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Development of a CO_2 certification and monitoring methodology for Heavy Duty Vehicles – Proof of Concept report

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Contents

1 Introduction

Following its commitment to reduce CO2 emissions from road transport in Europe, the European Commission has launched extensive research initiatives to develop a new methodology for monitoring CO2 emissions from heavy duty vehicles (henceforward, HDV). Due to the diversity and particular characteristics of the HDV sector it was decided that the core of the proposed methodology will be based on vehicle simulation. Similar approaches have been adopted in other major HDV markets such as the US, Japan and China. This development process is performed in collaboration with the European HDV manufacturers, component suppliers and other stakeholders. The aim is to produce a CO_2 emissions monitoring approach that will reflect realistically both the actual vehicle CO_2 emissions during operation and the relevant fuel economy performance of different vehicle models that belong to the same category and have similar characteristics.

To achieve this, it is necessary to develop the concept of vehicle simulation, new testing methods and practices and other provisions for vehicle categorization and characterization. The intended CO_2 monitoring mechanism should be technology neutral and reflect the technological advantages of each vehicle with respect to fuel economy in the best possible way. Finally, the results of the HDV CO_2 monitoring shall be included in the existing HDV certification procedure and become available to the European citizen and consumer.

In order to investigate the plausibility of such a simulation-based approach an extensive experimental study was launched by the European Commission DG Joint Research Centre (JRC) and DG Climate Change (CLIMA), in collaboration with vehicle manufacturers (DAF, DAIMLER, IVECO) and external consultants (TUG, TUV Nord), henceforth referred to as Proof of Concept study (PoC). This report summarizes the findings of the Proof of Concept activity and provides further insight with regard to future possible steps in the direction of the completion of the CO_2 emissions monitoring and certification framework. More specifically this report attempts to:

- Investigate the effectiveness of the monitoring methodology (as proposed up to spring 2013) regarding issues related to: accuracy, repeatability and reproducibility for the quantification of fuel consumption[1] from complete HDV[2]
- Investigate whether the methodology can serve the needs of CO_2 monitoring, certification, labeling and standards for complete HDVs
- Identify necessary future steps needed to a fully operational methodology and simulation tool.

In the following chapters a first insight is provided regarding these topics based on the results of the PoC activity.

[1] CO_2 emissions are directly proportional to fuel consumption. Provided that the chemical composition of the fuel is known, CO_2 emissions can be directly derived from fuel consumption metrics. For simplicity and because throughout the PoC activity emphasis has been put on accurate measurement of fuel consumption, this report will refer to fuel consumption metrics rather than CO_2 emissions.

[2] It was proposed that the first proposal of the Commission shall cover long haul, regional/delivery vehicles, coaches and city busses. In the PoC activity only long haul and regional delivery trucks were investigated. The experts involved in the activity agree that the main conclusions drawn are also applicable to other HDV categories such as city delivery trucks and coaches. Additional investigation is necessary in the case of city busses.

2 Methodological approach

The methodological approach followed in the PoC activity consisted of experimental measurements on 2 HDVs and one HD engine and simulation runs performed with dedicated software previously developed by the JRC. Further information regarding the vehicle simulator used is provided in the following paragraphs. The core of the experimental and analytical approaches adopted was based on the findings of the project "*Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2 Development and testing of a certification procedure for CO2 emissions and fuel consumption of HDV*"[3] (hence LOT2). In addition, important feedback and suggestions, received from the manufacturers and other stakeholders in the meantime and throughout the PoC activity, have been taken into consideration. The key features investigated were:

1. the accuracy, repeatability and reproducibility of the constant speed measurement method, as proposed by LOT2 and updated and optimized by ACEA, for measuring the aerodynamic characteristics of HDVs
2. the correlation between the tyre rolling resistance values calculated from the constant speed measurement (CSM) tests with the official type approval values
3. the engine mapping procedure proposed by LOT2 and amended by ACEA for deriving the necessary engine fuel consumption maps to be used as input for simulation
4. the ability of the proposed methodology (as of spring 2013) to produce representative results of real world fuel consumption and CO_2 emissions
5. the ability of the simulator to accurately reproduce the operation of a HDV over controlled and real world conditions

The selection of the parameters to be investigated was based on the results of a sensitivity analyses performed by the JRC on a 12ton Euro V delivery truck over mixed driving conditions. The analysis quantified the influence of the change of different vehicle parameters on HDV fuel consumption (see Figure 1) and demonstrated that for the vehicle categories of interest the most influential parameters affecting fuel consumption are: aerodynamic characteristics (air resistance), rolling resistance, vehicle weight, engine efficiency and auxiliary power consumption. A similar analysis conducted within the LOT2 study led to similar conclusions (see Figure 2).

[3] TU Graz, TUV Nord, VTT, AVL, LAT, HS (2012). Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2 Development and testing of a certification procedure for CO2 emissions and fuel consumption of HDV. Final report available at:
http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/hdv_2011_01_09_en.pdf, 2012

