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Comparison of fuel consumption and emissions for representative heavy-duty vehicles in Europe

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Comparison of fuel consumption and emissions for representative heavy-duty vehicles in Europe

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List of abbreviations

A/C	Air conditioning
ADAS	Advanced driver assistance systems
AMT	Automated manual transmission
avrg	Average
$BSFC_{eng}$	Engine brake specific fuel consumption
$BSFC_{wheel}$	Wheel brake specific fuel consumption
CD	Chassis dynamometer
CdxA	Air drag (product of Cd coefficient by frontal area A)
CO	Carbon monoxide
CO2	Carbon dioxide
CoP	Conformity of Production
CD	Chassis dynamometer
CDT	Coast down test procedure
CST	Constant speed test procedure
DOC	Diesel oxidation catalyst
dyno	Dynamometer
EC	European Commission
ECU	Electronic control unit
EGR	Exhaust gas recirculation
Eta / η	Efficiency, usually defined here as ratio from output work to input work of a component
FC	Fuel consumption
FVT	Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik
GCW	Gross combination weight, weight of truck and trailer
GCWR	Gross Combined Weight Rating, max. permitted weight of truck and trailer
GEM	Greenhouse Gas Emissions Model, US EPA
GHG	Greenhouse gas
GUI	Graphical user interface
GVW	Gross vehicle weight…..curb weight plus payload and driver. Curb weight… total weight of a vehicle in driving condition (i.e. all necessary operating consumables on board, such as fuel, motor oil, transmission oil, etc.), but without loading and without driver
GVWR	Gross vehicle weight rating, max. permitted vehicle weight
HC	Hydrocarbons
HDV	Heavy-duty vehicle
HDV CO2 TA	HDV CO2 legislation as adopted by the TCMV on the 11th of May 2017 and its technical annexes
HVAC	Heating, Ventilation and Air Conditioning
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine

LH	VECTO Long Haul cycle
LHV	Lower heating value
MT	Manual transmission
no.	Number
NO_x	Nitrogen oxides, sum of nitrogen monoxide (NO) & dioxide (NO_2)
OEM	Original Equipment Manufacturer
PEMS	Portable emission measurement system
PM	Particulate matter
RD	VECTO Regional Delivery cycle
RRC	Rolling Resistance coefficient (typically expressed in [N/kN])
SCR	Selective catalytic reduction, process for denitrification of exhaust
SOC	State of charge
VECTO	Vehicle Energy Consumption calculation Tool
TM	Torque meter
w/	with
w/o	without
WHTC	World Harmonized Transient cycle

1. Goals of the project

Starting point of the project was the ICCTs request for proposal (RFP) on “Comparison of fuel consumption and emissions for representative heavy-duty vehicles in Europe and the US” as published in July 2016. In this RFP it was aimed for a comparison of vehicle technology, fuel consumption and pollutant emissions for EU-US pairs of typical vehicles for different HDV applications. After further negotiations and discussions between ICCT and FVT the work allocated at FVT was concentrated on the analysis of representative European vehicles only. The main goals of the adapted work program at FVT were:

I. to determine typical fuel consumption (FC) and CO2 figures from current European HDV vehicle technology to support decision makers in the elaboration of baseline values for future CO2 emission limits[1].

II. to determine FC and CO2 figures in selected cycles from the US HDV CO2 certification for a comparison of tested European vehicles with corresponding US vehicles measured at US testing facilities.

III. to compare the methods for air drag measurement from Europe (Constant speed test) with the US EPA phase 2 coast down test procedure.

IV. to measure and analyze pollutant emission behavior of the tested European trucks.

V. to provide measurement data which allows a deeper analysis of current European HDV fuel efficiency and pollutant emission abatement technology. For this purpose an extensive set of measurement quantities (e.g. NOx engine out emissions, exhaust mass flow and temperature, EGR rate etc.) has been recorded during the chassis dyno measurements. The data has been evaluated and delivered to ICCT in electronic form.

This report focuses on the description of methods as well on a presentation of the results for abovementioned goals I. to IV.

Corresponding analysis on a US truck will be performed in a US lab in collaboration with FVT.

2. Overview of tasks in the project and content of the report

The work at FVT was structured into three main tasks.

Task 1: Selection of vehicles

In close consultation with the ICCT, three specific vehicles representative for the European market have been selected. The selection consisted of:

a) One representative rigid truck used for mid-distance distribution
b) Two tractors (one “average” and one “best-in-class” vehicle) with semi-trailer for long-haul transport purposes with a GCWR of approximately 40 t

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[1] For this purpose the methods applied to determine FC and CO2 have been designed in a way that the results are as close as possible to the values as if determined based on the European HDV CO2 legislation [1].

The performed analyses and the specifications of the selected vehicles are documented in Chapter 3.

Task 2: Vehicle measurements

Goal of the Task 2 was to measure fuel consumption, CO2 and pollutant emissions as well as other performance characteristics in operation conditions as close as possible to the definitions as made in the European and US HDV CO2 legislation. For this purpose a three step approach was chosen:

Task 2A: Air drag measurements

Air drag measurements have been performed on a test track to determine C_dxA values based on the physical test procedures as defined by the according EU and US test procedures. The measurements and test results are described in chapter 4.

Task 2B: Elaboration of road load settings and driving cycles for chassis dyno testing

In order to provide vehicle operation conditions on the chassis dyno which match the simulation based HDV CO2 certification (EU: model VECTO, US: model GEM), specific masses, road load parameters and driving cycles (vehicle speed and gradient over time) had to be elaborated. Road load settings have been calculated by conversion of vehicle specifications (curb mass from the vehicle documents, C_dxA as measured on the test track) according to the legislative provisions and on assumptions on typical rolling resistance coefficients (RRC) in the fleet. The driving cycles for the chassis dyno tests have been generated by VECTO simulations for each particular combination of vehicle and driving cycle. This work is described in chapter 5.

Task 2C: Chassis dynamometer measurements

The actual measurements on fuel consumption, CO2 and pollutant emissions took place at the heavy duty chassis dynamometer at the FVT in Graz. Chapter 6 documents the applied test systems and the testing procedures.

Task 3: Data analysis and reporting

The recorded measurement data from the chassis dyno have been post-processed in order to provide self-consistent datasets and comparable results between different measurements and different vehicles. Applied post-processing steps include time alignment of different measurement signals, corrections for deviations of actual vehicle driving pattern on the dyno compared to the target cycle and the selection of the most relevant quantities for the interpretation of the test results.

The applied methods as well as the results for FC, CO2 and pollutant emissions are given in chapter 7.

Chapter 8 gives a summary of the findings of the project.

3. Task 1: Selection of vehicles

In close consultation with the ICCT, three specific vehicles representative for the European market have been selected. The selection consisted of:

a) One representative rigid truck used for mid-distance distribution

b) Two tractors (one “average” and one “best-in-class” vehicle) with semi-trailer for long-haul transport purposes with a GCWR of approximately 40 t.

The selected vehicle models should have a substantial market share in the European Union. Focus was set to test “most common” vehicles and not vehicles with “average” parameters in the fleet. Information on the distribution of vehicle specifications in the EU was extracted from the IHS/POLK database[2] by ICCT. Analyzed vehicle parameters covered vehicle type, body type, GVWR, axle configuration, engine fuel type, engine rated power, engine capacity, transmission type as well as vehicle manufacturer and vehicle model. The analysis was done for the new registrations of the years 2014 and 2015. Further information on typical vehicle specifications (e.g. axle ratio) was consolidated from surveys performed at ICCT (e.g. [3]) and FVT [4]. The final selection consisted of vehicles of three different manufacturers.

The selection of tires was handled differently to other vehicle components. The representative rolling resistance levels for the selected vehicles were evaluated from data available at ICCT and FVT and were considered via the settings for the chassis dyno tests. Physical tires which were used during the vehicle tests have been selected based on other criteria.[3]

All three vehicles have been visually inspected for any kind of malfunctions. All vehicles have been in proper conditions when handed over to FVT. Additionally the OBD error status was monitored during the measurements. Only measurements without any error messages have been included in the reporting.

3.1. Selection of rigid truck for mid-distance distribution

Rigid trucks for delivery purposes are used in the EU in a broad range of GVWR from about 7.5 to 26 t. The distribution of the GVWR of new registrations shows a two-modal shape with peaks at 12 t and in the 16 t to 18 t range. As the initial phase of the European HDV CO2 certification starts with rigid trucks of vehicle “group 4”[4], it was decided to focus on an 18 t GVWR vehicle. Identified main specifications for a representative vehicle in this group used for delivery applications were found to be:

- Box body
- Engine rated power in the 150 kW to 200 kW range[5]
- Engine capacity in the 7 liter range
- Automated manual transmission (AMT) with 12 gears
- Axle ratio in the 3.0 to 4.0 range
- Specific vehicle manufacturer and vehicle model[6]

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[3] For the air drag testing similar tire models (low rolling resistance tires, energy efficiency class „A“ for drive tires and “B” for steer tires) have been used at all three vehicles in order to guarantee maximum comparability of test results. For chassis dyno testing special sets of test bed tires with removed profile have been used to prevent from tire damage.

[4] Group 4 vehicles are defined with 4x2 axle configuration, „rigid“ chassis configuration and a GVWR of more than 16 t.

[5] Group 4 vehicles in Europe are not only used for delivery purposes but also in long-haul transport. Typical vehicles for the latter application have larger engines (10 – 13 liters capacity, 250 to 350 kW rated power) and usually do also carry a trailer.

[6] Vehicles are anonymized in this report.

Based on this target vehicle specifications it turned out to be a complex problem to find a matching vehicle which could be measured with the available measurement systems at FVT (tire size relevant for rim torque meters, wheel base and total vehicle length relevant for chassis dyno testing) and which is additionally available for testing during open time slots on the test track and the chassis dyno. In the end two different physical vehicles have been tested to generate the results for the representative rigid truck in this project:

- A delivery truck with box body design was tested for air drag on the test track.
- A truck with a skip loader body was tested on the chassis dyno. In order to meet the requested specifications for axle ratio, the original axle of the skip loader body vehicle (ratio 5.13) had to be exchanged by an axle with the target ratio (3.73). For the final result the body of the skip loader vehicle is not relevant as the chassis dyno settings were based on the air drag values as measured on the box body vehicle. The mileage of the engine and gearbox of the skip loader vehicle were at 4.000 km, the mileage of the axle was at more than 100.000 km.[7]

The complete list of vehicle specifications for the representative rigid delivery truck is shown in Table 1 on page 10.

3.2. Selection of tractors for long haul transport

Tractor-semitrailer combinations with a GCWR of 40 t are the vehicle segment with the largest contribution to HDV mileage in the EU. The allocated vehicle group in the European HDV CO2 legislation is “group 5”[8]. Such vehicles are operated typically predominantly in long-haul operation and for regional delivery purposes.

In this project it was decided to measure two different group 5 vehicle models:

Vehicle 1 - currently most frequent vehicle technology

Vehicle 2 - currently best available vehicle technology

Makes and models of both vehicles were selected to meet the most frequent vehicles parameters for group 5 vehicles which are:

- Sleeper cab with 2.500mm width with aero package
- Engine rated power in the 320 kW to 340 kW range
- Engine capacity in the 12 liter to 13 liter range
- Automated manual transmission (AMT) with 12 gears
- Axle ratio in the 2.5 to 3.0 range
- Specific vehicle manufacturer and vehicle model

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[7] In the European HDV CO2 legislation the run-in provisions for component tests are as follows: Engine: no provisions; Transmission: below 100 hours (below 30 hours per gear); Axle: below 100 hours.

An estimation of the run-in time of engine and transmission of the skip loader based on the average vehicle speed from the VECTO construction cycle gives some 4000 km/57 km/h = 70 hours. So it is assumed that the skip loader vehicle had an engine run-in time shorter than typical in the component certification. For the quantification of the run-in influence on fuel consumption no data is available.

[8] Group 5 vehicles are defined with 4x2 axle configuration, „tractor“ chassis configuration and a GVWR of more than 16 t.

Selection of make and type of vehicle 1 was based on data from a market survey. Vehicle 2 was chosen after consultation with an OEM on the specifications of their best available model in the relevant vehicle category. Vehicle 2 is driven by a second generation EURO VI engine (model year 2015), whereas engine of vehicle was already type approved in 2012. The complete list of vehicle specifications of the selected representative group 5 tractors is shown in Table 1. Advanced driver assistance systems (ADAS)[9] have not been taken into consideration in this study as their impact can not be quantified by chassis dyno testing. For both tractors the same semi-trailer as defined as standard in the European HDV CO2 regulation was used.

3.3. List with vehicle specifications

Table 1 shows the specifications of the three vehicles investigated in this study. Makes and models are not intended to be published in this study. Characteristic specifications are given in indicative ranges only for this purpose. Vehicle masses are discussed in chapter 5 (Task 2B: Elaboration of settings for chassis dyno testing).

Table 1: List of vehicle specifications

	Rigid truck[10]	**Tractor #1**	**Tractor #2**
Vehicle category (N1 N2, N3, M1, M2, M3)	N3	N3	N3
Axle configuration	4x2	4x2	4x2
Gross vehicle weight rating (t)	18	18	18
Vehicle group	4	5	5
Cabin type	Extended day cab	Sleeper cab, 2500mm width	Sleeper cab, 2500mm width
Body type	Box body with tail lift	---	---
Vehicle height (m)	3.70 (actual body) 4.00 (standard body[11])	4.00	4.00
Engine model year	2013	2012	2015
Vehicle first registration year	2016	2014	2015

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[9] ADAS comprises vehicle control systems like engine start/stop, eco-roll and predictive cruise control. The CO2 saving impact of these systems is not yet covered by the European HDV CO2 legislation.

[10] Specifiations given for the rigid truck are the compilation of the engine and drivetrain specifications of the vehicle measured at the chassis dynometer and the cabin and body specifications of the vehicle used for air drag measurements.

[11] For CO2 certification with VECTO a „standard body“ is defined for each vehicle group. The standard bodies shall be constructed as a hard shell body in dry-out box design. The definitions comprise physical properties like dimensions, radii of corners and overall vehicle height (relevant for air drag testing) as well as body mass (relevant for VECTO simulation). In this study it was not possible to find a rigid truck where the superstructure matched with the related provisions. To compensate for the difference in overall vehicle height, the CdxA value as measured in the air drag test was scaled proportionally to the reference height in the legislation (see section 4.1).

	Rigid truck[10]	**Tractor #1**	**Tractor #2**
Engine rated power (kW)	175 - 200	320 - 340	320 - 340
Engine idling speed (1/min)	700	600	500
Engine rated speed (1/min)	2300	1800	1600-1800
Number of cylinders	6 cylinders inline	6 cylinders inline	6 cylinders inline
Engine capacity (lit.)	6 - 7	12 - 13	12 - 13
Engine reference fuel type	Diesel CI	Diesel CI	Diesel CI
Engine technology features	Common rail injection, 4 valves per cylinder, 1-stage turbocharging with VTG, intercooler	Common rail injection, 4 valves per cylinder, 2-stage turbocharging, intercooler, overhead camshaft, EGR	Common rail injection, 4 valves per cylinder, advanced exhaust gas turbocharger with fixed turbine geometry, intercooler, two overhead camshafts, EGR
Emission standard	EURO VI	EURO VI	EURO VI
Emissions control	EGR, DOC, DPF, SCR	EGR, DOC, DPF, SCR	EGR, DOC, DPF, SCR
Transmission type (SMT, AMT, APT-S, APT-P)	AMT	AMT	AMT
Number of gears	12	12	12
Transmission ratio final gear	0.81	1.00	1.00
Retarder type	Transmission Output Retarder	Transmission Output Retarder	Transmission Output Retarder
Power take off type[12]	only the drive shaft of the PTO / tooth clutch (incl. synchronizer) or sliding gearwheel	none	none
Axle type	Single reduction axle	Single reduction axle	Single reduction axle
Axle ratio	3.73	2.53	2.53
Aerodynamics	Aero package (roof spoiler, side flaps)	Aero package (roof spoiler, side flaps)	Aero package (roof spoiler, side flaps, side panels)
Tire dimension steer axle	315/70 R22.5	315/70 R22.5	315/70 R22.5

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[12] For auxiliaries and PTO the categorization refers to the definitions in the European HDV CO2 regulation.

	Rigid truck[10]	Tractor #1	Tractor #2
Tire dimension drive axle	315/70 R22.5	315/70 R22.5	315/70 R22.5
Twin axle drive axle (yes/no)	yes	yes	yes
Trailer tires	385/65 R22.5[13]	385/65 R22.5	385/65 R22.5
Engine cooling fan technology[12]	Crankshaft mounted, Bimetallic controlled visco clutch	Driven via transmission, electronically controlled visco clutch	Belt driven, electronically controlled visco clutch
Steering pump technology[12]	Fixed displacement	Fixed displacement	Variable displacement mech. controlled
Electric system[12]	Standard technology	Standard technology	Standard technology
Pneumatic system technology[12]	medium supply 1-stage	medium supply 1-stage	medium supply 2-stage + ESS[14] + AMS[15]
HVAC system technology[12]	default	default	default
Engine torque limitations	none	none	"Top Torque"[16]
Vehicle mileage (km)	4 000	250 000	30 000

4. Task 2A: Air drag measurements

The vehicles' air drag was determined by measurements on the DEKRA test facility in Klettwitz. This test track proved to be very well suited for such tests and is currently the most common used site in Europe. Two different testing methods have been applied in this project:

- The constant speed test procedure (CST) as described in Annex VIII of the European HDV CO2 legislation [1]

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[13] For group 4 vehicles the trailer is not applicable for physical air drag testing. The trailer influence is considered in the VECTO simulation tool. In this study the trailer was considered in the settings on the chassis dyno (details see chapter 5).

[14] ‚Air compressor with Energy Saving System (ESS)' means a compressor reducing the power consumption during blow off, e.g. by closing intake side. ESS is controlled by system air pressure.

[15] 'Air Management System with optimal regeneration (AMS)' means an electronic air processing unit that combines an electronically controlled air dryer for optimized air regeneration and an air delivery preferred during overrun conditions (requires a clutch or ESS).

[16] „Top torque" is a fuel saving feature which provides an increased engine maximum torque in the highest gear(s).

- The coast down test procedure (CDT) as described in the US Phase 2 GHG regulation and described in § 1037.528 in [2].

The CST test procedure was applied to all three vehicles. The CDT test was performed for the rigid truck as well as for tractor #2.

The air drag tests were executed in two test series: Test series 1 was performed with the rigid truck from 3rd to 7th of February 2017. Test series 2 was performed with the two tractor models from 6th to 9th of June 2017.

Sections 4.1 and 4.2 give a documentation of the two test series and provide the results from the constant speed tests. Section 4.3 describes the methods applied for execution and evaluation of the US phase 2 coast down tests and compares the air drag values from the CDT with the corresponding value from the CST.

4.1. Test series 1 (rigid truck)

Table 2 gives the specifications of the measurement systems installed on the rigid truck during the air drag tests.

Table 2: Specification of measurement systems (test series 1, rigid truck)

Measurement quantity	Measurement system / data source
Wheel torque	Kistler RoaDyn® P1HT torque measurement rims for HD applications
Vehicle speed	CAN bus
Engine speed	CAN bus
Vehicle position	Kistler GPS-Sensor 100Hz
Mobile anemometer	Gill Windsonic Wind Speed & Direction Sensor with Kistler transducer Windsonic to DTI
Ambient temperature on the vehicle	Type K thermocouple
Proving ground temperature	Kistler DTI IR-temperature sensor IRN3-100-20

Additional required data from a stationary weather station (ambient pressure, ambient temperature, relative humidity) was provided by the DEKRA test facilities.

The applied GPS system used in test series 1 did not fully meet the accuracy provisions as described for the constant speed test.[17] For the particular measurement data recorded in test series 1 the influence of the non-compliance on the test results has been analyzed and was found to be of negligible influence. For the second test series a compliant DGPS system has been used. All other measurement systems were compliant.

Weather conditions were very winterly during the first test series. Ambient conditions were slightly below the legislative minimum temperature of 0°C. Test track conditions were partly

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[17] In the technical annex the use either of a DGPS system or of optical barriers for detection of vehicle position is described. Both systems have not been available for the first test series. The accuracy influences the calibration quality of the vehicle speed signal.

snowy during the misalignment test and partly wet during the CSTs. As ambient wind increased during the test day it was only possible to complete two out of three planned constant speed tests.

In the test evaluations additional algorithms[18] compared to the legislative provisions have been applied in order to gain correct numbers for rolling resistance during the measurements. This was done in order to check whether the road load force calculated from the tire labeling meets the measured forces on a track. Rolling resistance values for the road loads to be applied on the chassis dyno have been defined separately (see chapter 5).

In the test evaluations some of the validity criteria (temperature, torque stability and maximum cross wind) in evaluation tool VECTO Air Drag had to be relaxed compared to the legislative boundary conditions.[19]

Table 3 gives the boundary conditions and the results for the constant speed test with the rigid truck. Despite the unfavorable ambient conditions (varying test track conditions during the test, significant cross wind during the second measurement) both CST tests give nearly the same C_dxA value with 4.97 m² and 5.00 m² (average 4.99 m²). With a vehicle height of 3.7 m and a frontal area of 9.435 m² this number refers to a C_d-value of 0.528 [-]. For input into VECTO the measured C_dxA values are defined to be scaled to a reference vehicle height. This height is defined with 4 m for group 4 trucks.[20] With an actual vehicle height of 3.7 m the resulting C_dxA value is at 5.39 m². This value has been applied in the road load settings on the chassis dyno tests

For the first CST the rolling resistance coefficient (RRC)[21] was evaluated to be at 5.15 N/kN. This matches very well with the RRC derived from the tire labeling (B for steer tires, A for drive tires) if additional corrections for wheel load and ambient conditions are considered. For the second test the RRC was significantly higher (8.26 N/kN) which can be explained by the wet test track conditions.

