2	0	99	15
RigidTruck	8x4	0	99	16
RigidTruck	8x6	0	99	17
RigidTruck	8x8	0	99	17
CityBus	4x2	0	18	B1
InterurbanBus	4x2	0	18	B2
Coach	4x2	0	18	B3
CityBus	6x2	18	99	B4
InterurbanBus	6x2	18	99	B5
Coach	6x2	18	99	B6

Table 42 shows the Mission Profiles which are assigned to each HDV Class.

Table 42: Mission Profile assignment

HDV Class	Driving Cycles									
	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
0		x	x							
1		x	x							
2	x	x	x							
3		x	x							
4	x	x		x						
5	x	x								
6				x	x					
7					x					
8					x					
9	x	x		x						
10	x	x								
11					x					
12					x					
13					x					
14					x					
15		x								
16					x					
17					x					
17					x					
B1						x	x	x		
B2									x	
B3										x
B4						x	x	x		
B5									x	
B6										x

Table 43 and Table 44 show the body/trailer weights and reference loadings for each HDV Class and Mission Profile. For HDV classes 1, 2 and 3 the reference loading is calculated based on the GVW, Figure 86.
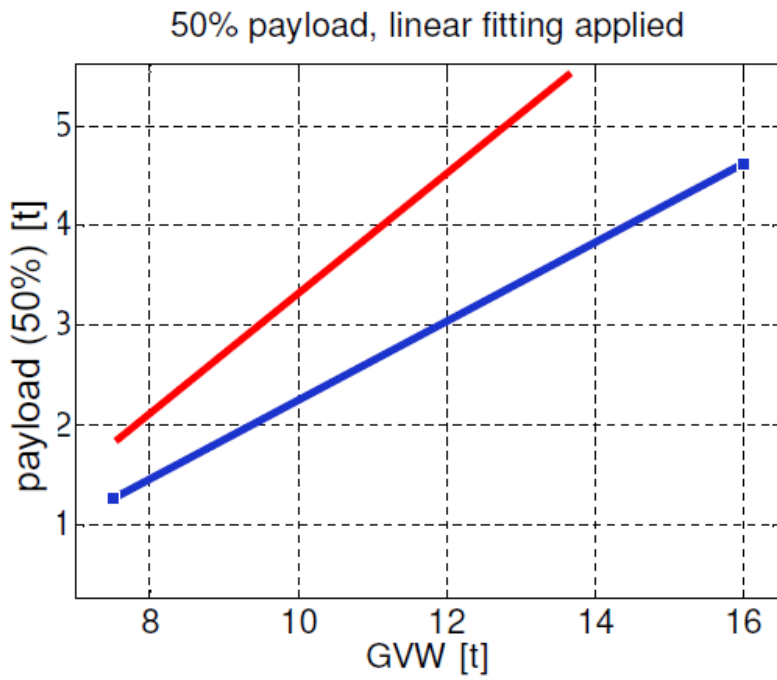
Figure 86: Reference loading for HDV classes 1,2 and 3. Red: Long Haul, blue: other mission profiles

Table 43: Body/trailer weights

HDV Class	Curb Weight Extra Trailer/Body									
	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
0	-	N/A	N/A	-	-	-	-	-	-	-
1	-	1600	1600	-	-	-	-	-	-	-
2	1900	1900	1900	-	-	-	-	-	-	-
3	-	2000	2000	-	-	-	-	-	-	-
4	7500	2100	-	2100	-	-	-	-	-	-
5	7500	7500	-	-	-	-	-	-	-	-
6	-	-	-	N/A	N/A	-	-	-	-	-
7	-	-	-	-	N/A	-	-	-	-	-
8	-	-	-	-	N/A	-	-	-	-	-
9	7600	2200	-	2200	-	-	-	-	-	-
10	7500	7500	-	-	-	-	-	-	-	-
11	-	-	-	-	N/A	-	-	-	-	-
12	-	-	-	-	N/A	-	-	-	-	-
13	-	-	-	-	N/A	-	-	-	-	-
14	-	-	-	-	N/A	-	-	-	-	-
15	-	N/A	-	-	-	-	-	-	-	-
16	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
B1	-	-	-	-	-	N/A	N/A	N/A	-	-
B2	-	-	-	-	-	-	-	-	N/A	-
B3	-	-	-	-	-	-	-	-	-	N/A
B4	-	-	-	-	-	N/A	N/A	N/A	-	-
B5	-	-	-	-	-	-	-	-	N/A	-
B6	-	-	-	-	-	-	-	-	-	N/A