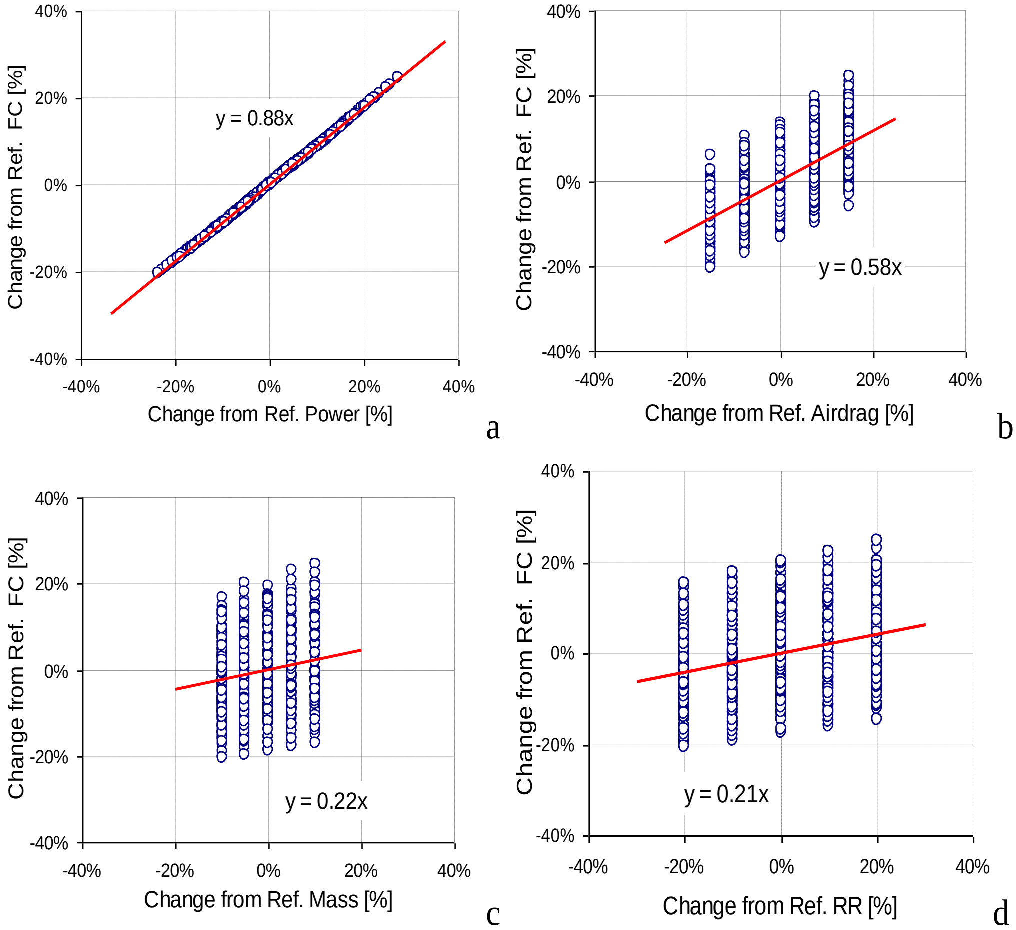


Figure 1 Impact of change (%) in Total engine power demand (a), Air drag (b), Mass (c), Rolling resistance (d) on Fuel consumption over a mixed operating profile (based on Euro V 12ton delivery vehicle).

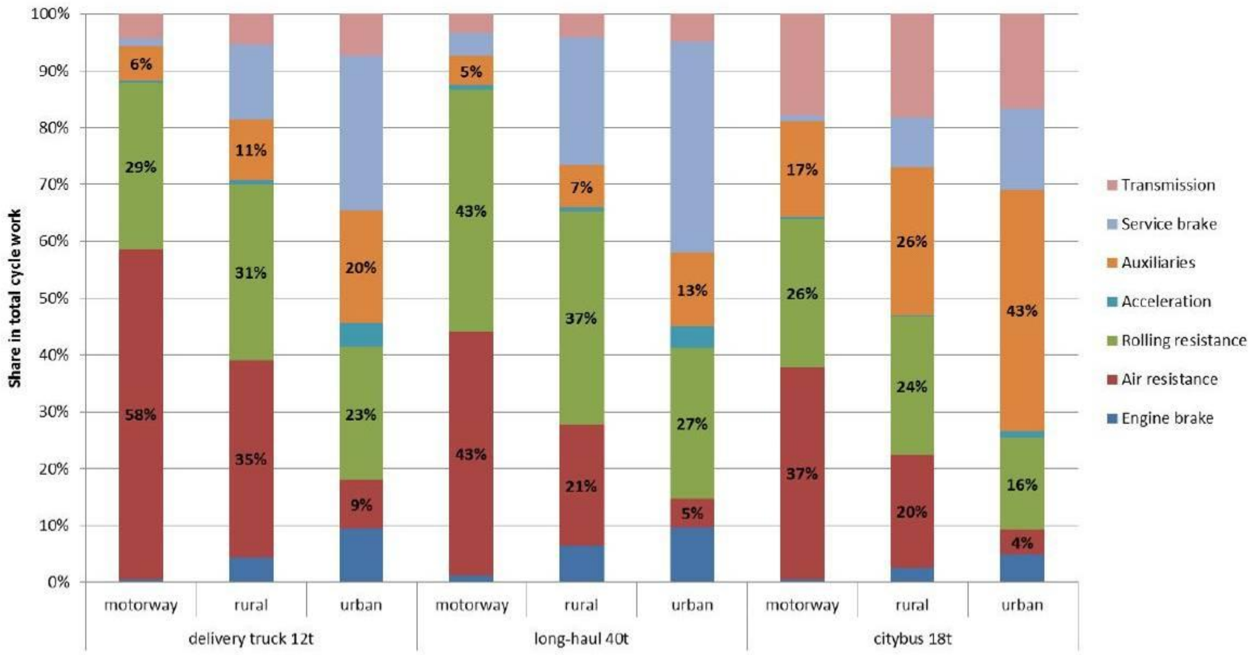


Figure 2 Share of the driving resistances in total cycle work for three vehicle categories (results for average loaded vehicles for generic HDV) ***Source LOT2 final report***

2.1 Experimental Measurements

An extensive number of experimental measurements was performed, covering the most important vehicle components and the entire vehicle operation, which can be categorized as follows:

- Vehicle constant speed measurement (CSM) tests for measuring aerodynamic and rolling resistances
- Vehicle on road and chassis dyno measurements for measuring complete vehicle operation over real world and controlled driving conditions
- Engine test bed steady state tests

In addition to the above, specific tests of various components were performed by the OEM's in order to provide the necessary input data to run the vehicle simulations. Those tests and their results are confidential and thus not described in this report. The most important details regarding the experimental procedure are presented below.