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[18] 1) Consideration of the altitude profile of the test track 2) manual correction for the torque meter drift in the measurement data

[19] It cannot be quantified how much this impacts the result for CdxA compared to a measurement in ideal ambient conditions. From theory lower torque stability should not lead to a systematic bias in CdxA. Low ambient temperatures and heavy crosswind could increase the CdxA figures derived from the constant speed test and the prescribed evaluation methods with the VECTO air drag tool.

[20] This provision is part of the “family concept” for air drag in the European HDV CO2 legislation. The family concept shall reduce testing burden for OEMs. For group 4 a vehicle height of 4 m is the most common vehicle configuration. Separate CdxA values for lower vehicle heights are not considered at the moment.

[21] Rolling resistance coefficient: Rolling resistance force divided by normal force of total vehicle mass

Table 3: Results constant speed test series 1 (rigid truck)

		Rigid	
		CST 1	CST 2
Test track conditions	[-]	dry	wet
Ambient temperature	[°C]	-2.0	-1.2
Average vehicle speed LS (low speed)	[km/h]	15.5	13.8
Average vehicle speed HS (high speed)	[km/h]	92.9	93.0
Average rolling resistance coefficient (RRC)	**[N/kN]**	**5.15**	**8.26**
CdxA w/o corrections	[m²]	5.15	5.26
Average yaw angle (cross-wind)	[°]	0.8	1.9
CdxA cross wind correction	[m²]	-0.03	-0.11
CdxA correction for anemometer influence	[m²]	-0.15	-0.15
CdxA single test	**[m²]**	**4.97**	**5.00**
CdxA average	**[m²]**	**4.99**	
Vehicle height	[m]	3.70	
Frontal area	[m²]	9.435	
Cd value	[-]	0.528	
Vehicle reference height (VECTO group 4)	[m]	4.00	
CdxA vehicle height correction	[m²]	0.40	
CdxA VECTO	[m²]	**5.39**	

4.2. Test series 2 (tractors)

In the execution of the air drag tests for the two tractors meticulous attention was given to gain test results with a maximum comparability between the two vehicles. As a consequence identical measurement equipment, identical tires and identical trailers have been used at both vehicles. Additionally all test runs have been executed in parallel (shifted by half a lap) on the test track.

Measurement systems installed on the vehicles were identical to the equipment used in test series 1, expept for vehicle position where a Kistler DTI DGPS 100Hz prototype with Javad TRIUMPH-1M reference station was applied.

As for test series 1 additional required data from a stationary weather station was provided by the DEKRA test facilities. All measurement systems were compliant with the provisions in the technical annex for constant speed testing.

A crucial boundary condition for air drag measurement with group 5 vehicles is the configuration of the semi-trailer. First priority in selection of trailers was given to have two identical units, second priority to match with the provisions of the standard semitrailer as specified in the European HDV CO2 legislation as good as possible. The pair of semi-trailers finally selected was compliant in terms of dimensions, only the following equipment details did not match with the provisions for the standard semi-trailer:

- With pallet box (instead of w/o)
- Only one instead of two spare wheels
- No mud flap before the axle assembly (only behind)

It is assumed that the pallet box, as its geometry is quite similar to partly side and underbody panels, slightly reduces the air drag compared to a standard semi-trailer. A study performed by FAT [3] quantifies the C_dxA reduction by such devices by 6% if fully covering the distance between end of tractor and end of vehicle. As the pallet box covers about one third of this distance, the influence of on the overall C_dxA is assumed to be less than 2%.

During the test series 2 the ambient conditions were fully compliant with the provisions for the constant speed test. In the test evaluations for some of the datasets the validity criteria for torque stability had to be slightly relaxed compared to certification provisions. All other validity criteria as specified in the constant speed provisions have been met. As for test series 1 also for the CSTs with the tractors additional algorithms have been applied to gain correct rolling resistance information from the measurement data.

Table 4 shows the boundary conditions and the results for the constant speed tests with the two tractors. Ambient conditions are identical between the trucks for each test number as the measurements have been operated in parallel. Average test speeds vary slightly due to differences in vehicle speed limiter calibrations and transmission ratios. The related effects on C_dxA results are corrected in the VECTO Air Drag test evaluation. The evaluation of RRC values shows very simlar levels at both vehicles in the range of 4.5 N/kN, which matches with the tire energy efficiency class of the mounted tires.[22]

Results for C_dxA values are lower for tractor #1 with an average value of 5.21 m^2 compared to tractor #2 with an average value of 5.53 m^2. Nearly the same difference in C_dxA values for all three tests has been found, hence this difference is concluded to be significant. Test results for C_dxA are lowest for the test 3 as this test was performed nearly without any ambient wind. Crosswind effects are corrected for in the VECTO Air Drag test evaluation, however, the functions are designed in a conervative way in order not to over correct crosswind influence for some vehicle configurations.

Test results for C_dxA have been discussed with the OEMs of both tractors. If the assumed 2% influence on the C_dxA value due to the presence of the pallet box is taken into consideration, the C_dxA values as measured in this study are within C_dxA confidence range as communicated by the OEMs, however in the lower region of this range. For the chassis dyno tests it was agreed with ICCT that the C_dxA values as measured (i.e. without correcting of the assumed pallet box influence) shall be applied in the chassis dyno tests.

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[22] Steer tires: B, drive tires: A, trailer tires: B

Table 4: Results constant speed tests test series 2 (tractors)

		Tractor #1			Tractor #2		
		CST 1	**CST 2**	**CST 3**	**CST 1**	**CST 2**	**CST 3**
Test track conditions	[-]	dry	dry	dry	dry	dry	dry
Ambient temperature[23]	[°C]	17	14	22	16	13	22
Average vehicle speed LS (low speed)	[km/h]	16.5	16.5	16.5	15.9	15.9	16.0
Average vehicle speed HS (high speed)	[km/h]	89.6	89.6	89.7	88.6	88.6	88.7
Average rolling resistance coefficient (RRC)	[N/kN]	4.6	4.6	4.4	4.4	4.6	4.4
CdxA w/o corrections	[m²]	5.43	5.42	5.27	5.81	5.76	5.61
Average yaw angle	[°]	0.5	0.3	0.7	0.6	0.5	0.8
CdxA cross wind correction	[m²]	-0.04	-0.02	-0.05	-0.04	-0.03	-0.06
CdxA vehicle height correction[24]	[m²]	0.03	0.03	0.03	0.00	0.01	-0.04
CdxA correction for anemometer influence	[m²]	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15
CdxA single test	**[m²]**	**5.27**	**5.27**	**5.10**	**5.62**	**5.59**	**5.37**
CdxA vehicle average	**[m²]**	**5.21**			**5.53**		
Vehicle height	[m]	4.00			4.00		
Frontal area	[m²]	10.20			10.20		
Cd	[-]	0.51			0.54		

4.3. Results coast down US phase 2

Part of the project was to determine the air drag value by the coast down method (CDT) as foreseen in the US Phase 2 GHG regulation and described in § 1037.528 [2]. Results should then be compared to the air drag derived from the constant speed test. This exercise was performed for the rigid truck as well as for tractor #2.

The CDT procedure as elaborated by US EPA for the phase 2 regulations has been published in 2016 and is a completely revised and extended method compared to the well-known phase 1 test. Partner labs in Europe and also European vehicle OEMs have been contacted to share their experiences, but none of these institutions already had investigated this test procedure. Contacts have been also made to an US vehicle OEM, which shared some experience from their contribution in the pilot phase of the phase 2 test procedure.

Based on the provisions described in § 1037.528, literature [6] and the above mentioned contact to an US OEM the coast down tests have been planned, executed and evaluated. In order to be practicable for European vehicles the speed ranges for the “High speed” (HI)

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[23] Values as measured on each vehicle

[24] Vehicle heights have been measured and if necessary adjusted before start of each CST measurement according to the legislative provisions. After zeroing of torque meters the heights have been re-measured and provided as input into the evaluation tool. A few centimeters difference to the reference vehicle height of 4.00 m due to influence of the air suspension was seen during measurements. This different vehicle height in the tests is the reason for the different values for CdxA vehicle height correction for tractor #2.

and the “Low speed” part (LO) of the coast down test had to be adapted.[25] This has been done by applying the vehicle speed differences between the single test elements from the US legislation to the operable speed range of European vehicles and rounding the values to even numbers. Table 5 shows the speed ranges applied for coast down testing in this study.

Table 5: Vehicle speed ranges applied for coast down testing

Coast down part		range upper limit	range lower limit	"nominal" speed
		[km/h]	[km/h]	[km/h]
HI	starting point	**88.0**	81.6	84.8
	ending point	71.4	**65.0**	68.2
LO	starting point	**35.0**	28.6	31.8
	ending point	18.4	**12.0**	15.2

The tests have been performed at the Klettwitz test track by doing so-called “split coast down runs” where it each a HI part (covering the range from 88 km/h to 65 km/h) and a LO part (from 35 km/h to 12 km/h) on a single 2.3 km straight were executed. At the end of the HI part the vehicle was decelerated by mechanical braking to the start speed of the LO part in order to reduce the required track length. For tractor #2 in total 32 runs per direction have been collected, partly in heavy crosswind conditions. For the rigid truck only 14 coast downs per direction were possible due to bad weather conditions.

The test evaluation was performed based on the description in § 1037.528. Due to the boundary conditions in this project the following modifications compared to official US EPA provisions had to be made:

- Primary filtering of raw data (“Hampel method”) has not been applied as the according description is not clear in the US EPA document. As the purpose of the filtering is to remove extreme outliers it is estimated that this does not influence the test results as the test data were visually checked for any outliers.
- The calibration of anemometer readings for air speed and yaw angle have been taken from the CST method as no weather stations close to the two test lanes according to the US EPA calibration approach were available.
- Parameters for tire rolling resistance (which have to be measured according to the phase 2 provisions with a specific test procedure on a tire test drum) were not available for the particular tires mounted during the tests. In the evaluations the parameter values from the US EPA example calculation have been used.
- The corrections for axle drag losses were performed using axle data from a different component with an axle ratio close to the installed components.

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[25] The original US procedure requires coast downs to be started at vehicle speeds higher than 72 mph (116 km). European vehicles normally cannot be operated at speeds higher than 89 km/h without any modifications in the vehicle control system.

The description of the CDT evaluation algorithms in the US EPA document leaves some open room how the datapoints are binned to the HI and LO parts of the CDT.[26]

Figure 1 shows the C_dxA values determined from the coast down tests and gives a comparison with the test results from the CST. The C_dxA values from the single CDT runs show a clear dependency with cross-wind expressed via yaw angle[27]. According to the phase 2 provisions the consolidated test result of a CDT series gives a pair of C_dxA value and related yaw angle. For the rigid truck the phase 2 CDT result is 4.47 m^2 at 3.3° yaw angle. For tractor #2 the phase 2 CDT result is 4.94 m^2 for 1.6° yaw angle.

In order to compare these test results with the C_dxA values from the CST, the C_dxA values have been converted to zero yaw angle conditions applying the functions for yaw angle dependency as stated in the European legislation. This results in C_dxA values of 4.26 m^2 for the rigid truck and 4.80 m^2 for tractor #2 from the CDT. Compared to the test results from the CST (4.99 m^2 and 5.53 m^2) the test result from the US phase 2 CDT are 15% lower for the rigid and 13% lower for tractor #2. A general trend of lower C_dxA numbers from the the US phase 2 CDT was expected, as the European CST test in its current version is known to result in rather conservative (i.e. higher) C_dxA values compared to other test methods (e.g. CFD, wind tunnel). Main reason is that the CST evaluation assumes the rolling resistance force to be constant over vehicle speed. However, in normal test conditions the tire rolling resistance is about 15% lower in the low speed test compared to the high speed test since the low speed is driven directly after the high speed, tire temperature and pressure are still on a high level but tire internal friction is lower due to the lower speed level. This assumption results in some 5% to 10% higher C_dxA values than if evaluated with the known speed dependency. The US EPA phase 2 test procedure considers this speed dependency of the rolling resistance force by using data measured at a tire drum test.

To further analyse the differences between the test methods, the data from the CDTs have been re-evaluated by setting the rolling resistance force speed correction to zero and so giving comparable conditions to the CST test evaluations. The related results are shown in Figure 2. For zero yaw angle a C_dxA value of 4.57 m^2 is obtained for the rigid truck, the according value for tractor #2 is at 5.23 m^2. Still a sigificant gap between results from the CDT compared to CST remains (-8% for the rigid truck, -5% for tractor #2). The specific reasons for the remaining differences between CDT and CST are not fully understood. One of the potential causes might be varying gearbox losses during the CDT. During the coast downs with tractor #2, a clear jump in transmission noise towards a higher pitch during the LO part of the procedure was audible. This could be an indication of higher gearbox losses during the LO part compared to the HI part resulting of C_dxA values biased towards lower figures.

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[26] The criterion how to determine the first and the last datapoint within the HI and the LO part is not described explicitely. In this study the datapoint with the vehicle speed nearest to the range upper / lower limt was sleclected as first / last datapoint in the evaluation. Alternative interpretations could be e.g. to select the first point below the upper limit and the last point above the lower limit.

[27] Yaw angle: Angle between air flow resulting from vehicle velocity and ambient wind with vehicle longitudinal axis

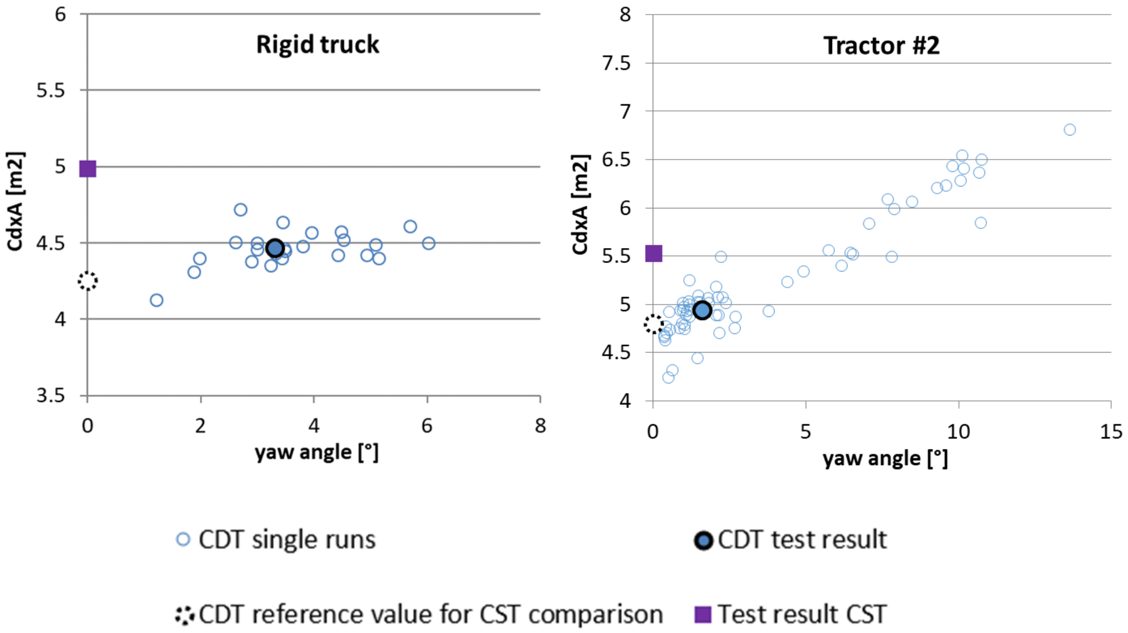

Figure 1: Test results CDT according to US EPA phase 2 compared with results from CST

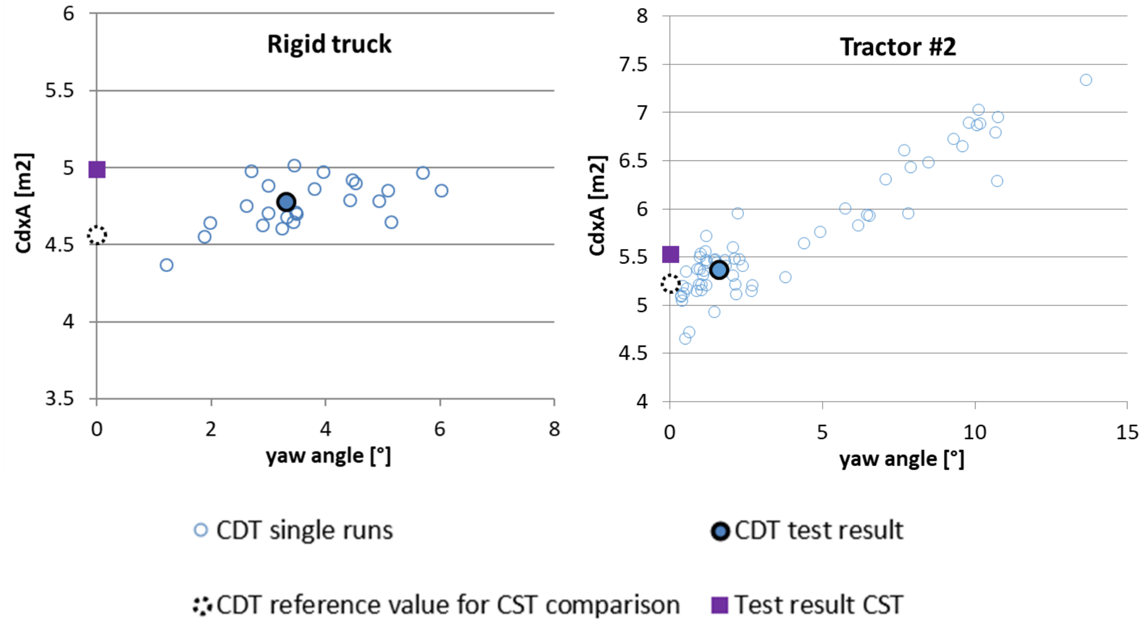

Figure 2: Test results CDT with RRC speed corrections set to zero and compared with results from CST

5. Task 2B: Elaboration of settings for chassis dyno testing

In order to provide vehicle operation conditions on the chassis dyno which match with vehicle operation conditions in the simulation based HDV CO2 certification (EU: model VECTO, US: model GEM) specific masses, road load parameters and driving cycles (vehicle speed and gradient over time) had to be elaborated. The cycles to be measured on the chassis dyno were:

- VECTO Long haul cycle (“VECTO LH”)
- VECTO Regional delivery cycle (“VECTO RD”)
- GEM Phase 2 cycle – ARB / HHDDT Transient (“GEM ARB Transient”)
- GEM Phase 2 cycle – 55mph w/ grade profile (“GEM 55mph”)
- Constant speed test at 55mph w/o grade profile (“55mph flat”)

Additionally a 6x6 grid of steady state points was measured on the chassis dyno for each vehicle. Goal was to reproduce the engine mapping cycle from the European HDV CO2 regulation by chassis dyno tests as good as possible.

5.1. Settings for masses and road load parameters

Table 6 gives the settings for masses and road load parameters elaborated for the chassis dyno test. The EU regulations specify that group 4 vehicles are simulated in the VECTO long haul cycle as a truck-trailer combination (with trailer “T2”) and in the regional delivery cycle as a rigid only. Also different payloads for different cycles apply.

Curb masses have been calculated from masses specified in the vehicle registration documents by corrections to reference conditions (5 m wheelbase for the rigid, 1000 liters tank volume for the tractors, 50% tank level as defined in VECTO).

Masses of body and trailer have been extracted from the VECTO definitions.

Equivalent rotational masses of wheels have been calculated based on the wheel dimensions, the related VECTO definitions (inertias in kgm²) and converted into a translatory inertia (in kg).

For the rolling resistance it was defined in agreement with the ICCT that tires with energy class “C” shall be considered as representative tires for all axles except for the steer axle of the tractors (energy class “B”). From this definitions the R0 parameter (rolling resistance force in Newton) to be set on the chassis dyno was then calculated based on the total vehicle mass, the axle load distributions (values from VECTO) and the RRC correction function for vertical wheel force influence (as defined in VECTO).

The C_dxA parameters have been taken over from the constant speed test. For the rigid truck the correction of C_dxA to the group 4 vehicle reference height of 4 m was taken into consideration. For the long haul cycle furthermore a delta C_dxA of +1.5 m² was applied to simulate the trailer influence for the group 4 vehicle similar as done by VECTO. For the two tractors analyzed in this study similar settings apply except for curb mass (tractor #2 almost 400 kg heavier than tractor #1) and C_dxA.

For simulation of air drag forces on the chassis dyno it was agreed with ICCT not to include the influence of average ambient wind as applied in VECTO.[28] As a consequence lower air drag forces are applied by the chassis dyno in comparison to a VECTO simulation. The influence of this circumstance is further analyzed in the discussion of results in section 7.2.

Table 6: Settings for masses and road load parameters

	Rigid truck	**Tractor #1**	**Tractor #2**
Curb mass (kg)[29]	**6598** calculated from mass of incomplete vehicle and corrected to 50% tank level of 840 l tank and 5 m wheel base	**7365** calculated from actual curb mass and corrected to 50% tank level of 1000 l tank	**7756** calculated from actual curb mass and corrected to 50% tank level of 1000 l tank
Mass of body and trailer (kg)	VECTO LH: **7500** Body "B4" + trailer "T2" other cycles: **2100** Body "B4"	**7500** Semi-trailer "ST1"	
Equivalent rotational mass of wheels (kg)	VECTO LH: **616** incl. trailer tires other cycles: **348**	**750**	
Payloads (kg)	VECTO LH: **14000** VECTO RD: **4400** GEM: **7500**	VECTO LH: **19300** VECTO RD: **12900** GEM: **17200**	
RRC (N/kN)[*1]	Steer tires: **5.5** (class "C") Drive tires: **5.5** (class "C") Trailer tires: **5.5** (class "C")	Steer tires: **4.5** (class "B") Drive tires: **5.5** (class "C") Trailer tires: **5.5** (class "C")	
C_dxA (m^2)	VECTO LH: **6.89** CST test result scaled to 4 m reference height plus generic 1.5 m^2 for trailer influence other cycles: **5.39** CST test result scaled to 4 m reference height	**5.21** value as measured by CST	**5.53** value as measured by CST

*1 In the calculation of the R0 parameter for the chassis dyno the RRC correction for wheel load influence as applied in VECTO has been additionally considered.