Table 44: Reference Loading

HDV Class	Reference Loading									
	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
0	-	N/A	N/A	-	-	-	-	-	-	-
1	-	f	f	-	-	-	-	-	-	-
2	f	f	f	-	-	-	-	-	-	-
3	-	f	f	-	-	-	-	-	-	-
4	14000	4400	-	4400	-	-	-	-	-	-
5	19300	12900	-	-	-	-	-	-	-	-
6	-	-	-	N/A	N/A	-	-	-	-	-
7	-	-	-	-	4300	-	-	-	-	-
8	-	-	-	-	N/A	-	-	-	-	-
9	17900	7100	-	7100	-	-	-	-	-	-
10	19000	12700	-	-	-	-	-	-	-	-
11	-	-	-	-	7600	-	-	-	-	-
12	-	-	-	-	12100	-	-	-	-	-
13	-	-	-	-	N/A	-	-	-	-	-
14	-	-	-	-	N/A	-	-	-	-	-
15	-	N/A	-	-	-	-	-	-	-	-
16	-	-	-	-	11600	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
B1	-	-	-	-	-	N/A	N/A	N/A	-	-
B2	-	-	-	-	-	-	-	-	N/A	-
B3	-	-	-	-	-	-	-	-	-	N/A
B4	-	-	-	-	-	N/A	N/A	N/A	-	-
B5	-	-	-	-	-	-	-	-	N/A	-
B6	-	-	-	-	-	-	-	-	-	N/A

"f" … payload depending on particular GVW, see Figure 86 above.

In chapter 6.1.1.25 the WHTC FC Correction is described. Table 45 shows the Weighting Factors for each mission profile.

Table 45: WHTC weighting factors

Mission profile	WFMW	WFRoad	WFUrb
Long haul	89%	0%	11%
Regional delivery	53%	30%	17%
urban delivery	4%	27%	69%
Municipial utility	2%	0%	98%
Construction	6%	32%	62%
Citybus	0%	0%	100%
Interurban bus	19%	36%	45%
Coach	78%	22%	0%

In Declaration Mode the axle load distribution is automatically assigned. For the Long Haul cycle there are different distributions as for the other mission profiles.

Rigid/Truck format: axle 1 / axle 2 / axle 3 in percent.

Trailer format: total percent / number of axles, e.g. 50/3 means three trailer axles with 16.67% distribution each.

Table 46: Axle load distributions for truck and trailer.

HDV Class	Rigid/Truck Axles		Trailer Axles	
	Long haul	Other	Long haul	Other
0	N/A	N/A	N/A	N/A
1	-	45/55	0/0	0/0
2	40/60	45/55	0/0	0/0
3	-	40/60	0/0	0/0
4	20/30	45/55	50/2	0/0
5	20/25	25/25	55/3	50/3
6	N/A	N/A	N/A	N/A
7	N/A	N/A	N/A	N/A
8	N/A	N/A	N/A	N/A
9	20/30/15	35/40/25	35/2	0/0
10	15/10/20	20/10/20	55/2	50/2
11	N/A	N/A	N/A	N/A
12	N/A	N/A	N/A	N/A
13	N/A	N/A	N/A	N/A
14	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A
16	N/A	N/A	N/A	N/A
17	N/A	N/A	N/A	N/A
17	N/A	N/A	N/A	N/A
B1	N/A	N/A	N/A	N/A
B2	N/A	N/A	N/A	N/A
B3	N/A	N/A	N/A	N/A
B4	N/A	N/A	N/A	N/A
B5	N/A	N/A	N/A	N/A
B6	N/A	N/A	N/A	N/A

For the electric system constant power consumption is defined for each mission profile. The consumption is reduced if power-saving technologies are installed. Currently only LED lights are available as power-saving technology and can be selected in the Job File. Table 47 shows the power baseline consumption and the reduction for the power-saving technology.