2.1.1 Test vehicles

Two vehicles were used in the study, a Daimler Actros Euro VI and a DAF CF75 Euro V (see . The detailed characteristics of the vehicles are summarized in Table 1.

Table 1 Main vehicle characteristics and main input data origin

OEM	Daimler	DAF
Model	Actros	CF75
Maximum vehicle weight [kg]	40000	18600
Test mass [kg]	33580	14270
Engine Emission Standard	Euro VI	Euro V
Rated power [kW]	330	265
Rated Torque [Nm]	2200	1050
Displacement [l]	12.8	9.2
Fuel Consumption Map	From steady state RPM vs Torque points as measured by manufacturers	
Gearbox & Final Drive characteristics	As provided by manufacturers	

a

b

Figure 3 Vehicles used in the study a: Actros low liner tractor with semi trailer, b:e CF75 rigid truck

2.1.2 Constant speed tests for aerodynamic resistance measurement

During the constant speed test the driving torque, vehicle speed, wind speed and direction are measured at two different constant speeds (low and high speed) under defined conditions on a test track. The constant speed tests were performed in the Iveco proving ground at Balocco, Italy.

Both trucks were driven on the peripheral (outer) track at two different constant speeds at 15 km/h and 89 km/h, according to the constant speed measurement protocol provided by DAF and Daimler respectively[4]. Measurements were performed in the effective segments (long straights) as indicated in Figure 4. The measurements were performed while the vehicle is cruising at constant speed (2 speeds were recorded 15km/h and 89 km/h). During this time a series of parameters such as wind speed, wind angle, torque at the wheel or wheel half shaft, vehicle speed, vehicle position were measured to derive slope, weather data and engine data. Accurate calculation of the resistances applied on the vehicle is then possible which allows the quantification of the aerodynamic drag coefficient and the rolling resistance coefficient.

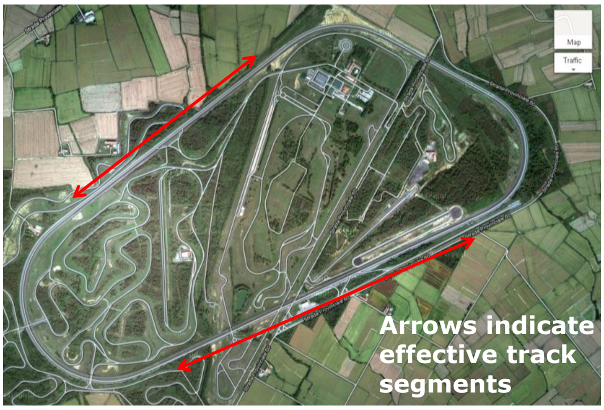


Figure 4 Balocco proving ground overview.

The measurements in each case were performed according to the guidelines received by each OEM and in cooperation with them. The basic testing concepts followed were the same in both cases but certain details differed. A more detailed description of the basis of the test protocol followed can be found in section 6.1.1 (Annex). The key points in common as well as the most important differences in the procedures followed for each of the two vehicles are summarized in Table 14 of the Annex. In terms of instrumentation, the most important instruments introduced with this test are the mobile anemometer and the wheel rim-half shaft torque measurement sensors (see following Tables).

Table 2 Anemometer characteristic

Instrument	Mobile anemometer
Sensor type	Ultrasonic
OEM	GIL
Model	WindSonic
Airspeed accuracy at 12m/sec [m/s][5]	±2%
Airspeed resolution at 12m/sec	0.1m/sec
Wind angle accuracy at 12 m/sec [degrees]	±3º
Wind angle resolution at 12 m/sec	1º
Sampling rate [Hz}	5

[4] DAF and Daimler at that time followed two different measurement procedures with respect to vehicle and torque measurement system conditioning and vehicle position registration. Since then ACEA has issued a draft proposal for a common constant speed measurement protocol based on both methods. Details remain to be defined.

[5] Improved airspeed and angle accuracy can be achieved for the anemometer through specific tests that take place on the in the sidelines of the actual measurement which allow the development of correction functions. First results indicate a +/- 0.6 m/s accuracy for wind speed and a +/- 0.9 º accuracy for wind angle. The details of the method are currently studied.

Table 3 Torque sensor characteristic

Vehicle	Actros	CF75
Torque sensor type	Wheel rim torque meter (torque at rim)	Torque meter on wheel hub (torque at half shaft)
OEM	Kistler	Himmelstein
Full scale [Nm]	±5000 (at low range)	±5650
Non linearity	±0.1 % (of full scale)	±0.1 % (of full scale)
Hysteresis		±0.5 % (of full scale)
Sample rate [Hz]	20	20
Total theoretical accuracy [Nm]	±	±29

It is important to note that measurement results of both vehicles were analysed in the same way using VECTO-CSE software developed for the JRC by the TU-Graz[6]. More information is available in section 6.1.3 (Annex).

Figure 5 Anemometer used in the tests

2.1.3 On road and chassis dyno tests

A series of complete vehicle tests were performed with both vehicles on the road (7 for CF75 and 7 for Actros) and on the JRC HDV chassis dyno.

2.1.3.1 On road tests

The same route was used for both vehicles for the on road tests (Figure 6). The on road route had a total length of about 107km comprising of urban rural and highway sections. The cycle statistics of a typical route performed with the CF vehicle are summarized in Table 4.