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[28] In VECTO the calculation of air drag forces considers an average ambient wind of 3 m/s uniformly distributed from all directions. This results in an effective CdxA value which is a function of vehicle speed.

[29] Curb mass of chassis (w/o body) according to the provisions for „actual corrected curb mass“ in Annex III of the European HDV CO2 legislation

5.2. Driving cycles

As input for the chassis dyno tests driving cycles comprising actual vehicle speed and gradient over time had to be elaborated. As the VECTO cycles are defined as target speed over distance, the actual speed pattern simulated in VECTO significantly depends on the vehicle specifications (vehicle mass, engine rating and powertrain characteristics). To reproduce this driving behavior on the chassis dyno, each combination of vehicle configuration and VECTO cycle was simulated in VECTO and the actual speed and gradient pattern over time was exported to the chassis dyno[30]. Simulations with VECTO have also been used to pre-process the GEM 55mph with grade cycle to consider the vehicle limitations in maintaining the 55mph speed in uphill driving. Before start of the measurement program, the drivability of the generated cycles and the predicated full-load performance was checked for each vehicle on the dyno.

For the VECTO regional delivery cycle a shortened cycle version was elaborated for chassis dyno testing. The original version has a driving time of approx. 1h 40min, which exceeds the limitations of continuous measurement time on the FVT chassis dyno. Target of the shortening exercise was to generate a cycle with a duration of approximately 1 h which results in a fuel consumption similar to the original cycle in a general way (i.e. for a broad range of vehicle configurations). For the shortening various combinations of different subparts of the full VECTO RD cycle (one extracted from the low speed part at the beginning of the cycle, one extracted from the high speed part from km 28 to km 97) have been analyzed. Sub-parts have been extracted starting with different time stamps and also with variation in length. The shortened cycle for the chassis dyno tests was selected by the criteria to have a start to end altitude difference of less than 1 m and to have simulated fuel consumption (in g/h) as close as possible to the original cycle. In the VECTO simulations the fuel consumption of the final selected cycle matches with the values from the original cycle by +/-1% for the three vehicle configurations analyzed in this study and by +/-1.5% for a broader range of vehicle analyzed for the purpose to validate the shortening exercise. Figure 3 shows the VECTO regional delivery cycle and the extracted parts for the shortened version.

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[30] The HDV chassis dyno control can actually only handle driving cycles in the actual speed over time format.

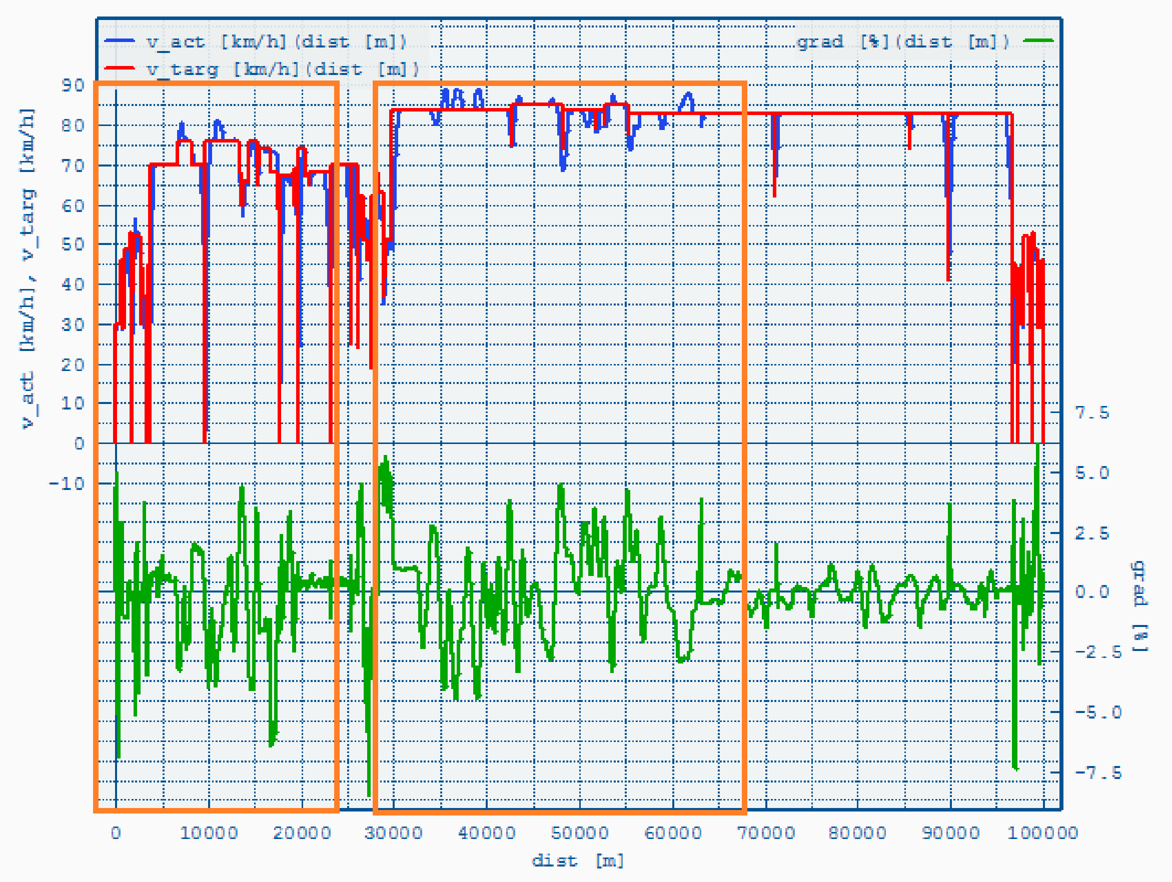

Figure 3: Parts of the VECTO regional delivery cycle extracted for chassis dyno testing in orange (v_targ: target speed, v_act: actual vehicle speed, grad: gradient)

During the project planning phase it was discussed whether the gear shift points simulated by VECTO shall be applied during the chassis dyno tests or if the vehicle shall be run in automated gear mode. In the end it was decided to go for the latter option due to the following reasons:

- The drivability of the VECTO gears during the chassis dyno tests is uncertain as the driver might be overburdened and the vehicle control might overrule the manual shifts.
- The current VECTO AMT gear shift strategy is discussed to be updated in 2018 as the gear selection in low speed driving has obvious shortcomings.

6. Task 2C: Chassis dynamometer measurements

This chapter describes measurement systems and test procedures as applied during the chassis dyno tests at FVT.

6.1. Measurement systems

Table 7 gives the specifications of the HD chassis dynamometer at the FVT test facilities. The test stand is fully capable to simulate any steady state or transient driving conditions of the vehicles analyzed in this study.

Table 7: Specifications HD chassis dynamometer at FVT

Make	AVL ZÖLLNER
Test bed type	Twin roller layout for single driven axle vehicle
Roller diameter	0.5 m
Maximum speed	120 km/h
Simulated vehicle mass	3.5 to 40 t
Brake	Thyristor controlled DC machine, 4 quadrant operation
Maximum traction force	22 kN
Maximum DC braking power	300 kW

The applied measurement systems and evaluated measurement quantities are listed in Table 8. Wheel force conditions were recorded via the chassis dyno and additionally via rim torque meters as provided by Kistler. Fuel flow was measured via AVL KMA mobile device installed in the low pressure fuel system of the vehicle. Tailpipe emissions (components CO2, NOx, NO, HC, PM and PN) have been measured by the standard CVS measurement equipment of the FVT chassis dyno. Additional measurement systems have been used to further analyze fuel efficiency relevant quantities (battery voltage and current, engine cooling fan speed) and to further analyze the pollutant emission behavior (NOx engine out concentrations, exhaust mass flow, exhaust gas temperature). Additional signals were available via connection with the vehicles' CAN bus (engine speed, engine torque, fuel consumption, current gear etc.).

Table 8: Measurement systems and quantities

Measurement system / data source	Measurement quantities
Chassis dyno	Traction force, Vehicle speed
Kistler RoaDyn® P1HT torque measurement rims for HD applications	Wheel torque
AVL KMA Mobile	Fuel mass flow
Full flow CVS system (modal emissions and bag values) Exhaust gas analysis AVL CEB II PES PM Filter Sampling System	Tailpipe emissions CO2, NOx, NO, HC, PM

Measurement system / data source	Measurement quantities
PMP VPR Dilution System + TSI CPC 3790	Tailpipe emissions PN
Sensors Semtech DS + Sensors Exhaust mass Flow Meter	Tailpipe emissions CO2, NOx, NO, CO Exhaust mass flow
Continental Smart NOx Sensor 24V UniNOx Generation 2.8; Measurement range: 0 – 1500 ppm	NOx engine out concentration
FLUKE i410 current probe	Battery current, battery voltage
Braun optical sensor	Engine cooling fan speed
Type K thermocouple	Exhaust gas temperature tailpipe
CAN bus connection via VECTOR CANalyzer	All vehicles: engine speed, engine torque, fuel consumption, current gear, tachograph vehicle speed, cardan shaft speed Additionally at rigid truck: Air mass flow, external EGR rate, accelerator pedal position

At the rigid truck additionally EGR rates have been measured (via CO_2 concentration measurement in the engine inlet) and the pulse-width modulation signal of the urea injector was recorded.

6.2. Test procedures

Special focus in the project was given to provide highest standards in the determination of fuel consumption results comparable to the values from the EU and US CO2 certification and to achieve best possible inter-comparability of test results between the three vehicles. For this purpose in-depth analysis of the achieveable accuracies when evaluating fuel consumption and efficencies by chassis dyno tests have been performed in this study. The applied procedures and the results from this analysis performed are described in this section.

6.2.1. Calibration of the chassis dyno

The chassis dynamometer was calibrated for all three vehicles according to an identical test protocol. The standard calibration procedure was extended by measuring the wheel torques during the “loss run”-procedure, which allowed for correction of the vehicles’ driveline losses on the calibration results. This correction is an important element to achieve that the applied resistance forces from the rollers to the wheels do exactly match with the nominal resistance parameters as set in the chassis dyno control.[31]

Figure 4 displays the losses as determined in six repetitions of the chassis dyno calibration procedure performed for tractor #2. Although similar boundary conditions for all repetitions were provided (tires, axle load, fully warmed up vehicle and driveline), the losses determined differ by some 75 N. This range of uncertainty was observed also in previous projects and is assumed to be related to slow temperature effects (tires, vehicle driveline, testbed) which cannot be fully controlled by a predefined and practicable preconditioning procedure and the accuracy of applied measurement systems (chassis dyno load cell, torque measurement rims). This 75 N uncertainty is also carried forward to the applied road load forces during measurement of driving cycles. The resulting range of uncertainty was analyzed to be some 1% fuel consumption in the VECTO LH cycle and 1.5% FC in the VECTO RD cycle.

Further uncertainties on applied road loads during chassis dyno measurements, which may result from tire temperature and wheel slip conditions different to the loss run procedure, cannot be quantified. It is assumed that such effects do not significantly lower the inter-comparability of test results.

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[31] Important part of the calibration of a chassis dynamometer is to determine the internal losses of the roller mechanics as well as the losses between rollers and tires (i.e. the rolling resistance of the driven tires on the test bed). These losses have to be subtracted from the road load to be applied from the chassis dyno brake. At the TUG chassis dyno a loss run procedure similar to the method applied for passenger cars and LDV is applied, where the idling vehicle mounted on the rollers is accelerated and decelerated by the rollers. In this procedure the determined losses do not only include the rolling resistance between rollers and tires but also the idling losses of the vehicle driveline.

Driving resistance parameters derived from conventional coast down tests as implemented in the European LDV regulations also include driveline idling drag. If these values are applied to a chassis dyno parameterized with the loss run procedure, these effects are cancelled out resulting in a road load which refers to real world conditions.

However, in case of the actual study, the road load parameters have been calculated from separate figures for air resistance and rolling resistance and do not include any driveline loss contribution. Therefore, the chassis dyno parameterization from the loss run procedure has to be corrected for the driveline losses in oder to obtain correct road loads during the measurements.

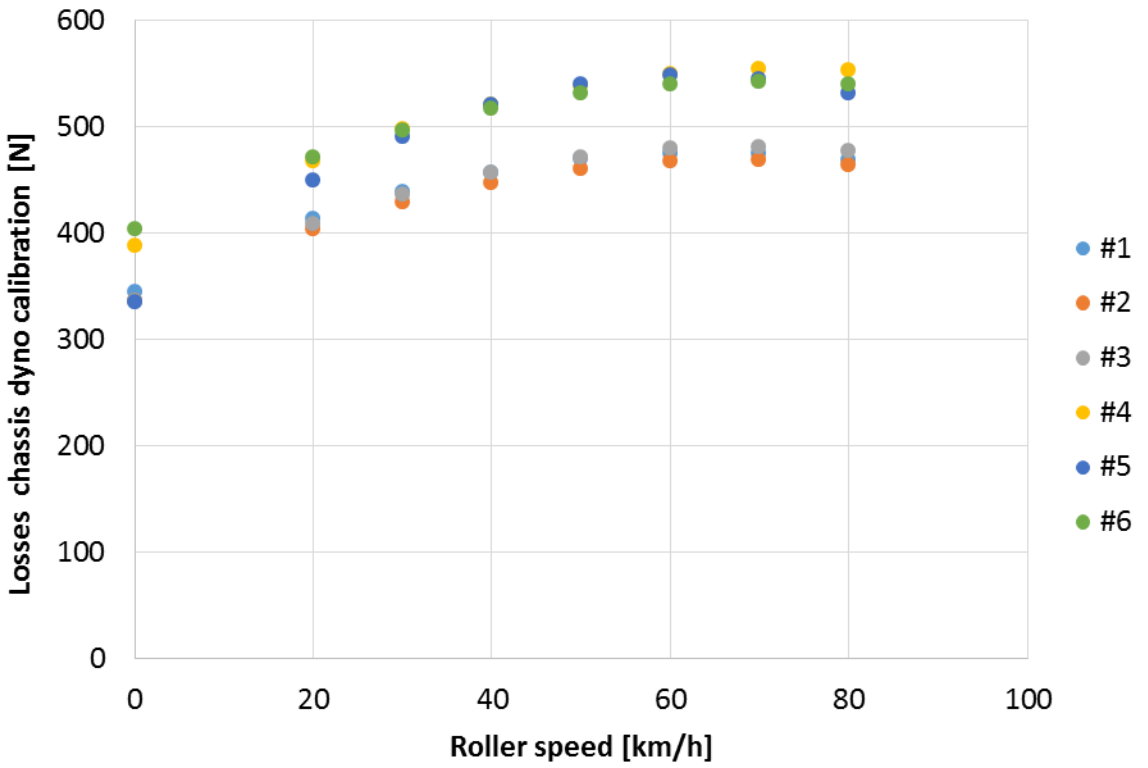

Figure 4: Losses as determined in six repetitions of the chassis dyno calibration for tractor #2

6.2.2. Measurement of wheel torques

To allow for an independent check of the road loads applied by the chassis dynamometer, wheel torques have been measured by the Kistler RoaDyn® P1HT torque measurement rims. In a measurement application this device is a “black box” system as it cannot be calibrated on-site. Important element of a proper application of torque measurement devices - especially in case of piezo-effect based systems - is the consideration of torque meter drift. This was done by zeroing the devices before start of measurement (when the vehicle is lifted and the wheels are free rotational) and recording of torque meter readings at the end of the tests (again with free rotational wheels). The Kistler system is known to have low drift levels in steady state conditions (e.g. for a valid air drag result from the constant speed test there is a provision for the drift to be less than +/-25 Nm per wheel). Much higher drift levels have been observed in transient cycles and especially in combination with high systems temperatures occuring during chassis dyno tests. For the chassis dyno tests performed in this study typical drift values per rim were from values close to zero to levels of approx. +/-100 Nm over a period of 2 to 3 hours. It is assumed that the significantly higher drift levels compared to steady state testing is mainly caused by the heat released by the vehicle brakes during transient vehicle operation.

In the post processing it was assumed that the torque meter drift evolves linear over testing time. The measured torque values have been corrected accordingly. The resulting uncertainty from this assumption has been evaluated to be up to 3% on the total result for wheel work in a typical driving cycle[32].

6.2.3. Quality checks for applied road loads on the chassis dyno

Before start of actual measurements for each chassis dyno setting constant speed tests at 50 km/h and 85 km/h have been performed and the measured wheel torques have been compared with the target values calculated from road load settings and vehicle speed. In case the observed deviations were higher than +/-3% a recalibration of the chassis dyno was performed.

In the post-processing of measurement results the deviations between integrated positive wheel work determined by the rim torque meters (TM) and the chassis dyno (CD) have been analyzed. The wheel power was determined for the TM data using the wheel rotational speed calculated from CAN data. Slightly higher wheel work numbers determined via TM are reasonable as the CD cannot detect power losses from wheel slip (ca. 1% influence). The analysis is shown in Table 9. For the rigid truck the deviations between TM and CD were found in the range from -0.8% to +4.1% in single tests and at +1.2% on average. For tractor #1 a clear tendency to higher wheel work derived from TM was found (average deviation: +3.4%, single values from +0.9% to +7.3%). During the tests with tractor #2 one measurement rim failed, hence TM values are only available for the VECTO RD and the GEM ARB transient cycle. During these tests the TM values were very close to the CD numbers (average deviation: +0.6%, single values from -1.2% to +3.9%).

Looking at the deviations between wheel work from TM and CD for tractor #1 the question arises whether too high road loads have been applied by the chassis dyno for this vehicle, which would cause a slightly biased ranking compared to the other vehicles analyzed in this study. This question cannot be clearly answered based on the available data. There are indications that road loads applied by the chassis dyno in the cycles VECTO LH, RD and GEM ARB transient might be some 2 to 3% too high.[33] This would result in some 2% fuel consumption disadvantage for tractor #1 in these cycles. Deviations between TM and CD exceeding the 2% to 3% levels as observed for the VECTO RD and the GEM ARB transient cycles are estimated to be allocated rather to uncertainties with the TM systems than with problems of the chassis dyno calibration.[34] As a main conclusion of this analysis it can be stated, that some 2 to 3% in fuel consumption levels seem to be an inherent uncertainty of chassis dyno tests when comparing different vehicles measured in different test series.

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[32] Underlying assumption for the uncertainty analysis is that the drift event appears instantaneously at the beginning or the end of the measurement compared to a linear increase over time. Drift effects which change signs during a test would result in higher uncertainties.

A similar range for uncertainty of wheel work measurement in transient driving cycle was also reported by ACEA.

[33] These indications are a comparison of TM with CD data for steady state measurements as well as a recalculation of fuel consumption recorded during the air drag tests, where a better agreement is achieved if the specific fuel consumption from the chassis dyno steady state test using TM work is used compared to using work from the CD.

[34] These tests had the highest TM drift levels.

Table 9: Integrated positive wheel work from torque meters (TM) versus chassis dyno (CD)

Driving cycle and measurement number		Rigid truck			Tractor #1			Tractor #2		
		CD	TM	Deviation TM vs. CD	CD	TM	Deviation TM vs. CD	CD	TM	Deviation TM vs. CD
		[kWh]	[kWh]	[-]	[kWh]	[kWh]	[-]	[kWh]	[kWh]	[-]
VECTO Long haul	#1	113.9	114.4	**0.4%**	117.7	121.4	**3.1%**	121.4	n.a.	n.a.
	#2	114.6	113.6	**-0.8%**	118.1	121.9	**3.2%**	122.3	n.a.	n.a.
	#3	114.2	114.9	**0.6%**	118.3	121.3	**2.6%**	121.7	n.a.	n.a.
	#4	---	---	**---**	118.6	121.3	**2.3%**	---	---	---
VECTO Regional delivery	#1	47.6	48.0	**0.7%**	75.5	79.3	**5.1%**	79.0	79.2	**0.3%**
	#2	47.2	48.2	**2.1%**	75.5	78.4	**3.8%**	79.1	78.1	**-1.2%**
	#3	47.1	47.4	**0.7%**	75.2	78.5	**4.4%**	78.1	77.2	**-1.1%**
GEM ARB trans.	#1	4.5	4.5	**0.9%**	7.9	8.5	**7.3%**	8.2	8.3	**1.2%**
	#2	4.6	4.6	**0.3%**	7.9	8.4	**6.9%**	8.3	8.6	**3.9%**
GEM 55mph	#1	17.5	18.3	**4.1%**	24.4	24.9	**2.3%**	26.0	n.a.	n.a.
	#2	17.6	18.0	**2.6%**	24.4	24.8	**1.8%**	25.9	n.a.	n.a.
FLAT 55mph	#1	17.1	17.0	**-0.3%**	21.4	21.7	**1.2%**	22.7	n.a.	n.a.
	#2	16.7	17.3	**3.4%**	21.4	21.6	**0.9%**	22.7	n.a.	n.a.
Average deviation				**1.2%**			**3.4%**			**0.6%**

6.2.4. Execution of transient chassis dyno measurements

The chassis dyno measurements have been executed under the following boundary conditions:

Vehicle warm up:

Before the first measurement of the day chassis dyno and vehicle have been warmed up with a VECTO regional delivery cycle (duration 1 hour).

Preconditioning:

Each driving cycle was preconditioned by driving 10 minutes at 85 km/h.