Table 47: Auxiliary power consumption: Electric system.

Technology	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
Baseline electric power consumption	1240	1055	974	974	975	N/A	N/A	N/A	N/A	N/A
LED lights	-50	-50	-50	-50	-50	N/A	N/A	N/A	N/A	N/A

For the fan a predefined technology list is available, Table 48. The particular technology is selected in the VECTO Job File.

Table 48: Auxiliary power consumption: Fan.

Technology	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
Crankshaft mounted - Electronically controlled visco clutch (Default)	618	671	516	566	1037	N/A	N/A	N/A	N/A	N/A
Crankshaft mounted - Bimetallic controlled visco clutch	818	871	676	766	1277	N/A	N/A	N/A	N/A	N/A
Crankshaft mounted - Discrete step clutch	668	721	616	616	1157	N/A	N/A	N/A	N/A	N/A
Crankshaft mounted - On/Off clutch	718	771	666	666	1237	N/A	N/A	N/A	N/A	N/A
Belt driven or driven via transm. - Electronically controlled visco clutch	889	944	733	833	1378	N/A	N/A	N/A	N/A	N/A
Belt driven or driven via transm. - Bimetallic controlled visco clutch	1089	1144	893	1033	1618	N/A	N/A	N/A	N/A	N/A
Belt driven or driven via transm. - Discrete step clutch	939	994	883	883	1498	N/A	N/A	N/A	N/A	N/A
Belt driven or driven via transm. - On/Off clutch	989	1044	933	933	1578	N/A	N/A	N/A	N/A	N/A
Hydraulic driven - Variable displacement pump	738	955	632	717	1672	N/A	N/A	N/A	N/A	N/A
Hydraulic driven - Constant displacement pump	1000	1200	800	900	2100	N/A	N/A	N/A	N/A	N/A
Hydraulic driven - Electronically controlled	700	800	600	600	1400	N/A	N/A	N/A	N/A	N/A

For the simulation of the steering pump VECTO uses two tables to calculate the power consumption. In Table 49 four power demand shares (Unloaded/Friction/Banking/Steering) are defined for each HDV class and mission profile In Table 51Table 50 the scaling factors for each share are defined for different technologies. The total power demand is calculated by Equation 20:$P_{SP} = P_U.U + P_F.F + P_B.B + P_S.S \; [W]$

<div align="right">Equation 20</div>

Table 49: Steering pump power demand shares (P_U/P_F/P_B/P_S) in Watt

HDV Class	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
				Power demand per share						
0	-	N/A	N/A	-	-	-	-	-	-	-
1	-	110/130/20/0	100/120/20/30	-	-	-	-	-	-	-
2	150/190/30/0	130/160/30/0	120/140/20/30	-	-	-	-	-	-	-
3	-	140/170/30/0	130/150/30/40	-	-	-	-	-	-	-
4	230/280/100/0	220/270/40/0	-	220/270/40/0	-	-	-	-	-	-
5	270/330/120/0	250/290/90/0	-	-	-	-	-	-	-	-
6	-	-	-	N/A	N/A	-	-	-	-	-
7	-	-	-	-	N/A	-	-	-	-	-
8	-	-	-	-	N/A	-	-	-	-	-
9	270/330/120/0	220/270/60/0	-	220/270/60/0	-	-	-	-	-	-
10	200/250/120/0	200/240/90/0	-	-	-	-	-	-	-	-
11	-	-	-	-	N/A	-	-	-	-	-
12	-	-	-	-	N/A	-	-	-	-	-
13	-	-	-	-	N/A	-	-	-	-	-
14	-	-	-	-	N/A	-	-	-	-	-
15	-	N/A	-	-	-	-	-	-	-	-
16	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
B1	-	-	-	-	-	N/A	N/A	N/A	-	-
B2	-	-	-	-	-	-	-	-	N/A	-
B3	-	-	-	-	-	-	-	-	-	N/A
B4	-	-	-	-	-	N/A	N/A	N/A	-	-
B5	-	-	-	-	-	-	-	-	N/A	-
B6	-	-	-	-	-	-	-	-	-	N/A