[6] For more information regarding the exact data analysis approach followed please refer to: Constant Speed Evaluation Tool V1.0, Technical documentation, Report No. I 22/12/Rex EM I 10/12/679 from 6.12.2012

Table 4 Driving phase distribution of a typical trip performed with CF75 vehicle

Speed profile	Share in total trip time duration [%]
Low Speed [~City]	**26**
Medium speed [~Rural]	**26**
High Speed [~Motorway]	**48**

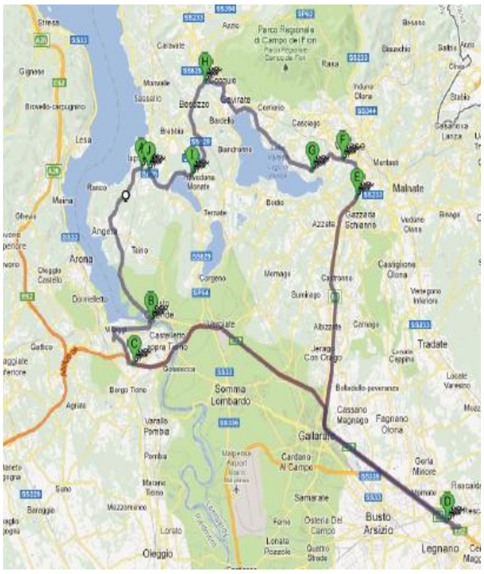


Figure 6 Drive path of the on road tests performed (A-C, warm up section, C-D-E highway conditions, E-G urban conditions, G-J rural driving)

In the case of the CF75 vehicle a complete PEMS system was loaded on the vehicle for measuring CO_2 emissions and a mobile KMA fuel flow meter (of AVL) was used for measuring instantaneous fuel flow. In addition the signal of a fuel flow meter embedded by DAF was also recorded for comparison purposes.

Due to time restrictions it was not possible to install the PEMS system and the mobile flowmeter on the Actros vehicle for the on road tests. In that case an on board fuel flow meter installed by the OEM was used for recording instantaneous fuel consumption. Comparison of the instruments performance with that of the KMA during the chassis dyno tests suggested good instrument performance and accuracy.

2.1.3.2 Chassis dyno tests

All chassis dyno measurements were performed at the Vehicle Emissions Laboratory (VELA7) of the European Commission's Joint Research Centre. Further information regarding the VELA 7 facility can be found in the Annex (6.2).

As in the case of the on road tests in addition to the measurement of CO_2 emissions, fuel consumption was measured with an AVL KMA Mobile fuel flow meter.

The chassis dyno daily test protocol consisted of a series of test cycles that covered different operating conditions, from steady state conditions to highly dynamic cycles. The protocol included steady state speeds at 20, 40, 60, 80 km/h, the world harmonised heavy duty vehicle cycle (WHVC), the ACEA regional delivery cycle (ARDC) and the FIGE driving cycle. The cycle profiles are demonstrated in Figure 30 (see Annex - 6.3).

Each measurement day 2 repetitions of each cycle were performed under warm start conditions and the protocol was repeated for 4 days in the case of CF75 and 3 days for the Actros.

2.1.4 Engine tests

The approach for calculating the engine fuel consumption in the HDV CO_2 proposed certification scheme consists of three main elements:

1) The engine test procedure
2) The method of engine test evaluation for generation of VECTO input data
3) The simulation approach in the VECTO tool

In the PoC the combination of all three elements was evaluated. Additionally the engine fuel consumption was measured in real world transient engine torque and speed patterns related to the HDV CO_2 mission profiles. For proof of concept these measured values for fuel consumption have then been compared to the relevant VECTO results.

Two sets of engine measurements were performed during the PoC tests for assessing steady state engine mapping procedure. The first set was performed at the engine test bench dyno of the JRC following the measurement protocol proposed in January 2013 by TU Graz and JRC (see 6.6). Fuel consumption was measured with an AVL 735 +conditioning unit. The engine used in the tests presented the following characteristics (see Table 5).

Table 5 The JRC test engine used for the test bed measuremetns

Engine data	
Manufacturer	Daimler AG
Type	OM 501 LA
Code	OM 501 LA.III/5
Rated power	290kW at 1800 1/min
max. net torque	1850Nm at 1080 1/min
max. permitted speed	2300 1/min
Idle speed	560 ± 50 1/min
Power absorbed by fan	not to be considered
Bore	130mm
Stroke	150mm
Capacity	11 946 cm^3
exhaust gas mass flow at speed C and full load	1800 kg/h
max. permitted speed	2300 1/min

In late February 2013 ACEA have reached a consensus on a slightly different testing protocol. The analysis and the transient cycle correction was performed according to the method described in LOT 2 with the amendments described in annex 6.6. It is expected that the results with the method finally selected will have similar or better accuracy than the method applied here.

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

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

2.2 Vehicle simulation

The Vehicle Energy Consumption calculation tool (VECTO) was used as the vehicle simulation application of reference for the PoC activity. VECTO was developed by the TUG and the JRC in order to lay the foundations for the future HDV CO_2 monitoring and certification software application. This new simulation program aims to serve as:

- a platform which will incorporate the findings of on-going research activities in the field of HDV fuel consumption simulation
- a pilot application for future upgrades and developments of the software tool to be included in the European legislation

Emphasis has been put from the very beginning on specific features of importance to HDV, in order to reflect realistically both the actual vehicle CO_2 emissions during operation and the competitive advantages of various fuel/CO2 saving technologies of the vehicles. The main features of VECTO are presented in Figure 7. All vehicle simulation presented in this study were performed using VECTO version 1.1 beta 3. In addition, the results of the constant speed tests, performed for measuring the aerodynamic characteristics of the vehicles, were analyzed using the VECTO CSE module (constant Speed Evaluator)[7]. By the time this report is being written, a series of studies had been presented which provided evidence that VECTO performs adequately and in a similar way as other established commercial simulators. Hence the programming and architecture of VECTO, at least in terms of software, should not affect the findings and key conclusions of this analysis[8],[9].