External cooling fan:

An external cooling fan was applied to provide sufficient air stream for engine cooling. The fan was operated at 80 km/h air speed.

Test cell temperatures:

For the FVT HD chassis dyno there is no conditioning system for test cell temperature available. During the measurements the test cell temperature at the FVT chassis dyno was in a range of 25°C to 35°C.

Number of test repetitions:

The VECTO cycles have been measured three times, the GEM cycles two times.

6.2.5. Execution of steady state chassis dyno measurements

A 6x6 grid of steady state points was measured on the chassis dyno for each vehicle. Goal was to reproduce the engine mapping cycle from the European HDV CO2 regulation as good as possible under the given resources.[35] The measurements have been executed as follows:

- Definition of set points:
  - Engine speeds have been defined equally distributed up to engine rated speed (e.g. from 800 rpm to 1800 rpm in 200 rpm steps for the two tractors).
  - Engine loads have been defined with 0% load (motoring) to 100% load (full-load) in 20% steps.
  - The holding period for each steady state point was defined by minimum 90s starting after speed and torque have reached stable conditions.
- Operation on the chassis dyno:
  - The measurement sequence was defined by measuring all load points at a single engine speed starting with 100% load and followed by the next lower load point. Engine speeds were run in the sequence from high to low speeds.
  - Engine speed has been controlled via “constant vehicle speed mode” on the chassis dyno.
  - The vehicle was operated in the highest gear possible to be operated at the given engine speed on the chassis dyno.
  - Engine load has been set via throttle pedal operated by fixable lever. Load points were defined by traction force readings for motoring and fulload conditions at each engine speed and according scaling to the single load percentages.

Boundary conditions for vehicle warm up, preconditioning, external cooling fan and test cell temperatures were similar than for the transient tests. Steady state measurements have been measured only once for each vehicle.

6.3. Data evaluation

In the data evaluation the following steps have been performed:

1. Standard evaluation procedure for calculation of emission masses for CVS system (modal and bag values) and SEMTECH system
2. Consolidation of all measurement data into a single data file
3. Time alignment of modal emissions from CVS and SEMTECH to other signals
4. Correction of torque measured by the rim torque meters for measurement drift

   As already mentioned in the previous section, this has been done by subtracting the measurement drift by assuming that it evolves linear over measurement time from 0 Nm at zeroing to the reading at the drift check after the measurement.
5. Correction of fuel mass for deviations of actual driven cycle from target driving cycle

   As the target driving cycle cannot be exactly followed in a chassis dyno test, the test result for fuel consumption (and subsequent for CO2 emissions) was corrected for

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[35] The original engine mapping cycle from the European HDV CO2 regulation contains measurement of in total approximately 150 operation points at 10 engine speeds.

the deviations between actual driven cycle from target driving cycle according to equations (1) to (3).

$P_{wheel,i} = (R_0 + R_1 \cdot v + R_2 \cdot v^2) \cdot v + m \cdot g \cdot \sin(\propto) \cdot v + (m + m_{rot}) \cdot a \cdot v$	Eq. (1)
$W_{wheel,pos} = \frac{1}{3.6 \cdot 10^6} \cdot \sum_{i=1}^{n} \max(0, P_{wheel,i}) \cdot \Delta t$	Eq. (2)
$\Delta FC_{cycle} = k_{veline} \cdot (W_{wheel,pos\,TARGET} - W_{wheel,pos\,ACTUAL})$	Eq. (3)

Where:

$P_{wheel,i}$	[W]	Wheel power for time step “i” for vehicle operation point given by vehicle speed “v” and acceleration “a”
$W_{wheel,pos}$	[kWh]	Total positive wheel work calculated for the target cycle ($W_{wheel,pos\,TARGET}$) and for the actual cycle ($W_{wheel,pos\,ACTUAL}$) with Δt in [s]
ΔFC_{cycle}	[g]	Correction of fuel mass for deviations of actual driven cycle from target driving cycle
k_{veline}	[g/kWh]	grade of linear regression for fuel consumption (CAN) over engine power (CAN) in the measured cycle (example shown in Figure 5)

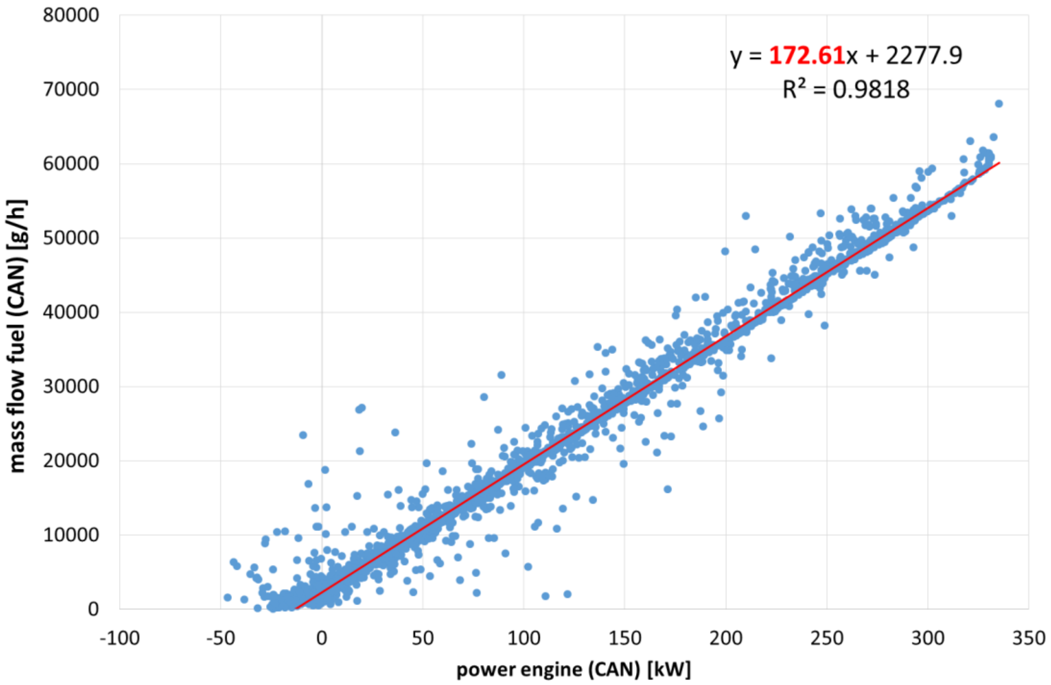

Figure 5: Example for determination of k_{veline} (172.61 g/kWh)

6. Correction of fuel mass for change of battery SOC over the test

   In order to correct the measured fuel consumption for the change of battery state of charge (SOC) over a test, the battery voltage and current have been measured and the change of SOC between beginning and end of cycle has been calculated according to Eq. (4).

$$W_{SOC}[kWh] = \frac{1}{3.6 \cdot 10^6} \cdot \sum_{i=1}^{n} U_{bat}[V] \cdot I_{charge}[A] \cdot \Delta t[s]$$

$$I_{charge} > 0\text{: alternator charges battery}$$

Eq. (4)

   The correction of fuel consumption has then been calculated assuming an alternator efficiency of 70% and using the $k_{willans}$ approach as applied in step 5 (Eq. 5).

$$\Delta FC_{SOC}[g] = -k_{veline}[\frac{g}{kWh}] \cdot \frac{W_{SOC}[kWh]}{0.7}$$

Eq. (5)

   With the corrections as described in 5. and 6., the repeatability in fuel consumption values between single repetitions of a test cycle was further increased.[36]

7. Calculation of volumetric fuel consumption, energy consumption and reference CO2 emissions using fuel analysis

   Based on the mass based fuel consumption as measured by the fuel flow meter and corrected according steps 5. and 6., the results for volumetric fuel consumption (liters), energy consumption (MJ) as well as for CO2 emissions (g) have been calculated. This approach is similar to the method as applied in VECTO. In the calculations the specific fuel properties as analyzed by ASG Analytik for each fuel batch used at the chassis dyno tests have been used. Fuel used was a commercial available diesel fuel according to EN590. Table 10 shows the properties as analyzed for the three batches and gives a comparison with the typical Diesel fuel as defined in VECTO. Lower heating values differ by max. 0.7% between the vehicles and by 0.3% between tractor #1 and tractor #2. The CO2 mass per MJ fuel differs by maximum 0.9%.

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[36] The influence of the correction for deviations of actual driven cycle from target driving cycle (5.) is in a range from -1.7% to +2.5% in fuel consumption with -0.1% on average.

The influence of the correction for change of battery SOC over the test (6.) is in a range of -0.1% to +0.2% in fuel consumption with +0.1% on average. The maximum observed change in battery SOC over a test was 0.088 kWh.

Table 10: Fuel specifications

	Rigid truck	**Tractor #1**	**Tractor #2**	**VECTO**
Density (kg/m³) @15°C	838.7	837.6	830.7	836.0
Lower heating value (MJ/kg)	42.47	42.64	42.78	42.70
Carbon content (%mass)	84.7	85.6	86.1	85.4
CO_2 density (g CO_2/MJ)	73.13	73.61	73.80	73.33
Hydrogen content (%mass)	13.6	13.6	13.8	not def.
Oxygen content (%mass)	0.7	0.5	<0.5	not def.

The CO2 results from the CVS bag measurement have been compared with the CO2 values calculated by the above mentioned method. Deviations in single tests are in a range from -0.8% to -3.5% with -1.9% as average over all tests (i.e. CVS bag values showing lower CO2 numbers). Differences are explained with the uncertainty of the measurement systems (CVS: analyzer, dilution air correction; KMA: fuel flow and density sensor) as well as in the uncertainty in the determined fuel carbon content. Reference values for discussion of results have been defined with the values as determined based on the fuel consumption measured by the fuel flow meter and calculated according to steps 5. to 7.

7. Results

The measurement results have been averaged for each combination of vehicle and cycle over all valid tests. Table 13 and Table 14 in the Annex of this report give the consolidated results of the measurements.

This chapter gives a detailed discussion of results for wheel work and average speeds, fuel consumption and CO2 emissions as well as pollutant emission behavior. Further analysis is provided for the comparison of fuel efficiency characteristics of tractor #1 and tractor #2 as these vehicles can be compared directly. The discussion focuses on results in the legislative driving cycles. Selected results from the steady state engine mapping are shown at the end of the chapter.

7.1. Wheel work and average speeds

Figure 6 shows the results for positive wheel work per driven kilometer. Values mainly depend on vehicle mass, vehicles' driving resistances and driving cycles. For the rigid truck the values (range 0.73 to 0.95 kWh/km) are significantly lower than for the tractors (range 1.00 to 1.79 kWh/km) which is primarily caused by lower payloads and a smaller trailer in the VECTO LH cycle. For the tractors the GEM ARB transient cycle is the driving pattern with the highest work demand due to the combination of high vehicle mass with highly transient driving. Positive wheel work values of tractor#1 and #2 can directly be compared due to similar boundary conditions. Tractor #2 has a higher wheel work demand compared to tractor #1 in a range of +2.0% (GEM ARB Transient cycle) to +3.9% (55mph flat) and approximately +2.5% in the VECTO cycles. This is caused by the higher vehicle curb mass (ca. +400 kg) and the higher C_dxA value (+6%) compared to tractor #1.

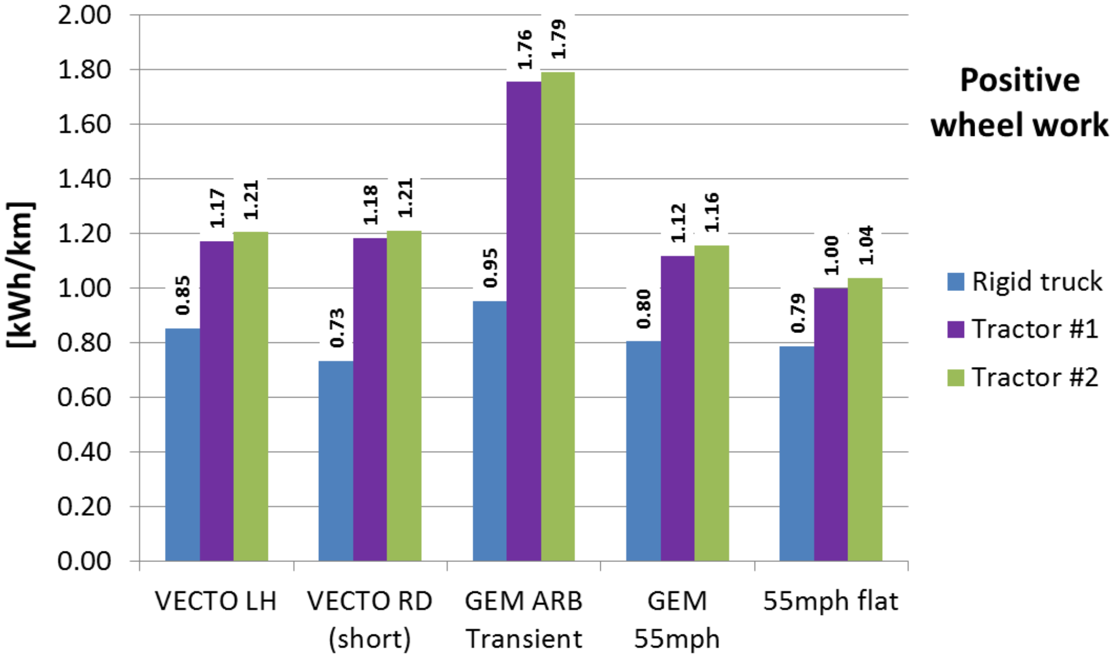

Figure 6: Results positive wheel work as calculated by VECTO

Figure 7 gives the results for average vehicle speeds. The tractors have some 3.5 km/h higher average speeds in the VECTO LH cycle caused by the higher specific motorization (tractors: 9.5kW rated power per ton vehicle mass, rigid: 6.5 kW rated power per ton vehicle mass). The results show that the motorization level in the rigid truck would hardly suitable for long-haul operation with an additional trailer because vehicle speed goes down close to 20 km/h during the uphill motorway part in the cycle. Average speeds in all other cycles are very close between the vehicles as also the specific vehicle motorization is nearly similar (ca. 11 kW/t for all vehicles).

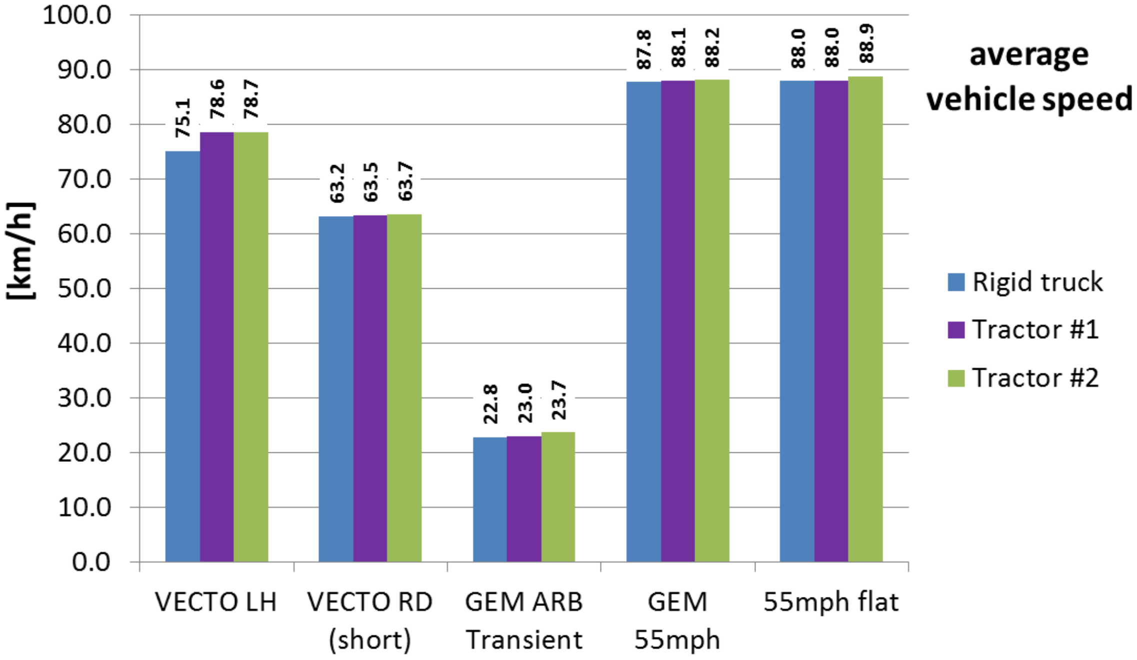

Figure 7: Results average vehicle speed

7.2. Fuel consumption and CO2 emissions

Figure 8 shows the results for fuel consumption in liters per 100 km. For the rigid truck the values are at 31.3 l/100km in the VECTO LH and at 21.6 l/100km in the VECTO RD cycle. Results for the GEM cycles are in a similar l/100km range. For the tractors the results are at 32.6 l/100km (tractor #1) and 29.9 l/100km (tractor #2) for the VECTO LH cycle and at 34.3 l/100km (tractor #1) and 31.6 l/100km (tractor #2) for the VECTO RD cycle. The highest fuel consumption numbers have been measured for the tractors in the GEM ARB transient cycle with 60.3 l/100km (tractor #1) and 56.4 l/100km (tractor #2). Fuel consumption figures determined for tractor #2 are some 6% to 8% lower than for tractor #1 despite the higher vehicle curb mass and the higher air drag. Obviously the efficiencies of engine, drivetrain and vehicle auxiliaries of tractor #2 are able to over-compensate mass and air drag disadvantage. This issue is analyzed in section 7.4 in more detail.

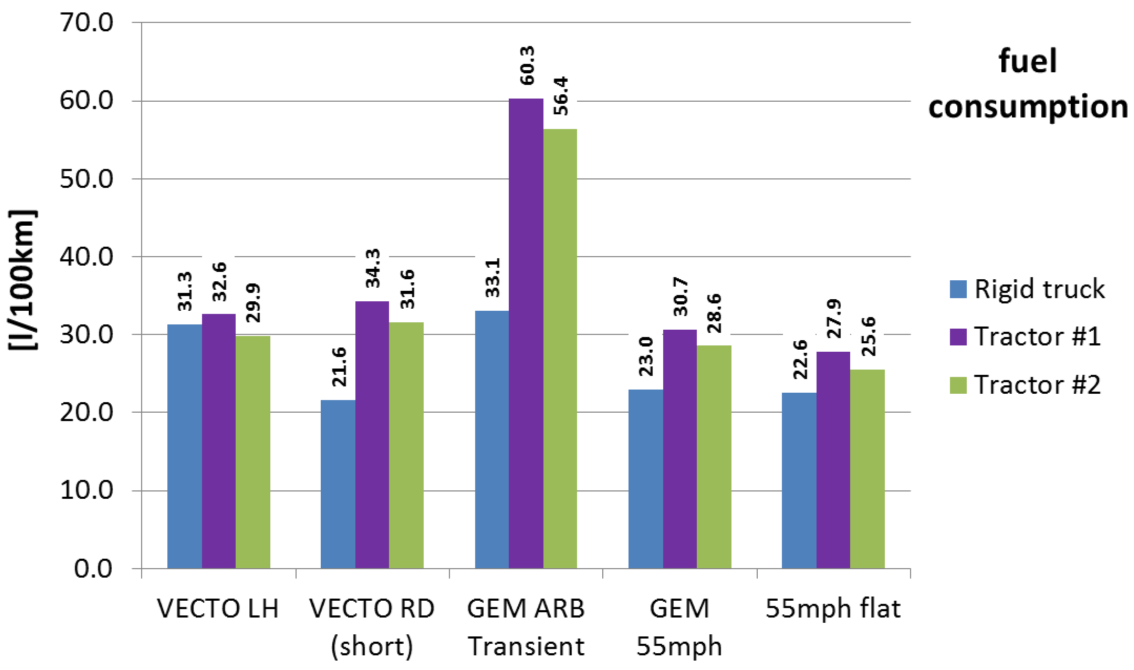

Figure 8: Results fuel consumption (liter per 100km)

In Figure 9 the results for CO2 emissions per ton-kilometer are shown. This unit is the common used metric for certification and limitation of CO2 emissions from HDV (e.g. g/ton-mile of US EPA GHG Phase 2). Results for the rigid are at 56.9 gCO2/t-km in the VECTO LH and at 125.2 gCO2/t-km in the VECTO RD cycle. Values for the GEM cycles are in between the figures for the VECTO cycles. Due to higher payload conditions the results for the tractors are at a much lower level with 43.5 gCO2/t-km (tractor #1) and 40.1 gCO2/t-km (tractor #2) in the VECTO LH cycle as well as 68.5 gCO2/t-km (tractor #1) and 63.4 gCO2/t-km (tractor #2) in the VECTO RD cycle. Relative differences of gCO2/t-km between the tractors are similar to the results for fuel consumption.