Table 50: Steering pump scaling factors per technologies

Scaling Factors	U	F	B	S
Fixed displacement	1	1	1	1
Variable displacement	0.6	0.6	0.6	0.6
Hydraulic supported by electric	0.7	1	0.9	0.9
Dual displacement	N/A	N/A	N/A	N/A
Electric	N/A	N/A	N/A	N/A

The power consumption for HVAC and the pneumatic system is defined for each HDV class and mission profile,

Table 51 and Table 52.

Table 51: HVAC power consumption in Watt

HDV Class	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
Power demand [W]										
0	-	N/A	N/A	-	-	-	-	-	-	-
1	-		150	150	-	-	-	-	-	-
2	200	200	150	-	-	-	-	-	-	-
3	-	200	150	-	-	-	-	-	-	-
4	350	200	-	300	-	-	-	-	-	-
5	350	200	-	-	-	-	-	-	-	-
6	-	-	-	N/A	N/A	-	-	-	-	-
7	-	-	-	-	200	-	-	-	-	-
8	-	-	-	-	N/A	-	-	-	-	-
9	350	200	-	300	-	-	-	-	-	-
10	350	200	-	-	-	-	-	-	-	-
11	-	-	-	-	200	-	-	-	-	-
12	-	-	-	-	200	-	-	-	-	-
13	-	-	-	-	N/A	-	-	-	-	-
14	-	-	-	-	N/A	-	-	-	-	-
15	-	N/A	-	-	-	-	-	-	-	-
16	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
B1	-	-	-	-	-	N/A	N/A	N/A	-	-
B2	-	-	-	-	-	-	-	-	N/A	-
B3	-	-	-	-	-	-	-	-	-	N/A
B4	-	-	-	-	-	N/A	N/A	N/A	-	-
B5	-	-	-	-	-	-	-	-	N/A	-
B6	-	-	-	-	-	-	-	-	-	N/A

Table 52: Auxiliary power consumption for the pneumatic system in kW.

HDV Class	Power demand [kW]									
	Long Haul	Regional Delivery	Urban Delivery	Municipal Utility	Con-struction	Heavy Urban	Urban	Suburban	Inter-urban	Coach
0	-	N/A	N/A	-	-	-	-	-	-	-
1	-	1.3	1.24	-	-	-	-	-	-	-
2	1.18	1.28	1.32	-	-	-	-	-	-	-
3	-	1.36	1.38	-	-	-	-	-	-	-
4	1.3	1.34	-	N/A	-	-	-	-	-	-
5	1.34	1.82	-	-	-	-	-	-	-	-
6	-	-	-	N/A	N/A	-	-	-	-	-
7	-	-	-	-	N/A	-	-	-	-	-
8	-	-	-	-	N/A	-	-	-	-	-
9	1.34	1.54	-	N/A	-	-	-	-	-	-
10	1.34	1.82	-	-	-	-	-	-	-	-
11	-	-	-	-	N/A	-	-	-	-	-
12	-	-	-	-	N/A	-	-	-	-	-
13	-	-	-	-	N/A	-	-	-	-	-
14	-	-	-	-	N/A	-	-	-	-	-
15	-	N/A	-	-	-	-	-	-	-	-
16	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
17	-	-	-	-	N/A	-	-	-	-	-
B1	-	-	-	-	-	N/A	N/A	N/A	-	-
B2	-	-	-	-	-	-	-	-	N/A	-
B3	-	-	-	-	-	-	-	-	-	N/A
B4	-	-	-	-	-	N/A	N/A	N/A	-	-
B5	-	-	-	-	-	-	-	-	N/A	-
B6	-	-	-	-	-	-	-	-	-	N/A

Table 53 shows the wheel dimensions that can be selected in the Declaration Mode. These are used to define the wheels inertia and dynamic tyre radius according to Figure 87.