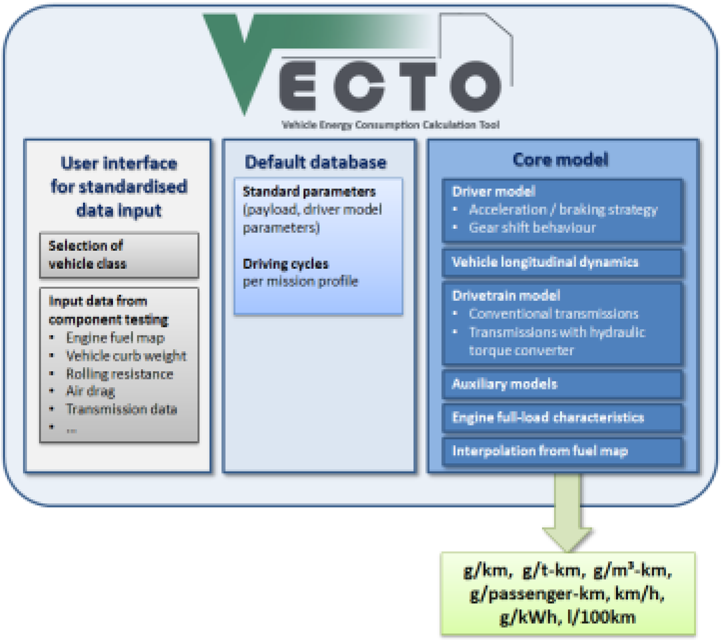


Figure 7: Scheme of the VECTO model

[7]More information is provided in the Annex.
[8] Daimler presentation, "Concept proof evaluation", Teleconference with Clima and JRC, March 26th
[9]ACEA Workgroup - CO2 HDV, "Evaluation of VECTO tool", report communicated by ACEA to JRC and CLIMA, January 2013

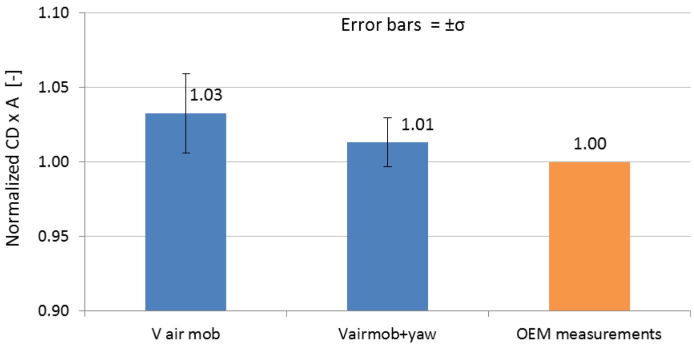
3 Results

3.1 Aerodynamic characteristics (CS tests)

As mentioned, the aerodynamic characteristics and the rolling resistance are for the particular HDV categories two of the most influential factors affecting fuel consumption. Therefore the accurate calculation of the air drag and rolling resistance value is essential for achieving simulation results of high accuracy. Below are summarized the results of the constant speed tests for the calculation of aerodynamic drag and rolling resistance. It should be noted that all constant speed test results were analysed using the VECTO-CSE tool version 1[10].

3.1.1 CF75

Figure 8a presents the results of the constant speed tests performed with the CF75 vehicle (the results are normalized by the average value measured by the OEM). Two sets of results were calculated from the measurements performed with the CF75, without corrections applied for yaw angle ($v_{air,mob}$) and with corrections applied ($v_{air,mob+yaw}$). As presented the $v_{air,mob+yaw}$ approach gave the best results in both terms of accuracy and variability (see also
Table 6). Only a marginal 1.3 % difference from the value reported by the OEM was calculated fact, which indicates good reproducibility characteristics for the method. The variability of the results was also limited, presenting a standard deviation of 1.6 % fact, which suggests good precision of the method in addition to good accuracy characteristics.



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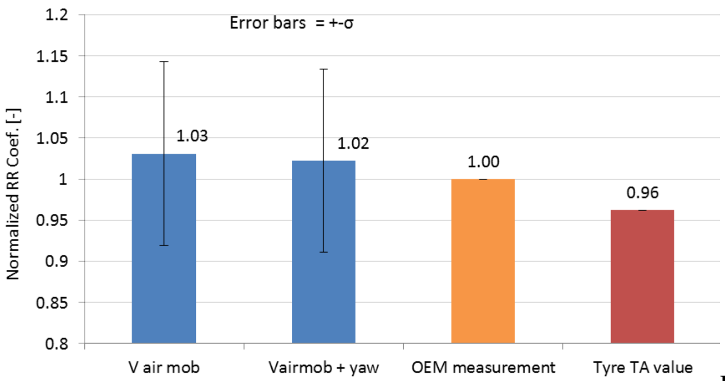


b

Figure 8 Aerodynamic resistance (a) and tyre rolling resistance (b) measurement results for CF75, normalized by the average value measured by the OEM

[10] OEMs used their own tools for deriving the results also presented in this section however cross comparison between VECTO-CSE and in house tools showed only minor differences in the end results.

A key assumption of the method is that the rolling resistance retains a constant value between the tests. Table 6 summarizes the results of the calculated total rolling resistance coefficient. The calculation of the RRC showed that indeed the calculated value presents limited variations and reproducible results, compared to the OEM measurements conducted on a different test track. The type approval RRC value for the particular set of tyres is also provided for comparison. It should be noted though, that the latter is measured on a drum rig under very strict operating conditions, so the comparison is rather indicatory. The RRC was found only 2.2 % different compared to previous OEM and results with a standard deviation of 10 %. The results are in line with similar results reported by other studies.