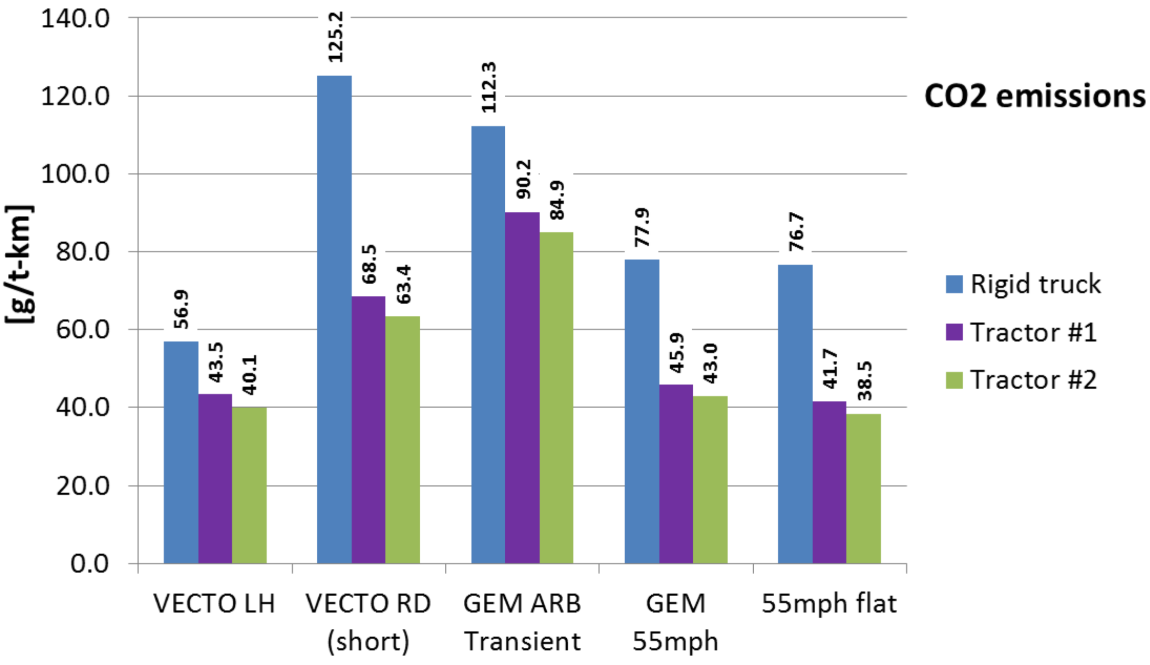

Figure 9: Results CO2 emissions per ton-kilometer

7.3. Analysis of potential differences compared to VECTO results

In an evaluation for possible differences of the above shown results for gCO2/t-km determined based on chassis dynamometer measurements to values determined based on the VECTO method (component testing and simulation) the following main causes for differences have been identified:

1) Ambient wind influence

As described in section 5.1 it was decided not to include the ambient wind influence as considered in VECTO into the road load parameterization on the chassis dynamometer. The influence of this circumstance on the results for fuel consumption and CO2 emissions was investigated by VECTO simulations (w/ and w/o ambient wind functions enabled) for the particular vehicle configurations of this study. For the rigid truck the influence was found to be at +6.5% in the LH cycle and at +3.0% in the RD cycle. The influence on the results for the tractors was calculated with +4.2% in the LH and +3.5% in the RD cycle (Table 11).

Table 11: Change of FC / CO2 due to VECTO ambient wind functions

VECTO Long haul		VECTO Regional delivery (shortened version)	
Rigid truck	Tractor #1 and #2	Rigid truck	Tractor #1 and #2
+6.5%	+4.2%	+3.0%	+3.5%

As this influence is systematic and can be quantified exactly, this effect has been incorporated into the CO2 results for the three vehicles in the VECTO cycles. The resulting values are shown in Figure 10 and can be seen as the reference values for the three vehicles analyzed in this study to the current VECTO method as foreseen in the European CO2 certification.

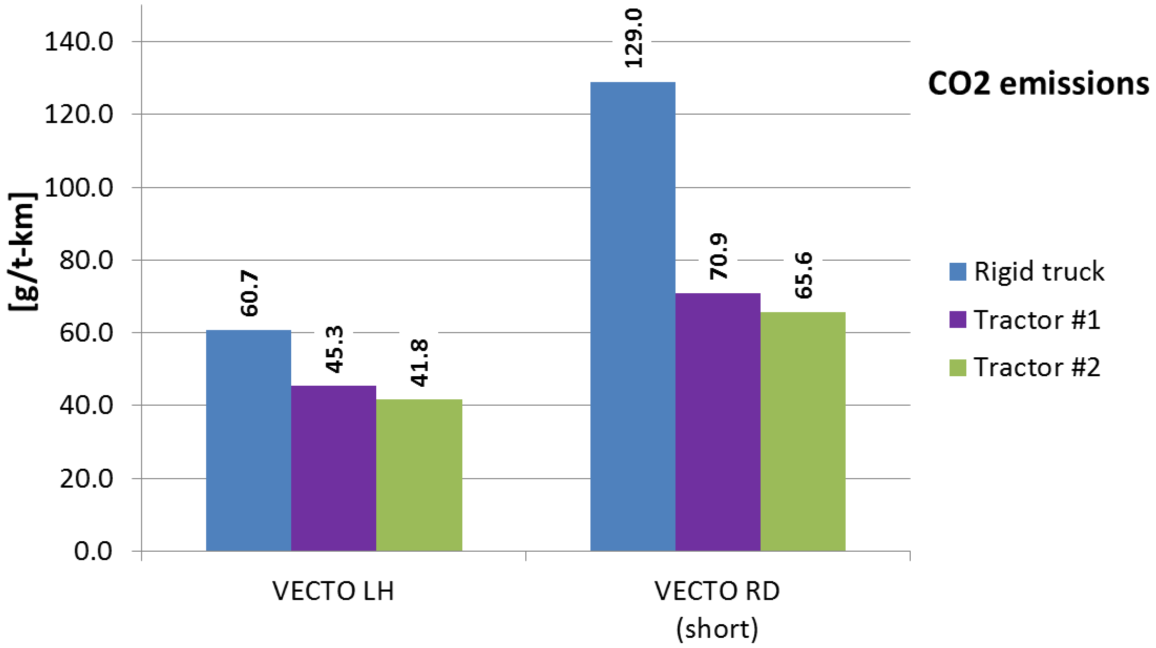

Figure 10: Results CO2 emissions per ton-kilometer (reference values to current VECTO method including ambient wind influence)

2) Gear shifts
   In the simulations for the official CO2 certification gear selection and hence engine speeds depend on the gear shift algorithms as implemented in VECTO and in GEM. As further explained in section 5.2 it was decided to operate the vehicles on the chassis dyno in automated AMT mode and not to use the predefined gears by the simulation models. The influence on the results cannot be quantified exactly but is identified to be of negligible influence for the VECTO LH and the GEM 55mph cycle due to vehicle speeds levels which results in highest gear driving in any case.

3) Modelling vs. Measurement
   Results from measurements certainly differ from simulation results. Therefore the CO2 numbers from measurements are not exactly reproducing the EU and US certification. For the VECTO method there is no evidence that this circumstance should result in a systematic bias in the absolute results from this study. Difference can occur in the ranking of vehicles, where certain technologies (e.g. auxiliary systems) show different influence on during a chassis dyno test than in VECTO. This was observed for the influence of the engine cooling fan, which was measured with significantly lower fan speeds at tractor #2 compared to tractor #1 and is hence assumed to contribute to the clear ranking between the vehicles based on the chassis dyno tests. In the VECTO method, both tractors have the similar nominal engine cooling fan technology (“belt driven or driven via transmission; electronically controlled visco clutch”) and hence would be simulated with similar mechanical power consumption from this auxiliary system.

Further influence factors (e.g. influence of semi-trailers used at air drag tests, run-in times differently to component certification tests, ambient conditions on the test bed) are considered to be of less importance.

7.4. Analysis of fuel efficiency figures

Based on the large amount of available measurement data further fuel efficiency figures have been analyzed. A key figure is the engine brake specific fuel consumption ($BSFC_{eng}$) expressed in grams fuel per kWh engine work. From the measurement setup at the chassis dyno the engine work cannot be directly measured. This quantity has been derived from engine torque and engine speed as broadcasted over CAN. Engine torque from CAN is known to have significantly lower accuracy as if measured on an engine dyno. From provisions in emission legislation, CAN engine torque is requested to have maximum 5% inaccuracy. Fuel mass is available both from the fuel flow meter and also broadcasted over CAN. For further analysis the $BSFC_{eng}$ values have been calculated by two methods:

a. Fuel mass flow from fuel meter, engine work from CAN
b. Fuel mass flow from CAN, engine work from CAN

The figures as determined by a. might be biased by inaccurate engine work. Method b. allows for an insight into the fuel efficiency data as implemented into the vehicles' ECUs. Figure 11 shows the results determined by the two methods. From the data the following conclusions have been drawn:

- ECU data (method b.) predict a $BSFC_{eng}$ in a range of 191 g/kWh to 200 g/kWh for the VECTO cycles and the 55 mph cycles with one outlier at 208 g/kWh for tractor#1 in the 55pmh flat cycle. For the highly transient and partly low engine load GEM ARB transient cycle the $BSFC_{eng}$ are higher reaching from 203 g/kWh for tractor#2 to 214 g/kWh for the rigid.
- If the BSFC is calculated using fuel mass measured by the fuel meter (method a.), values are on average some 4% higher than as determined by method b. The relative differences of the $BSFC_{eng}$ between the vehicles and the cycles are nearly independent of the method.
- On average over all cycles, tractor #2 is determined to have the lowest $BSFC_{eng}$ values with 203.1 g/kWh acc. method a. and 195.6 g/kWh acc. method b. The results for tractor #1 are at 211.4 g/kWh acc. method a. and 202.1 g/kWh acc. method b. This is some 3% to 4% higher than at tractor #2.
- $BSFC_{eng}$ numbers for the rigid are on average at 208.2 g/kWh acc. method a. and 199.0 g/kWh acc. method b. This is in between the $BSFC_{eng}$ results as determined for the two tractors. $BSFC_{eng}$ values between rigid and tractors cannot be directly compared due to different engine load patterns which are caused by different vehicle configurations and different engine sizes.

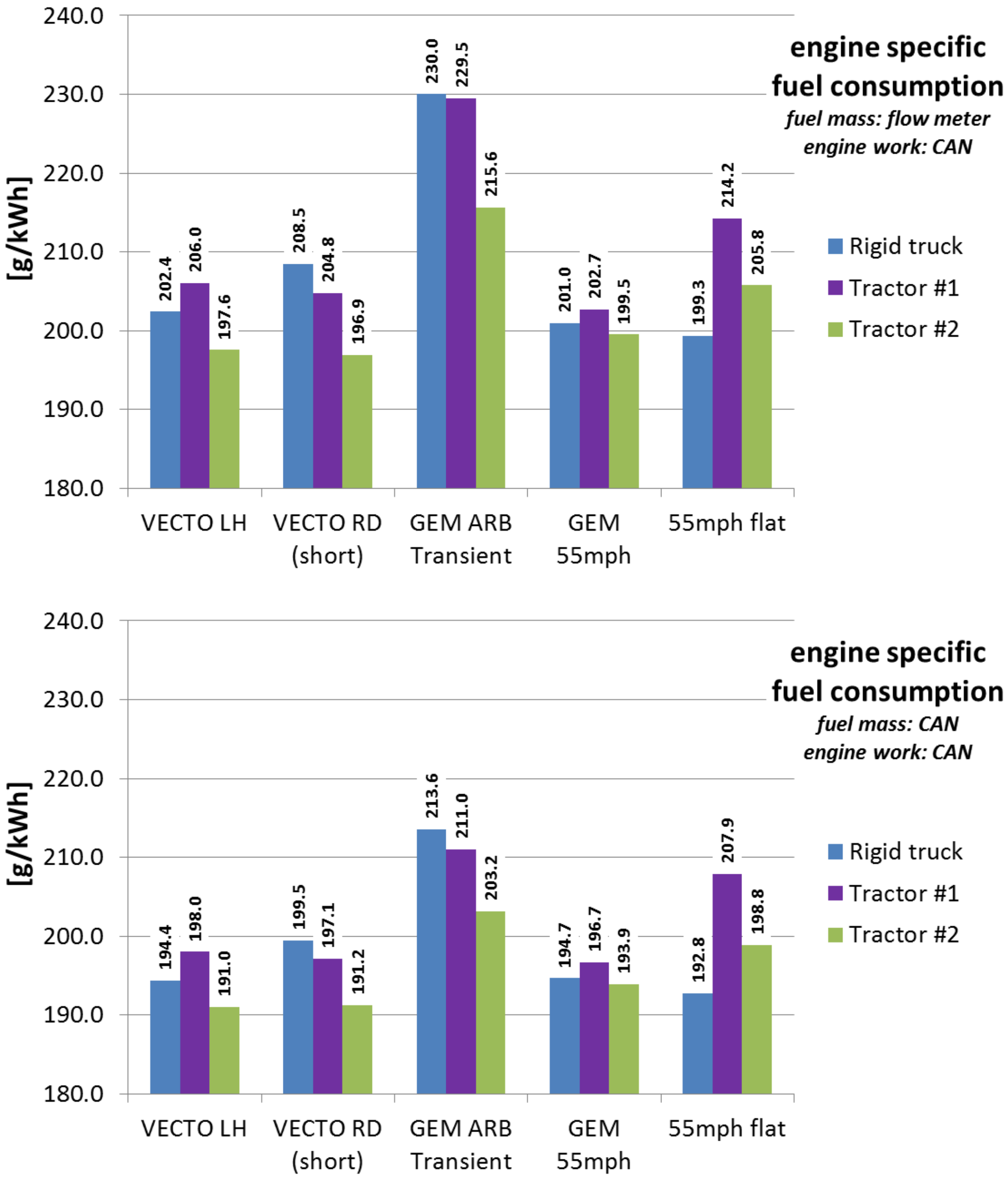

Figure 11: Results engine brake specific fuel consumption (BSFC$_{eng}$)

Figure 12 gives the results for wheel brake specific fuel consumption (BSFC$_{wheel}$). Compared to the engine work, work at the wheels does not include power demand from auxiliaries as well as losses in the drivetrain (transmission, retarder and axle). Work at wheels has also been determined by two methods:

i. Wheel torque from rim torque meters and wheel speed from CAN cardan shaft speed and axle ratio
ii. Traction force and vehicle speed from chassis dyno

Comparing average values for BSFC$_{wheel}$ over the cycles, results from the two methods match very well for the rigid truck and tractor #2 with an average deviation of approximately

1%.[37] For tractor #1 $BSFC_{wheel}$ differ on average by some 6% with the values based on method i. (rim torque meters) showing lower $BSFC_{wheel}$ numbers (i.e. higher efficiencies) than with method ii. (chassis dyno). This phenomenon was already analyzed in section 6.2.3. Based on the analysis discussed there it is assumed that for tractor #1 the average result of methods i. and ii. give a good estimation of $BSFC_{wheel}$ figures. Driving cycle with the highest powertrain efficiencies is the VECTO LH cycle with 225 g/kWh for the rigid, 224 g/kWh for tractor #1 and 202 g/kWh for tractor#2. Lowest powertrain efficiencies have been measured for the GEM ARB transient cycle with ca. 270 g/kWh both for the rigid truck and tractor #1 and with ca. 250 g/kWh for tractor #2.

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[37] Torque meters failed during the measurements with tractor #2, hence results from method i. are only available for cycles VECTO RD and GEM ARB transient.

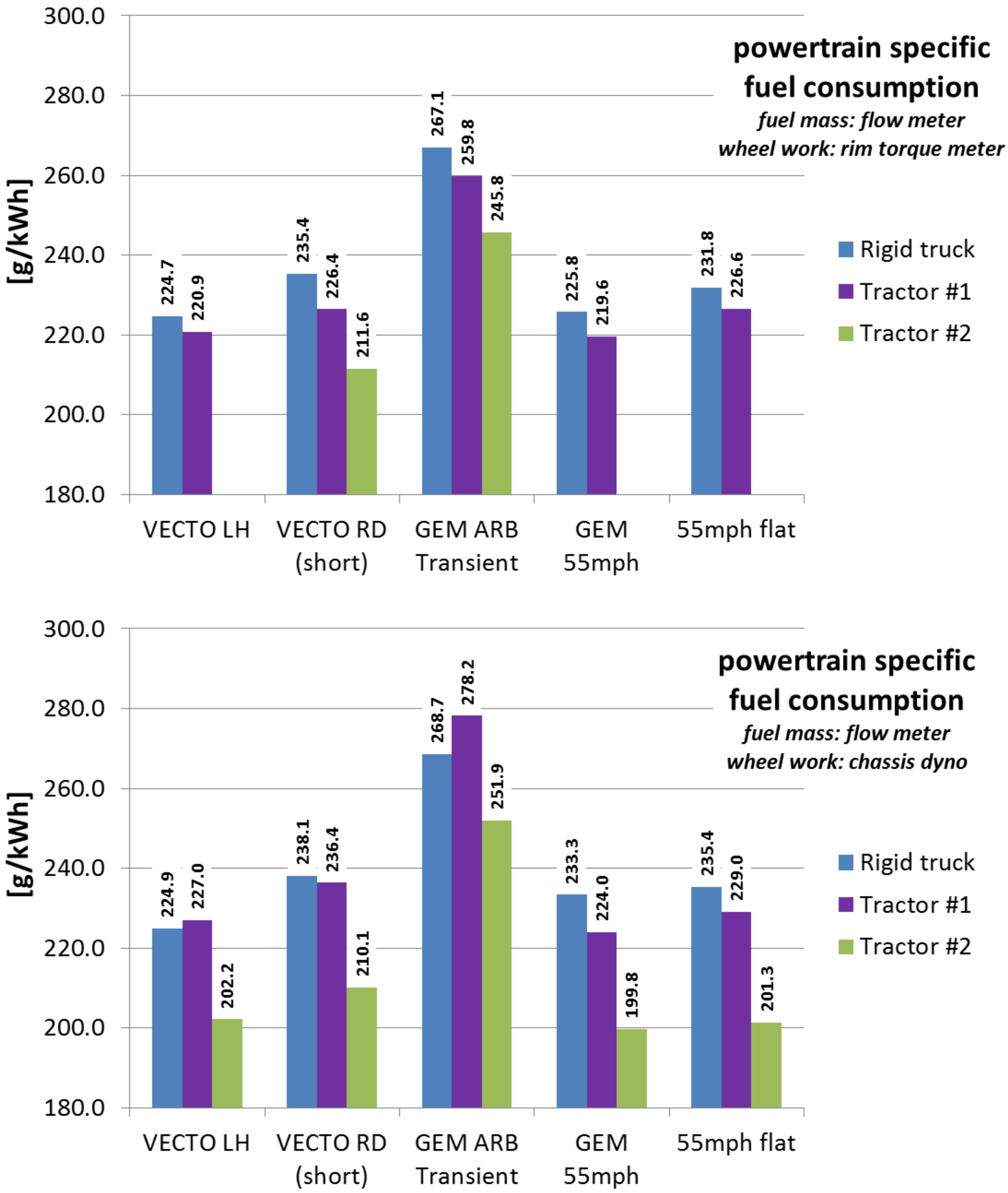

Figure 12: Results wheel brake specific fuel consumption (BSFC$_{wheel}$)

Based on these results an analysis was performed to differentiate power demand and energy efficiencies of different vehicle components. The analysis was performed for the VECTO RD cycle as measured on the chassis dynamometer. This cycle was chosen as it is the only VECTO cycle where data from the rim torque meter for tractor #2 are available. In the analysis the energy consumption of the main relevant vehicle components and the fuel consumption of the three vehicles have been calculated based on the following data and assumptions:

- Positive work at the wheels per distance (kWh/km) calculated by VECTO based on vehicle parameters and driving cycle

- Engine specific fuel consumption ($BSFC_{eng}$) values as measured on the chassis dyno (average values of methods a. and b. taken)
- Power demand from auxiliaries
    - Engine cooling fan: calculated from recorded fan speed and data on fan power consumption from [7]. Tractor #2 was measured with significantly lower fan speeds than the other vehicles.
    - Steering pump: Technology specific data from VECTO (100% of values taken as idling losses are the dominant source of steering pump power demand, hence power demand on chassis dyno is assumed to approx. match with VECTO figures for real world driving)
    - HVAC system: 50% of standard value from VECTO (A/C was off during measurements)
    - Pneumatic system: 75% of technology specific data from VECTO (air consumption from braking should be lower at the chassis dyno as fewer axles are operated)
    - Electric systems: 75% of standard value from VECTO (lights and consumers in the cabin were off during measurements)
- Average vehicle speeds and share of engine overrun conditions from VECTO
- Efficiency values for drivetrain (consisting of components transmission, retarder and axle) have been backward calculated to meet the measured $BSFC_{wheel}$ values (average values of methods i. and ii. taken).

The full calculation is shown in Table 12. From the backward calculation drivetrain efficiencies of 92.0% for the rigid, 90.8% for tractor #1 and 94.6% for tractor #2 have been derived. Power demand from auxiliaries is estimated to be 4.7kW for the rigid, 5.2kW for tractor #1 and 3.1kW for tractor #2. Numbers are only indicative as they are based on generic data for auxiliaries and the backward calculation of drivetrain efficiencies is highly sensitive to the accuracy of the measured $BSFC_{wheel}$ values.

Figure 13 gives a picture of the distance specific work demand of the main vehicle components and the resulting fuel consumption figures from this analysis. In the comparison of tractor #1 and tractor #2 the latter vehicle has a disadvantage related to work demand at wheels of 2.4% resulting form higher curb mass and higher air drag. Energy consumption from drivetrain losses and power demand from auxiliaries of tractor #2 is by some 40% lower as at tractor #1. This confirms the selection of tractor #2 to represent best available vehicle technology. The apportionment of energy savings at tractor #2 into improvements at drivetrain losses and at auxiliaries from the available data is uncertain. Total work demand at the engine is by 3.3% lower at tractor #2 compared to tractor #1. Combined with a 3.4% lower $BSFC_{eng}$ figure this gives a total advantage in fuel consumption of 6.6% for tractor #2 in this analysis. If the auxiliary consumption would be taken 1:1 from the technology dependent standard values in VECTO (w/o adaptations to measured fan speed and chassis dyno conditions) the fuel consumption advantage of tractor #2 would be at 5.5%.