$$C_R = F \cdot d \qquad r_{dyn} = \frac{1}{2\pi} F \cdot d$$

C_R = rolling circumference
r_{dyn} = dynamic tire radius
F = Factor, as defined below
d = design overall diameter
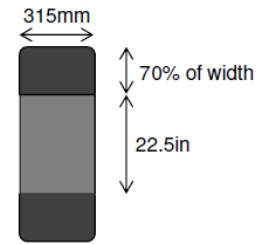
Tire category	F	Example	d [mm]	r_{dyn} [mm]
Sizes on 5° DC Rims	3.03			
45, 50, 55, 60 and 65 series sizes on 15° DC Rims	3.03	385/55 R 22.5	995	479.8
Other sizes on 15° DC Rims	3.05	315/70 R 22.5	1012.5	491.5
Multipurpose truck sizes – radial	3.00			
Multipurpose truck sizes – diagonal	2.94			

Figure 87: Calculation of dynamic tire radius

Table 53: Wheels inertia and diameter

Wheels	Wheels Inertia	Diameter (d)
9 R 22.5	8.9	970
9.00 R 20	10.5	1018
9.5 R 17.5	4.9	842
10 R 17.5	5	858
10 R 22.5	11	1020
10.00 R 20	13.1	1025
11 R 22.5	14.4	1050
11.00 R 20	14.6	1082
12 R 22.5	16.8	1084
12.00 R 20	19.5	1122
12.00 R 24	27.7	1226
12.5 R 20	12.7	1120
13 R 22.5	20	1124
14.00 R 20	30.8	1238
14.5 R 20	14.8	1092
16.00 R 20	47.5	1343
215/75 R 17.5	3.9	767
225/70 R 17.5	4	759.5
225/75 R 17.5	4	782
235/75 R 17.5	4.5	797
245/70 R 17.5	5.2	787.5
245/70 R 19.5	6	838.3
255/70 R 22.5	9.5	928.5
265/70 R 19.5	6.5	866.3
275/70 R 22.5	11.9	956.5
275/80 R 22.5	12.8	1011.5
285/70 R 19.5	7.9	894.3
295/55 R 22.5	10.2	896
295/60 R 22.5	10.8	925.5
295/80 R 22.5	15.5	1043.5
305/70 R 19.5	9.2	922.3
305/70 R 22.5	13.9	998.5
315/45 R22.5	9.9	347
315/60 R 22.5	12.8	949.5
315/70 R 22.5	14.9	1012.5
315/80 R 22.5	17.6	1075.5
365/80 R 20	17.2	1092
365/85 R 20	22.5	1128.5
385/55 R 22.5	15.9	995
385/65 R 22.5	19.2	1072

The PT1 values for the transient full load torque calculation are defined as a function of engine speed as shown in Table 54..

Table 54: PT1 time constant

engine speed [1/min]	PT1
400	0
800	0.47
1000	0.58
1200	0.53
1400	0.46
1500	0.43
1750	0.22
1800	0.2
2000	0.11
2500	0.11

The generic drag coefficient scaling factor depending on vehicle speed is shown in Table 55.

Remark: These values will be updated in June based on the data published in the ACEA WB April version. The scaling factor will then be a function of vehicle class and whether the vehicle is operated with or without trailer.

Table 55: Drag coefficient scaling factor

v_veh [km/h]	cdx_rel [-]
0	1.098791052
5	1.098791052
10	1.098791052
15	1.098791052
20	1.098791052
25	1.098791052
30	1.098791052
35	1.098791052
40	1.098791052
45	1.098791052
50	1.098791052
55	1.098791052
60	1.098791052
65	1.088803287
70	1.080533793
75	1.073611979
80	1.067741189
85	1.062704492
90	1.058339882
95	1.054524125
100	1.05116194

Table 56 shows the generic acceleration and deceleration limit used in declaration mode.

Table 56: Acceleration and deceleration limit over vehicle speed

v [km/h]	acc [m/s²]	dec [m/s²]
0	1	-1
25	1	-1
50	0.642857143	-1
60	0.5	-0.5
120	0.5	-0.5