Differences in RRC were expected, since the rolling resistance performance of tyres is highly affected by many factors, such as weather conditions, tarmac, ground temperature and mileage. After analysing the results, no significant dependencies between RRC and $C_d \cdot A_{cr}$ were found (e.g. $Cd \cdot A_{cr}$ being consistently lower when RRC was higher, see Table 7). Therefore, the results appear to verify the initial assumption of the method of limited RRC differentiations between tests.

Table 6 Summary of the differences of the measured values with respect to OEM or TA ones for aerodynamic resistance and rolling resistance

	$V_{air,mob}$	$V_{air,mo\beta+yaw}$
Difference from OEM value for $C_d \cdot A_{cr}$ [%]	3.3 %	1.3 %
Standard deviation of $C_d \cdot A_{cr}$ measurement [%]	2.6 %	1.6 %
Difference from OEM reported value for RRC [%]	3.1 %	2.2 %
Standard deviation of RRC measurement [%]	10.8 %	10.9 %

Table 7 Difference of individual test results from reference value for $C_d \cdot A_{cr}$ and RRC

	1st Dataset	2nd Dataset	3rd Dataset
Diff in $C_d \cdot A_{cr}$	3.2%	0.5%	0.3%
Diff in RRC	9.1%	-10.6%	8.2%

Figure 9 compares the results of the measurements performed in this study with those previously performed by the OEM. The normalized (to average OEM measurement at 0º yaw) air drag coefficient is plotted as a function of the average wind yaw angle. It is observed that the JRC results are totally in line with the values recorded by the OEM during previous measurements with the same vehicle but on a different test site and tyres. This is also an important indication suggesting a good reproducibility of the air resistance measurement method.

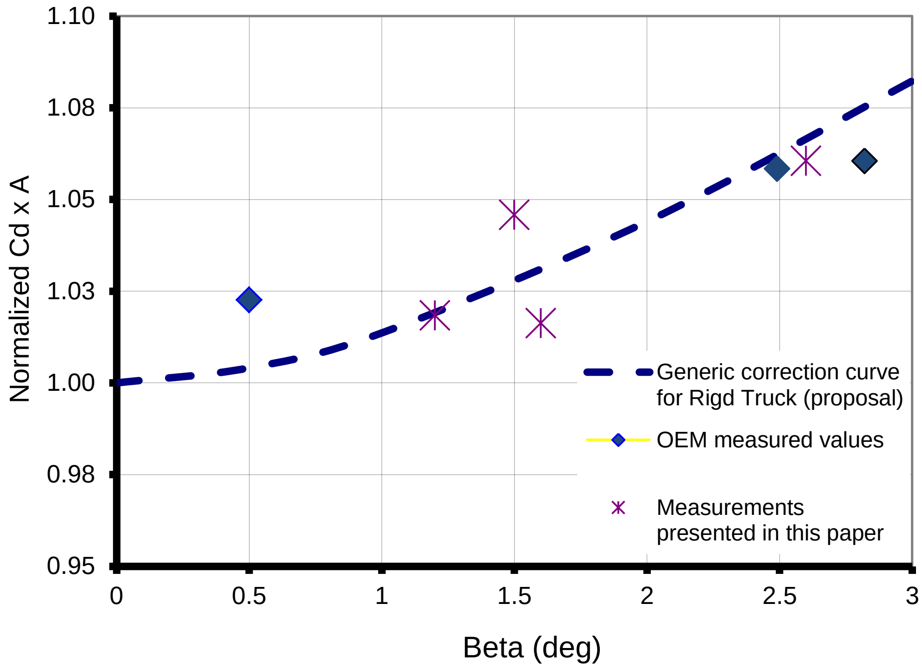


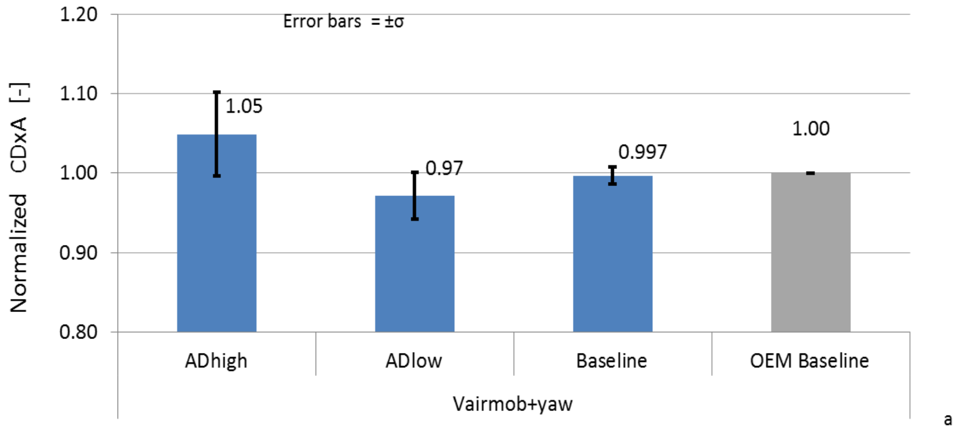
Figure 9 Normalized air drag vs yaw angle results for the CF75. Dashed line corresponds to the curve used for correcting results based on average yaw angle (β) in the Vairmob+yaw case.

In Figure 9 the generic curve used for correction of the average yaw value in the Vaimob+yaw case is also presented. With the exception of the measurements recorded by the OEM at vey low yaw, the curve appears to accurately capture the impact of wind angle β on vehicle's aerodynamic resistances. This is a first indication that the proposed correction factor approach foreseen by the proposed methodology is in the right direction. The final curves to be introduced in the proposed methodology for the various types of truck bodies and trailer combinations are still being elaborated.