Table 12: Analysis fuel efficiency figures for the VECTO RD cycle

		Rigid truck	Tractor #1	Tractor #2	Source	Tractor #2 vs. Tractor #1
Positive work per distance @ wheels	kWh/km	0.733	1.183	1.212	VECTO	2.4%
Efficiency drivetrain (transm., ret., axle)	-	92.0%	90.8%	94.6%	Backward calculated from BSFC total powertrain	---
Drivetrain losses (transm., ret., axle)	kWh/km	0.064	0.120	0.070	Calculated from figures above	-41.7%
Positive work per distance @ clutch	kWh/km	0.796	1.303	1.282	Calculated from figures above	-1.6%
Power demand engine cooling fan	kW	1.900	2.300	0.751	Calculated (measured fan speed and fan data [7])	-67.3%
Power demand steering pump	kW	0.570	0.670	0.503	100% of VECTO values	-25.0%
Power demand HVAC system	kW	0.100	0.100	0.100	50% of VECTO values	0.0%
Power demand pneumatic system	kW	1.050	1.050	0.638	75% of VECTO values	-39.3%
Power demand electric system	kW	1.071	1.071	1.071	75% of VECTO values	0.0%
Total power demand auxiliaries	kW	4.691	5.191	3.063	Calculated from figures above	-41.0%
Average speed	km/h	63.2	63.5	63.7	VECTO	---
Share overrun	-	27%	27%	27%	VECTO	---
Positive work per distance auxiliaries	kWh/km	0.054	0.060	0.035	Calculated from figures above	-41.2%
Positive work per distance @ engine	kWh/km	0.850	1.362	1.317	Calculated from figures above	-3.3%
BSFC engine	g/kWh eng	204.0	200.9	194.1	Measurement (average of two methods)	-3.4%
BSFC total powertrain (incl. aux)	g/kWh wheel	236.8	231.4	210.9	Measurement (average of two methods)	-8.9%
Fuel consumption	g/km	173.4	273.8	255.6	Calculated from BSFC engine x positive work per distance @ engine[38]	
Fuel consumption	lit/100km	20.7	32.7	30.6	Calculated from figures above (density diesel: 836 kg/m^3)	-6.6%

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[38] BSFC total powertrain x Positive work per distance @ wheels gives similar value.

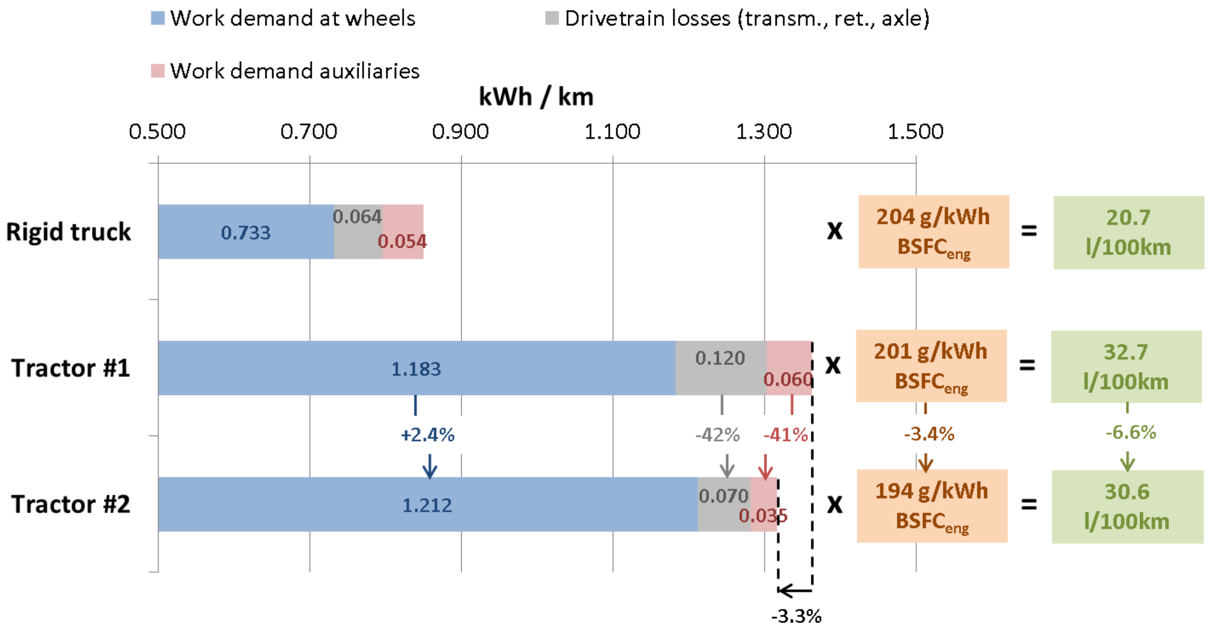

Figure 13: Analysis fuel efficiency figures for the VECTO regional delivery cycle

7.5. Pollutant emissions

This section gives a presentation of pollutant emission behavior as measured at the three EURO VI HDVs on the chassis dynamometer. The discussion of results is based on the unit g/kWh to be able to compare the results with the emission limits in the type approval test on the engine dynamometer (WHTC cycle) and with the emission limits in the In Service Conformity test (ISC) measured in real world driving with PEMS equipment. The comparison with limits is only indicative as the driving cycles measured in this study do not fulfill the boundary conditions for valid ISC tests. Results for vehicle emissions in g/km are included in Table 14 in the Annex.

Results for tailpipe NOx emissions as measured by the diluted CVS system are shown in Figure 14. Observed NOx levels are in the range from close to zero to 0.2 g/kWh and hence clearly below the EURO VI limit levels.

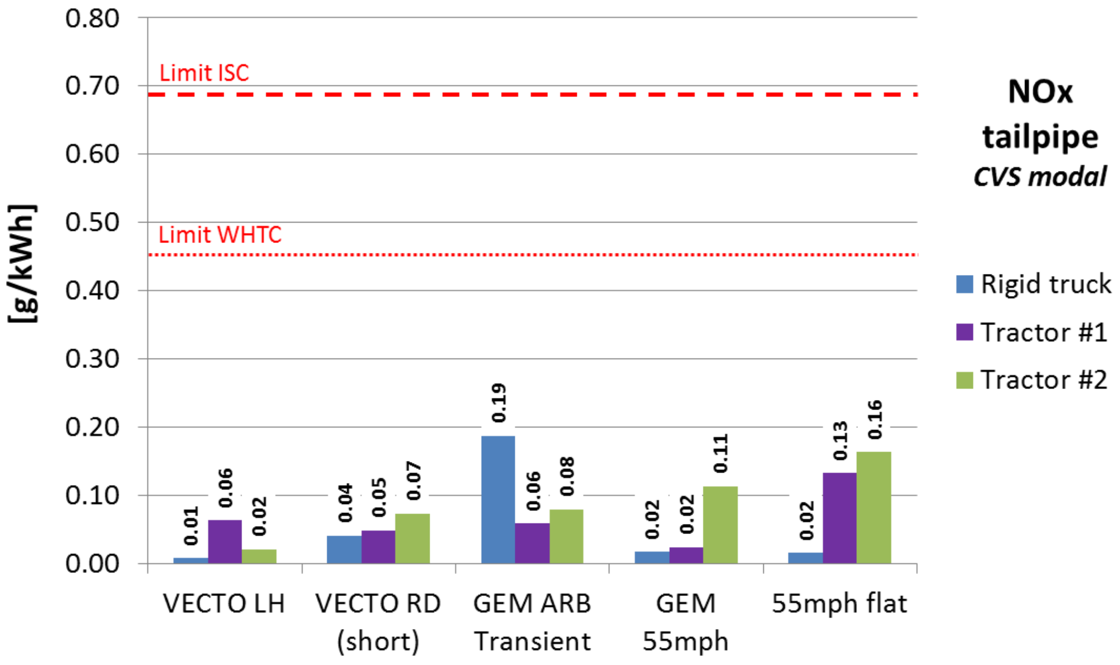

Figure 14: Results NOx tailpipe emissions (CVS modal)

Figure 15 shows the NOx engine out emission levels measured by a NOx sensor and the exhaust mass flow from the Semtech system. The rigid truck engine was measured with engine out NOx levels in the range of 8 g/kWh to 10 g/kWh. At this engine also the EGR rates have been measured. Average EGR rates were found at some 20% in the VECTO RD and the GEM ARB transient cycle and about 15% in the other cycles. This combination of rather high engine out NOx levels with the observed EGR rates has not been expected. However, as there is no known issue with the measurement equipment, there is no reason to doubt the results. For the tractors engine out NOx emissions were found at approx. 4 g/kWh for tractor #1 and at 6 g/kWh for tractor #2.

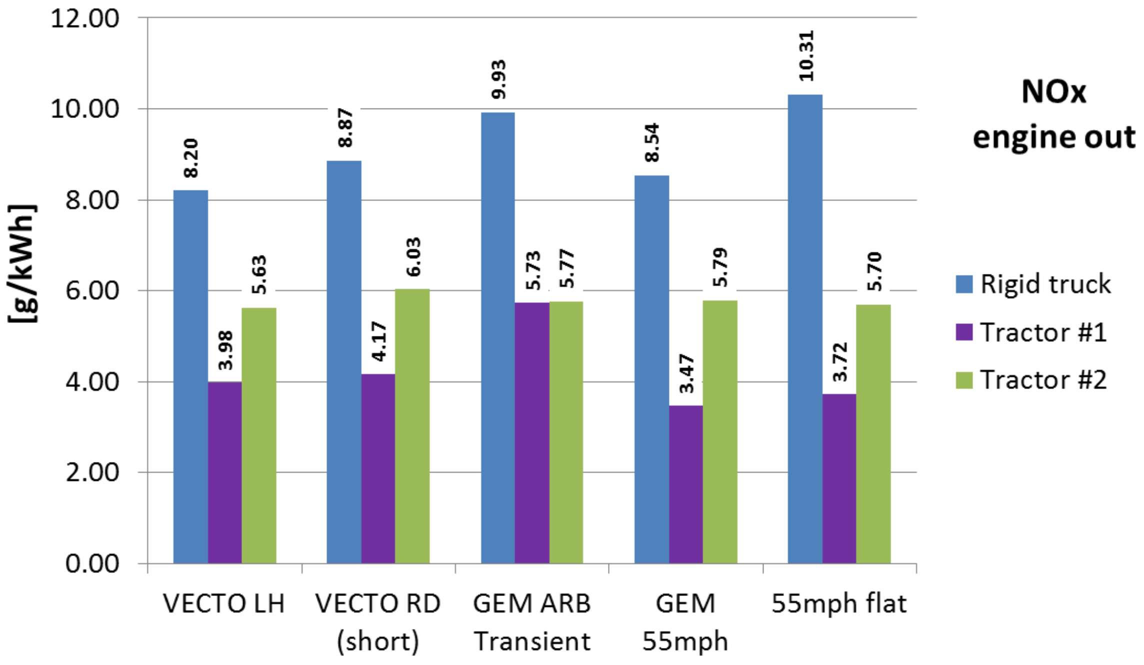

Figure 15: Results NOx engine out emissions

Figure 16 gives the cycle average NOx conversion rates ("DeNOx") in the SCR aftertreatment system as calculated from engine out NOx (undiluted measurement via NOx sensor as discussed above) and the tailpipe NOx emissions from diluted CVS measurement. DeNOx rates are in a range from 96.4% to close to 100%[39]. Tractor #1, which has a with 250.000 km a significantly higher mileage than the rigid (4.000 km) and tractor #2 (30.000 km), does not show any signs of deterioration in SCR efficiencies compared to the other two vehicles.

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[39] Calculated SCR efficiencies above 99% are only indicative due to the general limitations in accurately measuring tailipe emissions close to zero by diluted CVS.

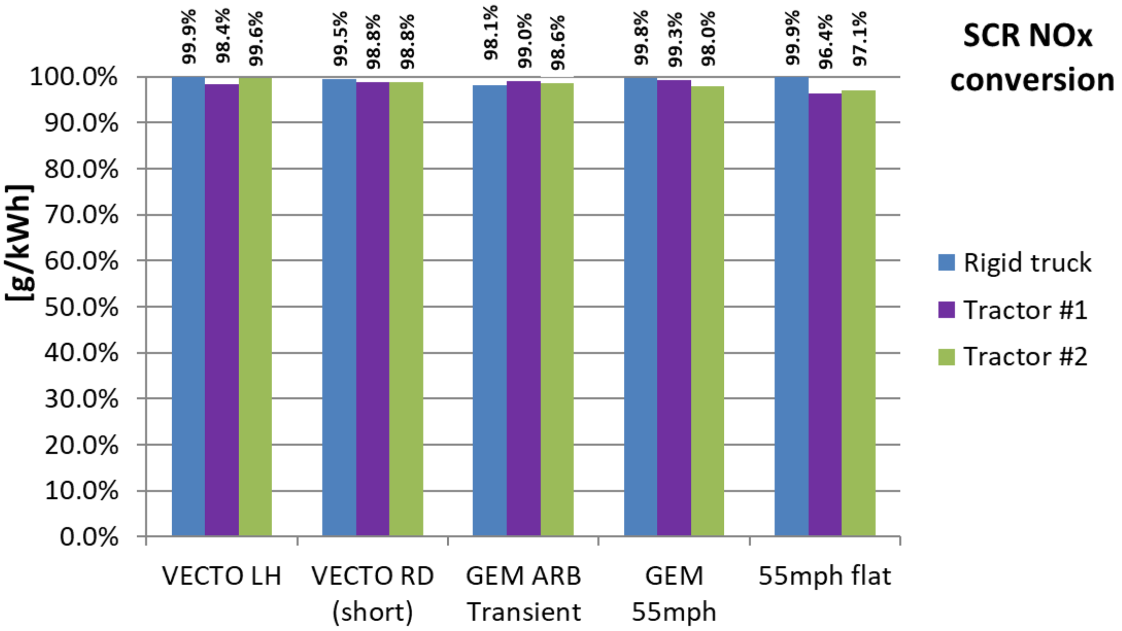

Figure 16: SCR NOx conversion rates

Figure 17 shows the results for particle mass (PM) emissions. In several tests the PM levels were below the detection limit of the CVS PM measurement system. All vehicles are clearly below the EURO VI limits as applicable for the WHTC.[40]

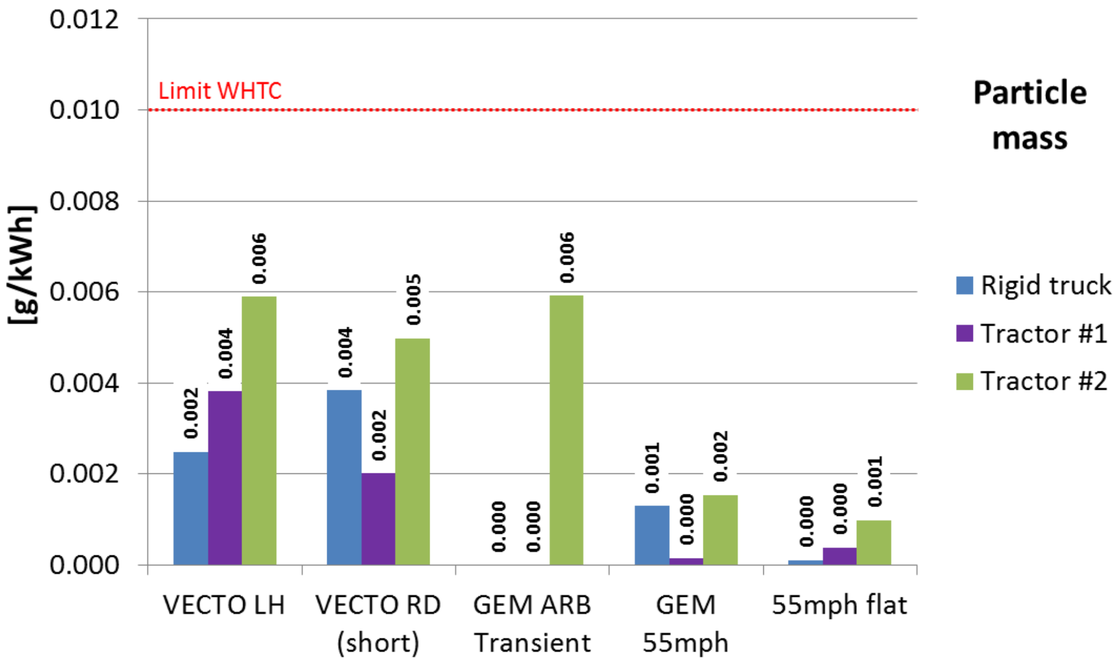

Figure 17: Results particle mass emissions

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[40] No ISC limit applicable for PM and PN as these pollutants are currently not measured in the on-board test.

The measurement results for particle number (PN) emissions are given in Figure 18. Except for the flat 55mph cycle measured with tractor #1 all PN emissions are below the EURO VI WHTC limit. Tractor #2 was measured with the lowest PN levels. The ranking for PN between the vehicles might not only be attributed to specific DPF technology but also to the current DPF soot load, as this factor influences the filtration efficiency significantly (filters with higher soot load have better filtration efficiencies than empty filters).

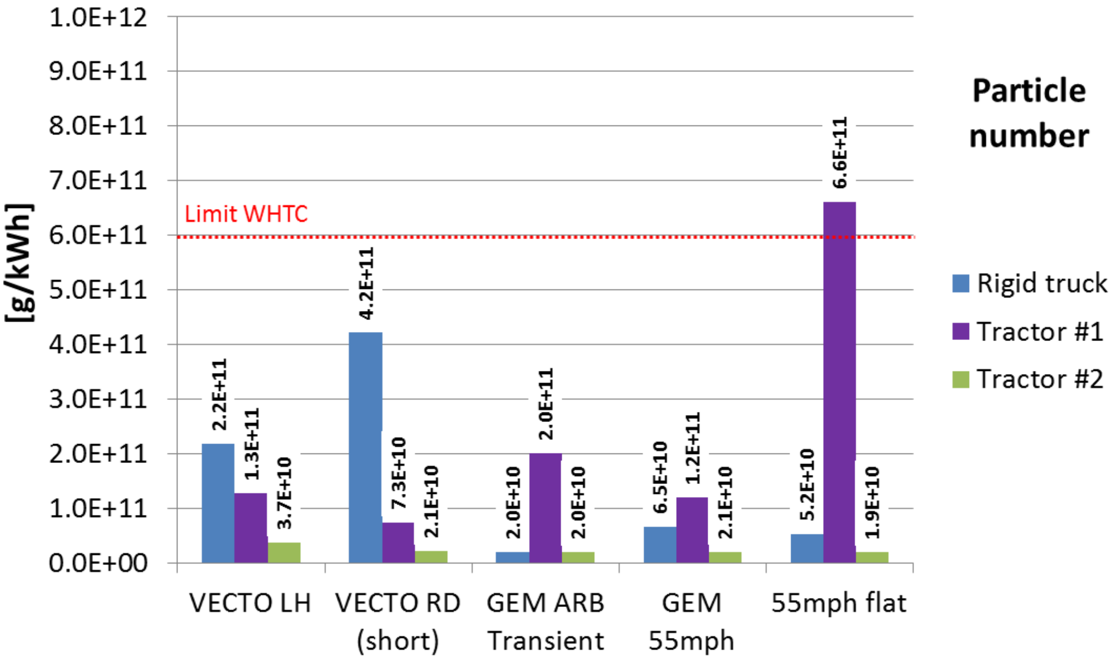

Figure 18: Results particle number emissions

Figure 19 and Figure 20 show the results for emissions of carbon monoxide (CO) and hydrocarbons (HC). Emission levels for both exhaust gas components are significantly below the EURO VI limits and especially for HC at the detection limits for the exhaust emission measurement systems.

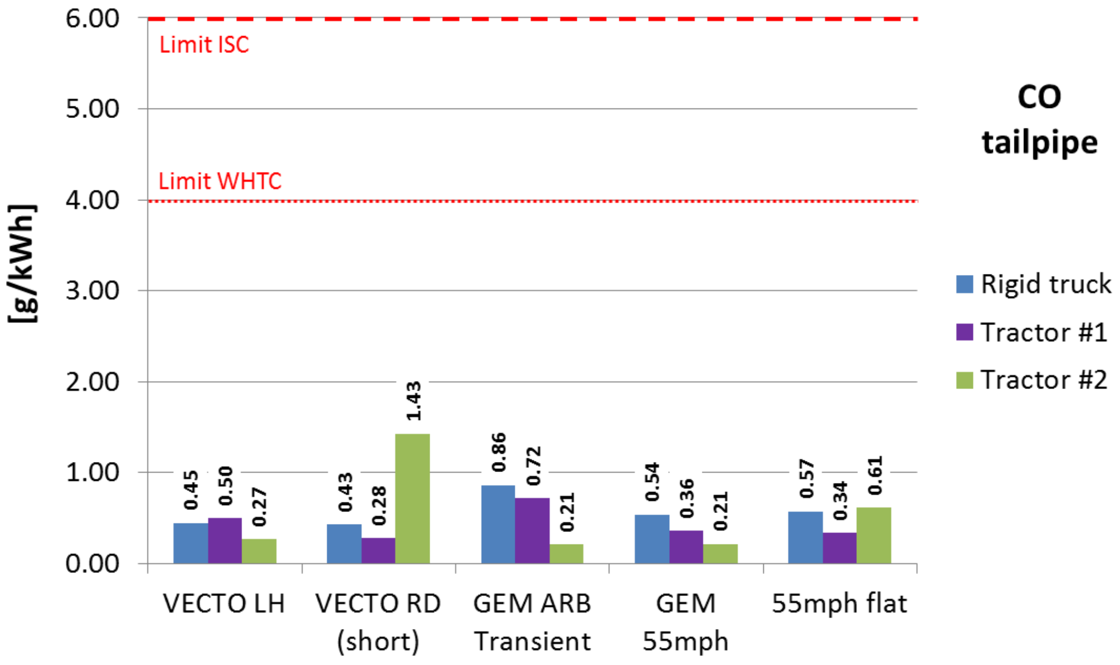

Figure 19: Results CO tailpipe emissions

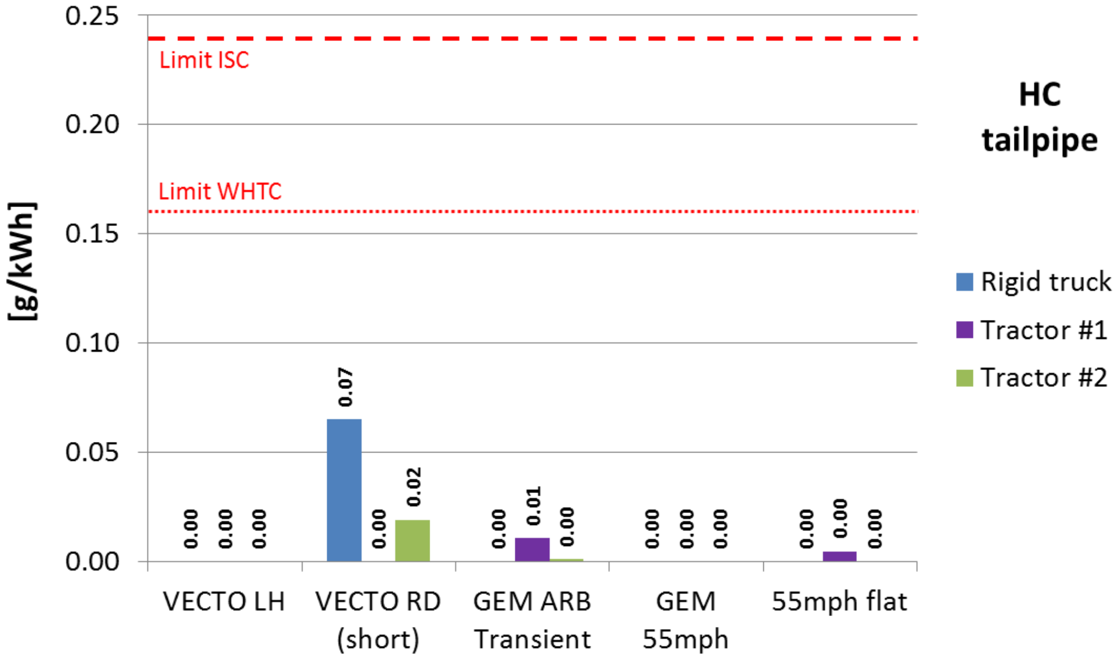

Figure 20: Results HC tailpipe emissions

7.6. Selected results from the steady state engine mapping cycle

At the chassis dyno also for each vehicle a grid of steady state points (6 engine speeds x 6 engine loads) was measured. Details on the definition of test points and on the test execution on the chassis dyno are given in section 6.2.5.

Figure 21 gives the results for engine brake specific fuel consumption ($BSFC_{eng}$). Only grid points with engine power higher than 10 kW are displayed. Similar to section 7.4 both the results calculated from measured fuel mass flow (left charts, method “a”) as well as based on fuel mass flow from CAN (right charts, method “b”) are shown. Data on engine power was determined based on CAN information in both cases. The figures as determined by method a. might be biased by inaccurate engine work. Method b. allows for an insight into the fuel efficiency data as implemented into the vehicles’ ECUs. Based on method a. the engine operation points with highest fuel efficiency are at 195 g/kWh for the rigid, and at 188 g/kWh for tractor #1 and 180 g/kWh for tractor #2. Method b. gives slightly lower g/kWh numbers (rigid: 189 g/kWh, tractor #1: 186 g/kWh, tractor #2: 180 g/kWh).

Figure 22 shows the brake specifc engine out NOx emissions as well as the EGR rates (EGR only for the rigid truck).[41] EGR rates were found at some 20% in the medium engine speed and load range. Correlated engine out NOx emissions are at 4 to 7 g/kWh. At fullload conditions EGR rates are reduced to 7.5% to 14%. Below approximately 1200 rpm and above engine rated speed no EGR is applied by the rigid engine. Correlated engine out NOx emissions are at 10 to 15 g/kWh. At tractor #1 engine out NOx emissions have been measured at significantly lower levels at some 2 to 4 g/kWh in most parts of the engine map area and with a minimum value at 1.8 g/kWh. Engine out NOx levels at the tractor #2 engine are in a range of 5 to 7 g/kWh in most parts of the engine map area with a minimum value at 4.6 g/kWh at fullload and rated speed. Engine of tractor #2 is a second generation EURO VI model (model year 2015) which are in general known to apply lower EGR rates than earlier EURO VI model years due to the avaiablility of more efficient SCR NOx aftertreatment. This difference is assumed to contribute to the difference in engine efficiencies between tractor #1 and tractor #2.

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[41] EGR rates were neither measured nor available from CAN for the tractors.

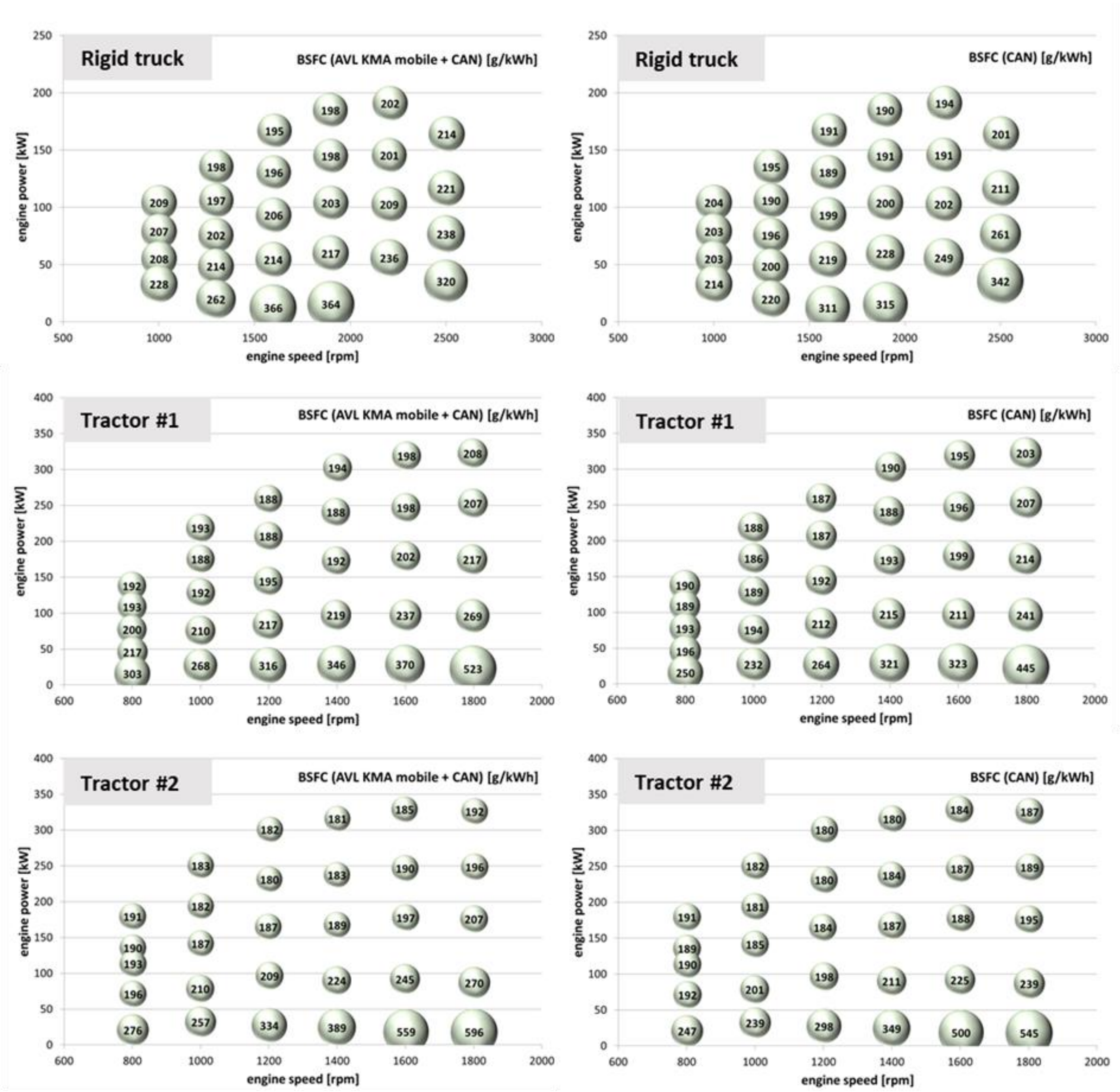

Figure 21: Results BSFC (engine) in the steady state mapping cycle

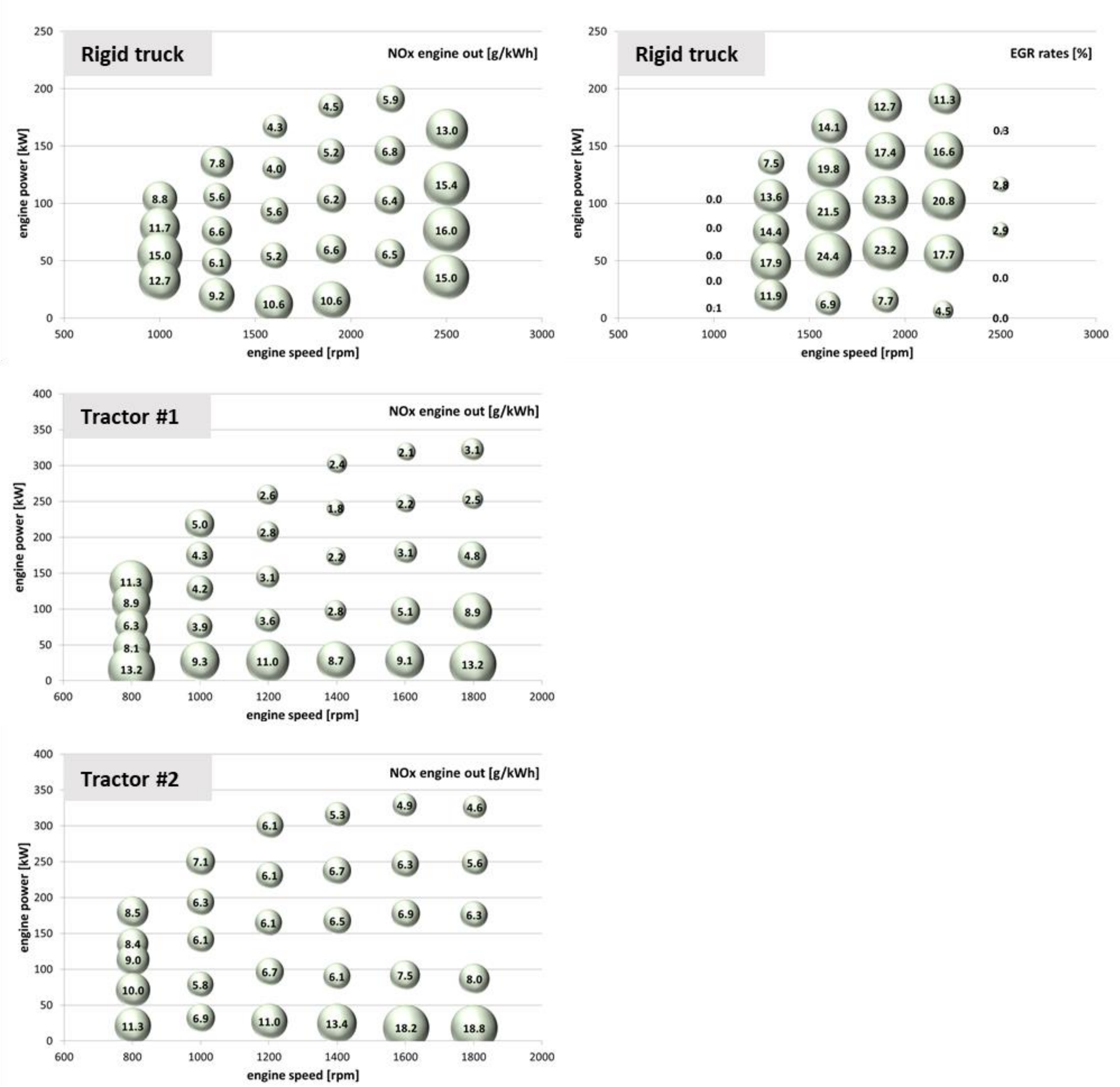

Figure 22: Brake specific engine out NOx emissions and EGR rates (only for the rigid) in the steady state mapping cycle

8. Summary

The main **goals of the project** performed at FVT in close consultation with the ICCT were:

- to determine typical fuel consumption (FC) and CO_2 figures from current European HDV vehicle technology as close as possible to the values as if determined based on the European HDV CO2 legislation and in selected cycles from the US HDV CO2 certification. The approach applied was to determine the vehicles' road load from air drag measurements and rolling resistance data from tire market analysis. The vehicles then have been measured at the heavy duty chassis dynamometer at the FVT in Graz in the regulatory CO_2 driving cycles from US and from Europe.
- to perform a comparison of air drag values (C_dxA) determined by the European test procedure (Constant speed test) and the phase 2 US EPA coast down test.
- to measure and analyze pollutant emission behavior of the tested European trucks.

The **selection of vehicles** aimed at gathering three vehicles representative for the European market. The selected vehicle models should have a substantial market share in the European Union. Focus was set to test "most common" vehicles and not vehicles with "average" parameters in the fleet. The selection consisted of:

- One typical rigid truck used for mid-distance distribution

  The main specifications of the vehicle were 4x2 axle configuration, 18 t GVWR, box body, engine rated power in the 175 kW to 200 kW range, automated manual transmission (AMT) with 12 gears and axle ratio in the 3.0 to 4.0 range
- Two typical tractors with semi-trailer for long-haul transport purposes with a GCWR of 40 t.

  The main specifications of the tractors were 4x2 axle configuration, 18 t GVWR, sleeper cab with 2.500mm width and aero package, engine rated power in the 320 kW to 340 kW range, AMT transmission with 12 gears and an axle ratio in the 2.5 to 2.6 range. In the selection of the two tractors it was especially taken into consideration to differentiate between "most frequent" (tractor #1) and "best available" (tractor #2) technologies for engine, drivetrain and auxiliaries.

For the three vehicles **air drag measurements** have been performed on the DEKRA test facility in Klettwitz. Two different testing methods have been applied in this project:

- The constant speed test procedure (CST) as described in the European HDV CO2 legislation
- The coast down test procedure (CDT) as foreseen in the US Phase 2 GHG regulation

The CST test procedure was applied to all three vehicles. The CDT was performed for the rigid truck as well as for tractor #2. In order to be practicable for European trucks and in the actual project, modifications in the coast down test procedure compared to official US EPA provisions had to be made.

In the CST tests the rigid truck has been measured with an average C_dxA value of 4.99 m^2. The results for the tractors are at 5.21 m^2 for tractor #1 and at 5.53 m^2 for tractor #2. These results according to the European method refer to zero yaw angle conditions. The US EPA phase 2 CDT test gives a pair of C_dxA value and related yaw angle as consolidated test result. For the rigid truck these values are 4.47 m² at 3.3° yaw angle, for tractor #2 the phase 2 CDT result is 4.94 m² for 1.6° yaw angle. In order to compare these test results with the C_dxA values from the CST, the CdxA values have been converted to zero yaw angle conditions applying the functions for yaw angle dependency as stated in the European legislation. This results in C_dxA values of 4.26 m² for the rigid truck and 4.80 m² for tractor #2 from the CDT. Compared to the test results from the CST the test result from the US phase 2 coast down is some 15% lower for the rigid and 13% lower for tractor #2. This result was to some extend expected, as the European CST test in its current version is known to result in rather conservative (i.e. higher) C_dxA values compared to other test methods (e.g. CFD, wind tunnel). Main reason is that the CST evaluation assumes the rolling resistance force to be constant over vehicle speed. This assumption results in some 5% to 10% higher C_dxA values than if evaluated with the known speed dependency. The specific reasons for the remaining differences between CDT and CST are not fully understood.

The **elaboration of road load settings and driving cycles for chassis dyno testing** was performed to provide vehicle operation conditions on the chassis dyno which match with the simulation based HDV CO_2 certification. Under this boundary conditions specific masses, road load parameters and driving cycles (vehicle speed and gradient over time) had to be elaborated. Road load settings have been calculated by conversion of vehicle specifications (curb mass from the vehicle documents, C_dxA as measured on the test track) according to the legislative provisions and on assumptions on typical rolling resistance coefficients (RRC) in the fleet. The driving cycles for the chassis dyno tests have been generated by VECTO simulations for each particular combination of vehicle and driving cycle. The cycles to be measured on the chassis dyno were:

- VECTO Long haul cycle ("VECTO LH")
- VECTO Regional delivery cycle ("VECTO RD")
- GEM Phase 2 cycle – ARB / HHDDT Transient ("GEM ARB Transient")
- GEM Phase 2 cycle – 55mph w/ grade profile ("GEM 55mph")
- Constant speed test at 55mph w/o grade profile ("55mph flat")

The **chassis dynamometer measurements** took place at the heavy duty roller test bed at FVT in Graz. Wheel force conditions were recorded via the chassis dyno and additionally via rim torque meters as provided by Kistler. Fuel flow was measured via AVL KMA mobile device installed in the low pressure fuel system of the vehicle. Tailpipe emissions (components CO2, NOx, NO, HC, PM and PN) have been measured by the standard CVS measurement equipment of the FVT chassis dyno. Additional measurement systems have been used to further analyze fuel efficiency relevant quantities (battery voltage and current, engine cooling fan speed) and to further analyze the pollutant emission behavior (NOx engine out concentrations, exhaust mass flow, exhaust gas temperature). Additional signals were available via connection with the vehicles' CAN bus (engine speed, engine torque, fuel consumption, current gear etc.).

Special focus in the project was given to provide highest standards in the determination of fuel consumption and to achieve best possible inter-comparability of test results between the three vehicles. Uncertainties in chassis dyno calibration were evaluated to have some 2% influence on measured fuel consumption for the tested vehicles. Applying the rim torque meters as an independent check of road loads applied by the chassis dynamometer is limited by the inaccuracy of the system resulting from measurement drift over a chassis dyno test. The resulting uncertainty on the result for wheel work measured by the torque meters in a typical driving cycle has been evaluated to be up to 3%.

The recorded measurement data from the chassis dyno have been post-processed in order to provide self-consistent datasets and comparable results between different measurements and different vehicles. Applied post-processing steps include time alignment of different measurement signals, corrections for deviations of actual vehicle driving pattern on the dyno compared to the target cycle and the selection of the most relevant quantities for the interpretation of the test results.

Figure 23 shows the **results for positive wheel work per driven kilometer** in the VECTO cycles. Values mainly depend on vehicle mass, vehicles' driving resistances and driving cycles. For the rigid truck the values (0.73 to 0. 85 kWh/km) are significantly lower than for the tractors (range 1.17 to 1.21 kWh/km) which is primarily caused by lower payloads and a smaller trailer in the VECTO LH cycle. Positive wheel work values of tractor#1 and #2 can directly be compared due to similar boundary conditions. Tractor #2 has a higher wheel work demand compared to tractor #1 of some +2.5% in the VECTO cycles. This is caused by the higher vehicle curb mass (ca. +400 kg) and the higher C_dxA value (+6%) compared to tractor #1.

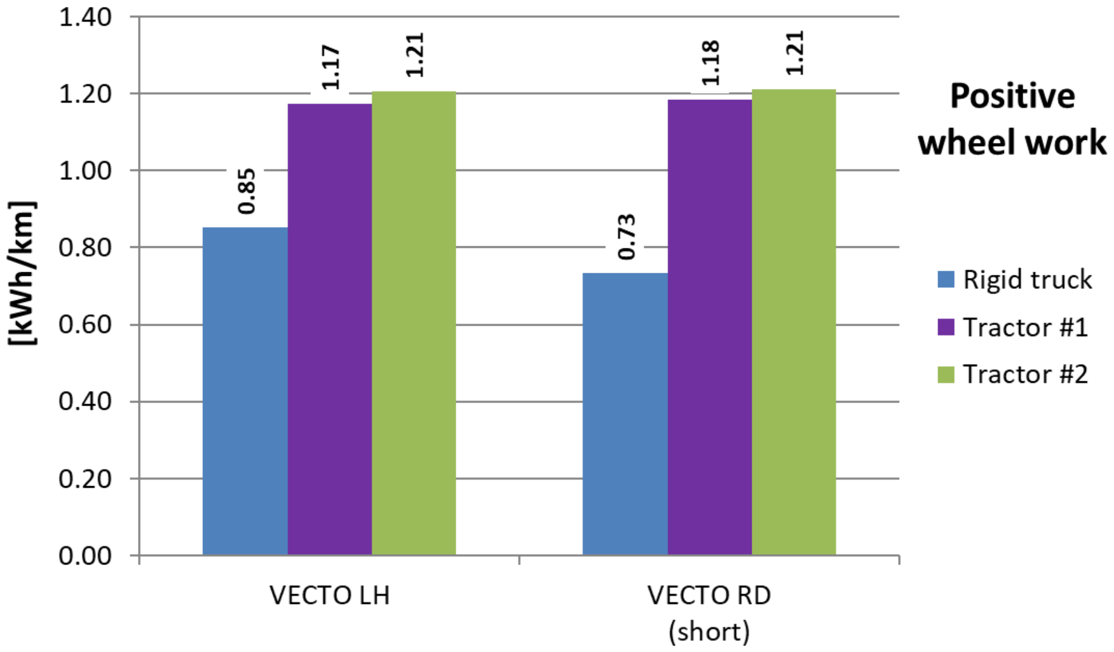

Figure 23: Results positive wheel work in the VECTO cycles

Figure 24 shows the **results for fuel consumption in liters per 100 km** in the VECTO cycles. For the rigid truck the values are at 31.3 l/100km in the VECTO LH and at 21.6 l/100km in the VECTO RD cycle. For the tractors the results are at 32.6 l/100km (tractor #1) and 29.9 l/100km (tractor #2) for the VECTO LH cycle and at 34.3 l/100km (tractor #1) and 31.6 l/100km (tractor #2) for the VECTO RD cycle. Fuel consumption figures determined for tractor #2 are 8% lower than for tractor #1 despite the higher vehicle curb mass and the higher air drag. Obviously the efficiencies of engine, drivetrain and vehicle auxiliaries of tractor #2 are able to by far over-compensate mass and air drag disadvantage.