3.1.2 Actros

Figure 10 and Table 8 summarize the results of the tests performed with the Actros vehicle based on the mobile anemometer value without yaw angle compensation ($v_{air,mob}$). As in the case of CF75 vehicle, the results measured with the baseline configuration were found close to the expected values (OEM measured average) for both air drag and calculated rolling resistance, with differences of - 0.3 % and 2 % respectively. The variability of the calculated air drag also reached similar values as for the previous vehicle (1.1 % compared to 1.6 %), while the variability of the calculated rolling resistance coefficient was much lower ranging at 2.3 % compared to 10.9 %.

It is reminded that in this case three different configurations of the vehicle were tested, baseline, one with slightly improved aerodynamic characteristics (AD_{low}) one with slightly deteriorated aerodynamic characteristics (AD_{high}) in order to test the sensitivity of the method. Both modifications were estimated according to OEM in the order of 2 - 4 %, with the exact amount being under investigation via CFD.



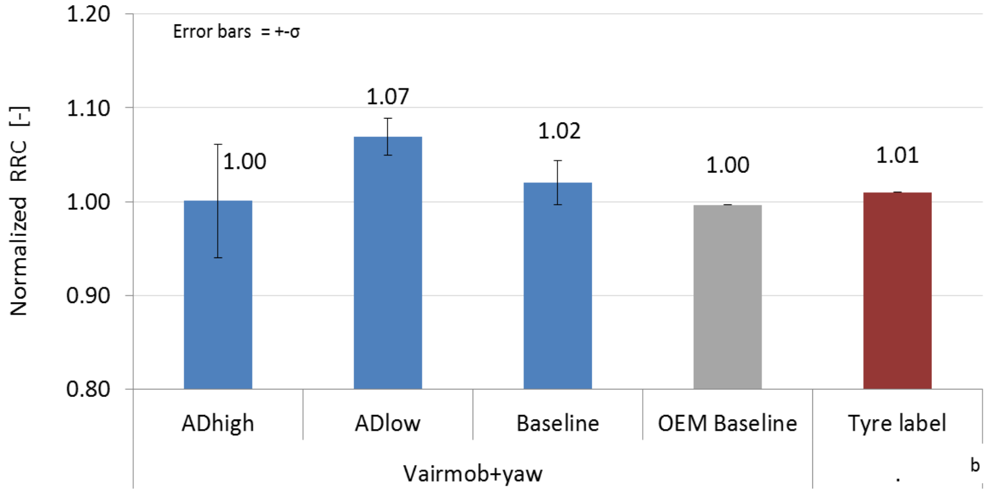


Figure 10 Aerodynamic resistance (a) and tyre rolling resistance (b) measurement results for Actros (values normalized by average OEM measured values)

The results show, that the test configurations AD_{low} and AD_{high} indeed present the lower and higher air drag, compared to the baseline configuration. The measured differences fall also within the expected ranges. This indicates that the air drag test method is sensitive enough to capture small changes in aerodynamic characteristics. Quantifying the exact limits of the method's sensitivity will require additional testing. In parallel supplementary work needs to be done with CFD or wind tunnel testing in order to accurately identify the effect of various additions on air drag before attempting to measure them on the test track.

Table 8 Summary of the differences of the measured values with respect to OEM for aerodynamic resistance and rolling resistance (results for baseline configuration)

Difference from OEM measurement for Cd • Acr [%]	- 0.3 %
Standard deviation of Cd • Acr measurement [%]	1.1 %
Difference from OEM value for RRC [%]	2.0 %
Standard deviation of RRC measurement [%]	2.3 %

The RRC values calculated during the measurements lay very close to the values officially reported for the particular tyres in most cases and also very close to the results of the tests performed by the OEM. The overall variability also recorded remained at lower levels compared to the tests performed with the rigid truck. Only exception regarding the RRC value measured is that of the ADlow test set. The latter may be attributed to a slightly different stabilization temperature of the tyres during this set of measurements. Still this increase of 7% probably had no influence on the final air drag calculated as the CDxA values remain in the expected range. Experience from the present and previous test campaigns suggests that the air drag calculation is rather robust with respect to fluctuations in the RRC value. Nonetheless an investigation on the topic is still on going.

3.1.2.1 Effect of Yaw angle and Comparison with Previous Tests on Actros

A further analysis of the the $C_d \cdot A_{cr}$ value was made in the case of the Actros vehicle in order to investigate the plausibility of the yaw angle correction option and compare with previous results. The options investigated included:

- Vehicle speed without consideration of the wind speed.
- Air flow speed measured with an on-board anemometer mounted above the driver's cabin.

In the case of on-board air flow measurement a correction for the yaw angle using a generic correction function for tractors with semitrailers was applied according to Figure 11.

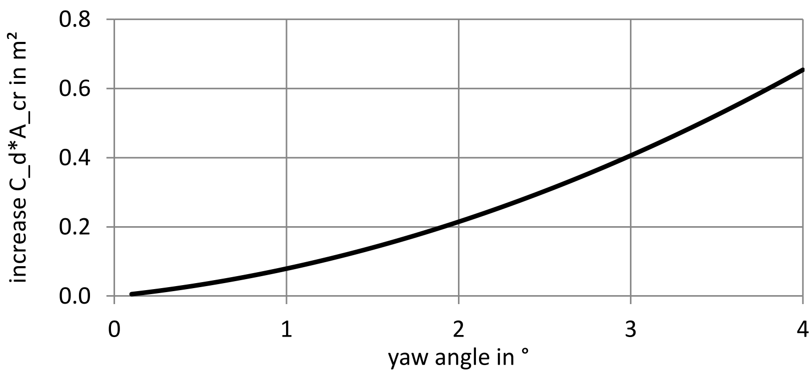


Figure 11: Characteristic curve of the yaw angle effect[11]

Results reported by ACEA, for the measurements of the Actros on the Klettwitz proving ground, show an average uncorrected $C_d \cdot A_{cr}$ value of 96.6 % of the correspondent Balocco value and an average absolute yaw angle of ca. 0.5 °[12].
Applying the generic yaw angle correction described above leads to a corrected $C_d \cdot A_{cr}$ value of 99.7 % of the correspondent Balocco value, also corrected for the yaw angle influence, see Figure 12.