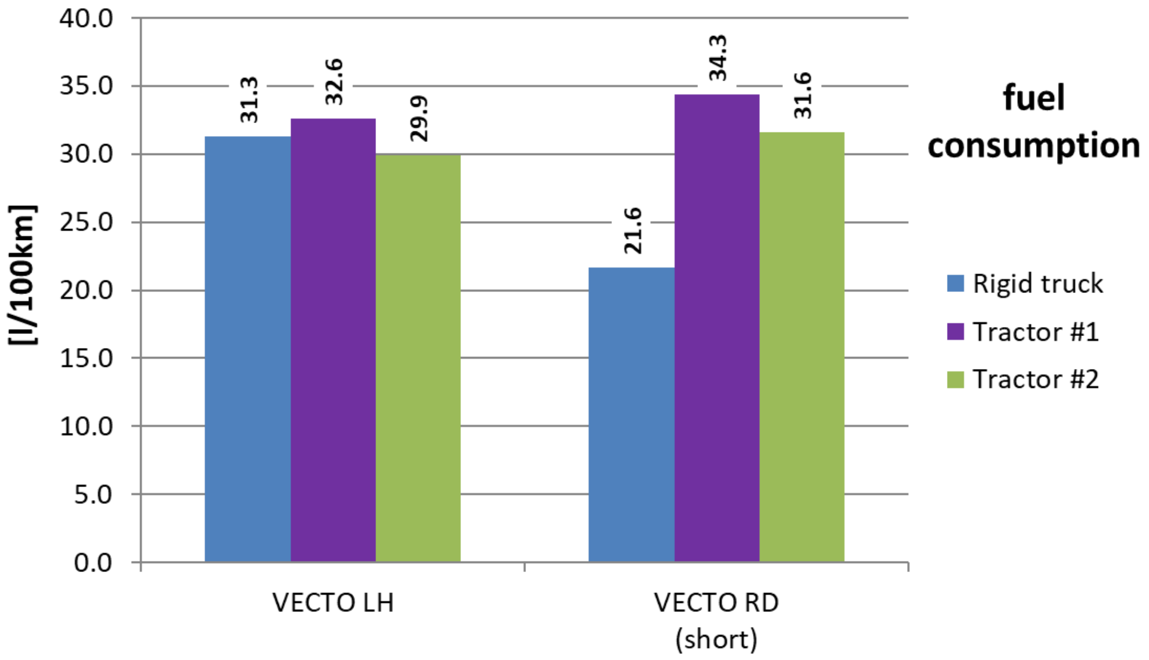

Figure 24: Results fuel consumption (liter per 100km) in the VECTO cycles

In Figure 25 the **results for CO2 emissions per ton-kilometer** are shown. This unit is the common used metric for certification and limitation of CO2 emissions from HDV (e.g. g/ton-mile of US EPA GHG Phase 2). Results for the rigid are at 56.9 gCO2/t-km in the VECTO LH and at 125.2 gCO2/t-km in the VECTO RD cycle. Due to higher payload conditions the results for the tractors are a much lower level with 43.5 gCO2/t-km (tractor #1) and 40.1 gCO2/t-km (tractor #2) in the VECTO LH cycle as well as 68.5 gCO2/t-km (tractor #1) and 63.4 gCO2/t-km (tractor #2) in the VECTO RD cycle. Relative differences of gCO2/t-km between the tractors are similar to the results for fuel consumption.

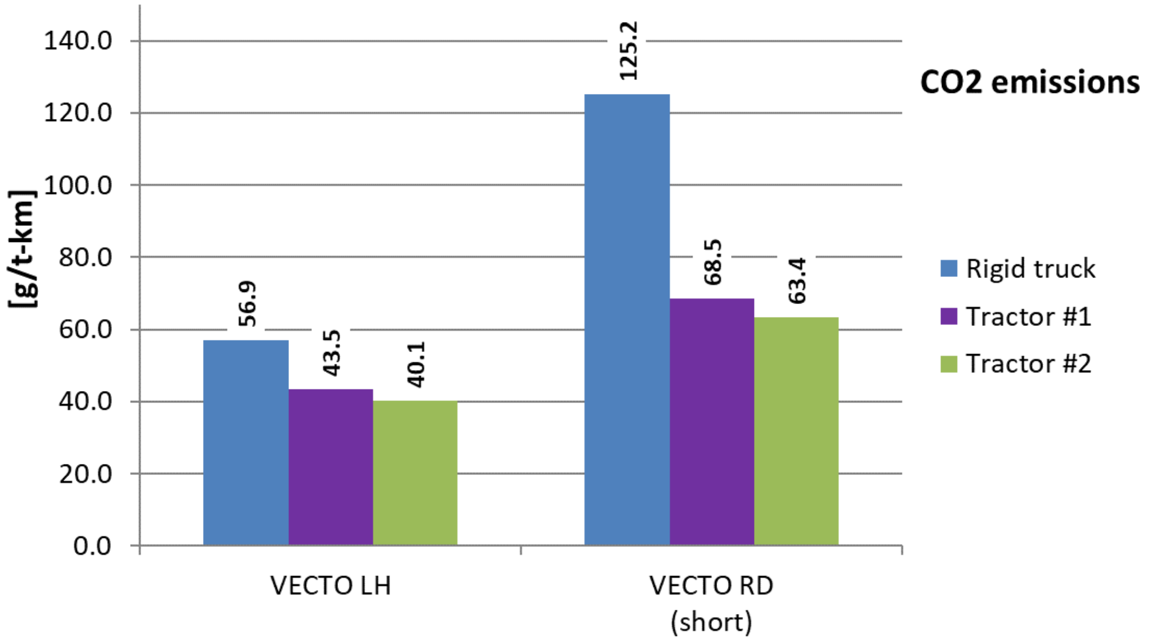

Figure 25: Results CO2 emissions per ton-kilometer (chassis dyno tests) in the VECTO cycles

In the chassis dynamometer measurements for the VECTO cycles the ambient wind influence as considered in VECTO was not included in the road load parameterization. This influence on the final CO2 figures has been incorporated in the post-processing. The resulting values are shown in Figure 26 and are the **reference values to the current VECTO method** as foreseen in the European CO2 certification for the three vehicles analyzed in this study.

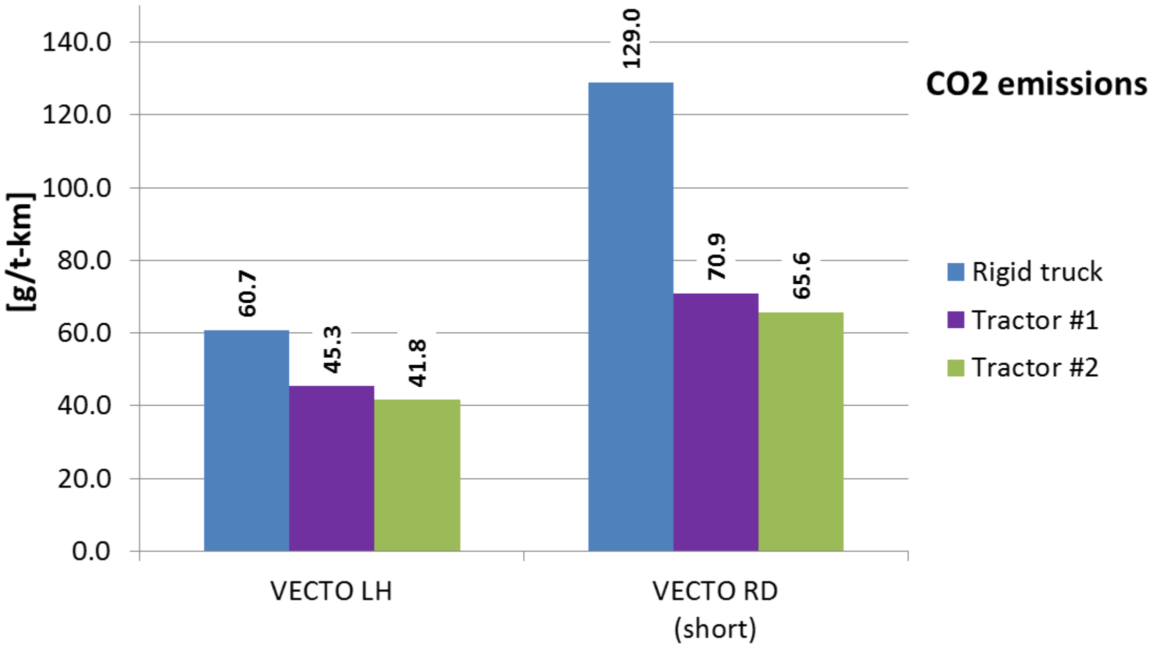

Figure 26: Results CO2 emissions per ton-kilometer (measured values aligned to current VECTO method by including ambient wind influence)

Based on the available data an **analysis on power demand and energy efficiencies of different vehicle components** has been performed. Engine brake specific fuel consumption figures have been derived from measured fuel consumption and engine operation data as broadcasted via CAN. Data on auxiliary power consumption have been taken from VECTO standard values and other data available at FVT. Efficiency values for the drivetrain (consisting of components transmission, retarder and axle) have been backward calculated to meet the numbers as measured for wheel specific fuel consumption on the chassis dynamometer. The analysis was performed for the VECTO RD cycle. From the backward calculation drivetrain efficiencies of 92.0% for the rigid, 90.8% for tractor #1 and 94.6% for tractor #2 have been derived. Power demand from auxiliaries is estimated to be 4.7kW for the rigid, 5.2kW for tractor #1 and 3.1kW for tractor #2. Numbers are only indicative as they are based on non component specific data for auxiliaries and the backward calculation of drivetrain efficiencies is highly sensitive to the accuracy of the measured $BSFC_{wheel}$ values.

Figure 27 gives a picture of the distance specific work demand of the main vehicle components and the resulting fuel consumption figures from this analysis. In the comparison of tractor #1 and tractor #2 the latter vehicle has a disadvantage related to work demand at wheels of 2.4% resulting from higher curb mass and higher air drag. Energy consumption from drivetrain losses and power demand from auxiliaries of tractor #2 is by some 40% lower as at tractor #1. This confirms the selection of tractor #2 to represent best available vehicle technology. The apportionment of energy savings at tractor #2 into improvements at drivetrain losses and at auxiliaries from the available data is uncertain. Total work demand at the engine is by 3.3% lower at tractor #2 compared to tractor #1. Combined with a 3.4% lower $BSFC_{eng}$ figure this gives a total advantage in fuel consumption of 6.6% for tractor #2 in this analysis.

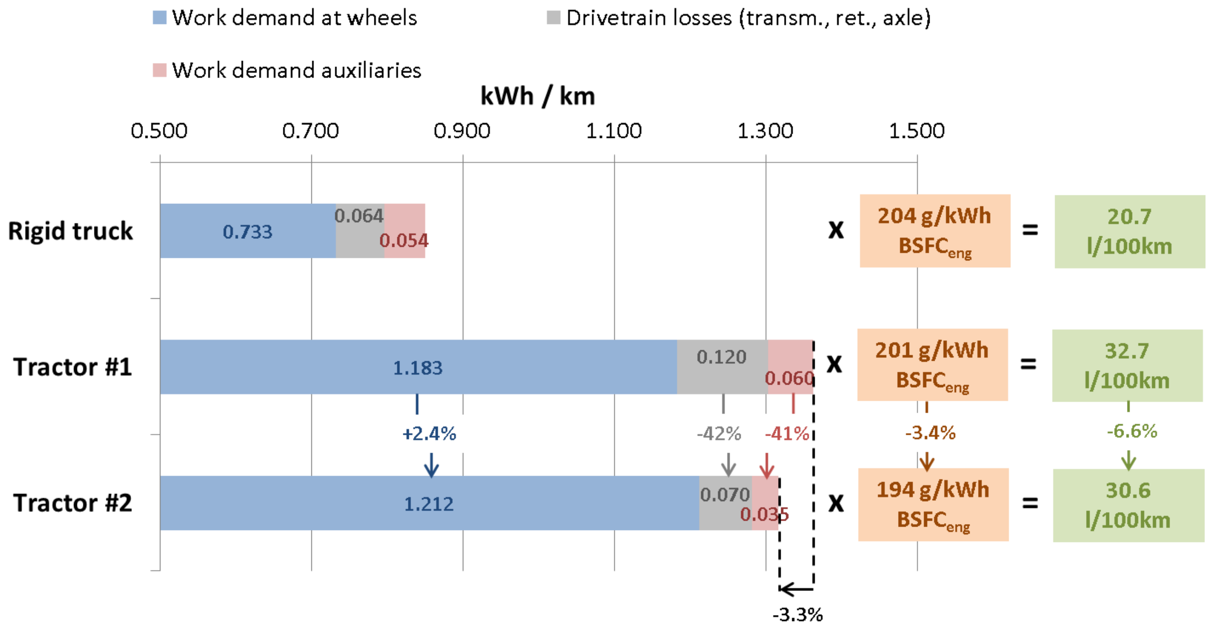

Figure 27: Analysis fuel efficiency figures for the VECTO regional delivery cycle

Emissions of regulated pollutants have also been recorded during the CO2 certification related driving cycles at the chassis dyno. All three vehicles were measured to have emission levels significantly below the EURO VI in service conformity limits for the pollutants NOx, HC and CO. Particle mass and number emissions also were below the limits for EURO VI in the WHTC.

9. References

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Annex I: Results fuel consumption and CO2 emissions

Table 13: Results fuel consumption and CO2 emissions

	VECTO Long Haul			VECTO Regional Delivery (short)			GEM ARB Transient			GEM 55mph			55mph flat		
	Rigid truck	**Tractor #1**	**Tractor #2**	**Rigid truck**	**Tractor #1**	**Tractor #2**	**Rigid truck**	**Tractor #1**	**Tractor #2**	**Rigid truck**	**Tractor #1**	**Tractor #2**	**Rigid truck**	**Tractor #1**	**Tractor #2**
Load (kg)	14 000	19 300	19 300	4 400	12 900	12 900	7 500	17 200	17 200	7 500	17 200	17 200	7 500	17 200	17 200
Total vehicle mass (kg) *1	28 098	34 165	34 556	13 098	27 765	28 156	16 198	32 065	32 456	16 198	32 065	32 456	16 198	32 065	32 456
Rotational equivalent mass (kg)*1	616	750	750	348	750	750	348	750	750	348	750	750	348	750	750
R0 (N)*1	1559.9	1826.6	1847.5	745.5	1498.1	1519.2	902.5	1730.1	1751.2	902.5	1730.1	1751.2	902.5	1730.1	1751.2
R1 (Ns/m)*1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
R2 (Ns²/m²)*1	4.092	3.095	3.285	3.201	3.095	3.285	3.201	3.095	3.285	3.201	3.095	3.285	3.201	3.095	3.285
Total driven distance (km)	100.184	100.185	100.185	63.699	63.699	63.699	4.511	4.492	4.498	21.644	21.610	21.656	21.661	21.612	21.637
Average speed (km/h)	75.1	78.6	78.7	63.2	63.5	63.7	22.8	23.0	23.7	87.8	88.1	88.2	88.0	88.0	88.9
Positive target wheel work (kWh/km)	0.852	1.173	1.205	0.733	1.183	1.212	0.954	1.757	1.791	0.805	1.119	1.157	0.787	0.999	1.038
Fuel consumption (g/km)*2	256.7	267.4	245.1	177.3	281.6	259.0	271.2	494.5	462.7	188.2	251.6	234.2	185.3	228.5	209.7
Fuel consumption (g/t-km)*2	18.34	13.85	12.70	40.30	21.83	20.08	36.16	28.75	26.90	25.09	14.63	13.62	24.71	13.28	12.19
Fuel consumption (l/100km)*2 *3	31.31	32.60	29.88	21.63	34.34	31.59	33.07	60.31	56.42	22.95	30.69	28.56	22.60	27.86	25.57
Fuel consumption (MJ/km)*2 *4	10.98	11.44	10.48	7.59	12.05	11.08	11.60	21.16	19.79	8.05	10.77	10.02	7.93	9.77	8.97
Fuel consumption (MJ/t-km)*2 *4	0.784	0.593	0.543	1.724	0.934	0.859	1.547	1.230	1.151	1.074	0.626	0.583	1.057	0.568	0.522
Engine specific fuel consumption (g/kWh)*2 *5	202.4	206.0	197.6	208.5	204.8	196.9	230.0	229.5	215.6	201.0	202.7	199.5	199.3	214.2	205.8
Engine specific fuel consumption (g/kWh)*6	194.4	198.0	191.0	199.5	197.1	191.2	213.6	211.0	203.2	194.7	196.7	193.9	192.8	207.9	198.8
Powertrain specific fuel consumption (g/kWh)*2 *7	224.7	220.9	n.a.	235.4	226.4	211.6	267.1	259.8	245.8	225.8	219.6	n.a.	231.8	226.6	n.a.
Powertrain specific fuel consumption (g/kWh)*2 *8	224.9	227.0	202.2	238.1	236.4	210.1	268.7	278.2	251.9	233.3	224.0	199.8	235.4	229.0	201.3
CO2 (g/km)*9	797.2	839.2	773.6	550.8	883.8	817.8	842.2	1552.2	1460.6	584.5	789.8	739.5	575.5	717.1	662.0
CO2 (g/t-km) *9	56.94	43.48	40.08	125.17	68.51	63.39	112.30	90.24	84.92	77.93	45.92	42.99	76.73	41.69	38.49
CO2 (g/t-km) *9 *10 (VECTO reference result)	60.66	45.31	41.78	128.97	70.88	65.59	-	-	-	-	-	-	-	-	-

*1 Settings chassis dynamometer
*2 Fuel consumption from fuel meter
*3 Density from fuel analysis (15°C)
*4 Lower heating value from fuel analysis
*5 Engine work from CAN
*6 Fuel mass and engine work: CAN
*7 Wheel work from rim torque measurement
*8 Wheel work from hassis dynamometer control
*9: CO2 calculated from fuel meter and carbon content from fuel analysis
*10: including ambient wind corrections as applied in VECTO

Annex II: Results fuel consumption and CO2 emissions

Table 14: Results pollutant emissions

	VECTO Long Haul			VECTO Regional Delivery (short)			GEM ARB Transient			GEM 55mph			55mph flat		
	Rigid truck	Tractor #1	Tractor #2	Rigid truck	Tractor #1	Tractor #2	Rigid truck	Tractor #1	Tractor #2	Rigid truck	Tractor #1	Tractor #2	Rigid truck	Tractor #1	Tractor #2
NOx tailpipe - CVS modal (g/km)	0.010	0.083	0.026	0.035	0.067	0.097	0.227	0.125	0.169	0.016	0.031	0.137	0.014	0.141	0.165
NOx tailpipe - CVS modal (g/kWh)	0.008	0.064	0.021	0.041	0.049	0.073	0.187	0.059	0.080	0.017	0.024	0.113	0.015	0.133	0.163
NOx tailpipe - Semtech (g/kWh)	0.003	0.097	0.030	0.024	0.070	0.069	0.230	0.043	0.021	0.000	0.037	0.028	0.071	0.196	0.359
NOx engine out (g/kWh)[*1]	8.20	3.98	5.63	8.87	4.17	6.09	9.93	5.73	5.77	8.54	3.47	5.79	10.31	3.72	5.70
PM tailpipe (g/km)[*2]	0.003	0.005	0.007	0.003	0.003	0.007	0.000	0.000	0.012	0.001	0.000	0.002	0.000	0.000	0.001
PM tailpipe (g/kWh)[*2]	0.002	0.004	0.006	0.004	0.002	0.005	0.000	0.000	0.006	0.001	0.000	0.002	0.000	0.000	0.001
PN tailpipe (g/km)[*3]	2.77E+11	1.66E+11	4.64E+10	3.61E+11	1.01E+11	2.84E+10	2.47E+10	4.34E+11	4.17E+10	6.16E+10	1.51E+11	2.49E+10	4.85E+10	6.99E+11	1.94E+10
PN tailpipe (g/kWh)[*3]	2.18E+11	1.28E+11	3.72E+10	4.23E+11	7.34E+10	2.14E+10	2.05E+10	2.01E+11	1.98E+10	6.53E+10	1.21E+11	2.08E+10	5.23E+10	6.61E+11	1.90E+10
CO tailpipe (g/km)[*4]	0.57	0.65	0.34	0.37	0.38	1.89	1.04	1.55	0.44	0.51	0.45	0.26	0.53	0.36	0.63
CO tailpipe (g/kWh)[*4]	0.45	0.50	0.27	0.43	0.28	1.43	0.86	0.72	0.21	0.54	0.36	0.21	0.57	0.34	0.61
HC tailpipe (g/km)[*5]	0.00	0.00	0.00	0.06	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00
HC tailpipe (g/kWh)[*5]	0.00	0.00	0.00	0.07	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Engine kWh from CAN

[*1] NOx engine out from NOx sensor and EFM mass flow measurement

[*2] PM emissions: CVS filter value

For parts of LH cycle not covered with filter data the allocated PM emissions have been estimated by via the modal PN signal and the PM/PN ratio from the cyle parts w/ filter

[*3] PN emissions: CVS + VPR + CPC 3790

[*4] CO emissions: Semtech + EFM

[*5] HC emissions: CVS modal