[11] Daimler: Concept proof evaluation, p. 10. Stuttgart : Daimler trucks, 2013-03-20
[12] Also Daimler 2013-03-20, p. 10

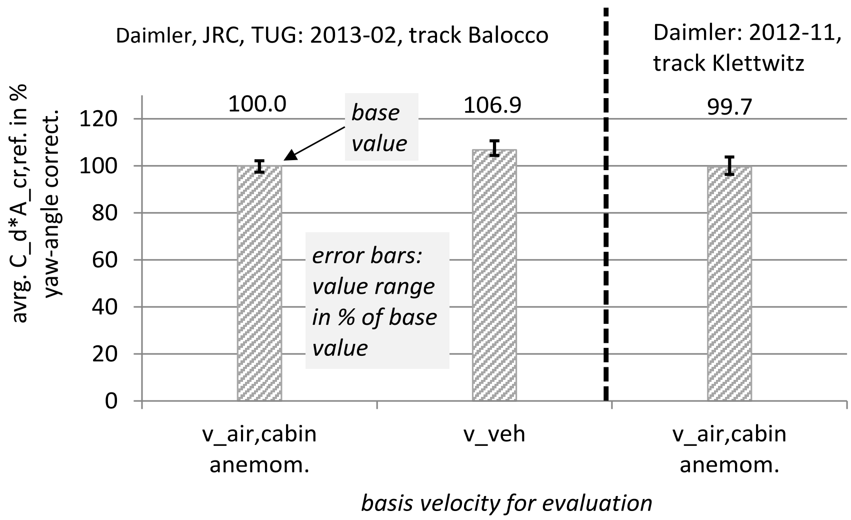


Figure 12: Comparison of the results for the $C_d \cdot A_{cr}$ evaluation for the Actros

Regarding the determination of the aerodynamic drag it can be concluded that:

- The novel method with constant speed and torque measurement is accurate and fulfills the demand of the CO_2 test procedure in terms of accuracy, repeatability and reproducibility.
- The details for instrumentation and for the calibration of the on-board wind speed measurement need to be finalized (accuracy of the anemometers and calibration of the angle). The methods applied here seem to perform adequately well.
- A correction for the yaw angle of the measured air flow around the vehicle improves the reproducibility of the results significantly. Thus it is suggested to try to elaborate robust generic functions as shown in Figure 11 for the different HDV categories.

3.1.3 Repeatability, reproducibility and robustness of the method

A first evaluation of the reproducibility and repeatability metrics of the proposed method were calculated based on the results of this study and those reported from previous measurements by the OEMs.Table 9 summarizes the calculated repeatability and reproducibility standard deviations (normalized by the average value recorded). The analysis is based on the results retrieved for corrected yaw wind angle. It was assumed that distribution of the test results is approximately normal

Table 9 Repeatability and reproducibility standard deviation of the method

	CF75 Present measurement	CF75 OEM tests	Actros Present measurement	-Actros OEM tests
Standard deviation	1.6%	1.8%	1.1%	1.4%
Repeatability standard deviation (σ_r)	2.4%		1.8%	
Between labs standard deviation	1.7%		1.3%	
Reproducibility standard deviation (σ_R))	2.9%		2.2%	

Given the fact that the method is still developing the achieved figures for the repeatability standard deviation (1.8-2.4%) and the reproducibility standard deviation (2.2%-2.9%) are considered satisfactory. Based on these results the repeatability limit (r), which is the value less than or equal to the absolute difference between two results, obtained under repeatability conditions, may be expected to be with a probability of 95%, is in the order of 4.9%-6.7% of the actual CD x A value measured [8].

With regards to the robustness of the method, first indications suggest good characteristics. When comparing the figures of

Table 6 for the C75F vehicle with those of Table 8 for Actros, one can observe an improved accuracy (0.3 % compared to 1.3 %) but also lower standard deviations (1.6 % vs 1.1 %) for $C_d \cdot A_{cr}$. The small differences in the two cases indicate a good robustness of the methodology in the sense, that differences in the instrumentation used during the measurements, ambient conditions and other details had a limited impact on the test results.

3.2 Vehicle measurements

3.2.1 On Road tests vs VECTO simulations

CF75[13]

A total of 7 different on road tests were performed with CF75 vehicle for the PoC study. Due to non-representative weather conditions (low temperatures, snow) 3 of them were not considered in the analysis. Over the remaining 4 measurements (tests no 1, 5, 6, 7) an average fuel consumption close to that claimed by the OEM was recorded. Over these tests the operation of the vehicle presented limited variations. The instantaneous vehicle speed and instantaneous RPM over the distance traveled during the 4 tests and the average performance are presented in Figure 13a and b respectively. All trips started and ended at the same position following the same route. Some limited differentiations in the total travelled distance (+-1km over a total of 107km) are attributed to minor changes in the path (eg different lanes) and measurement error. Figure 13 presents an overview of the vehicle instantaneous speed and instantaneous engine RPM values with respect to the trip distance traveled.

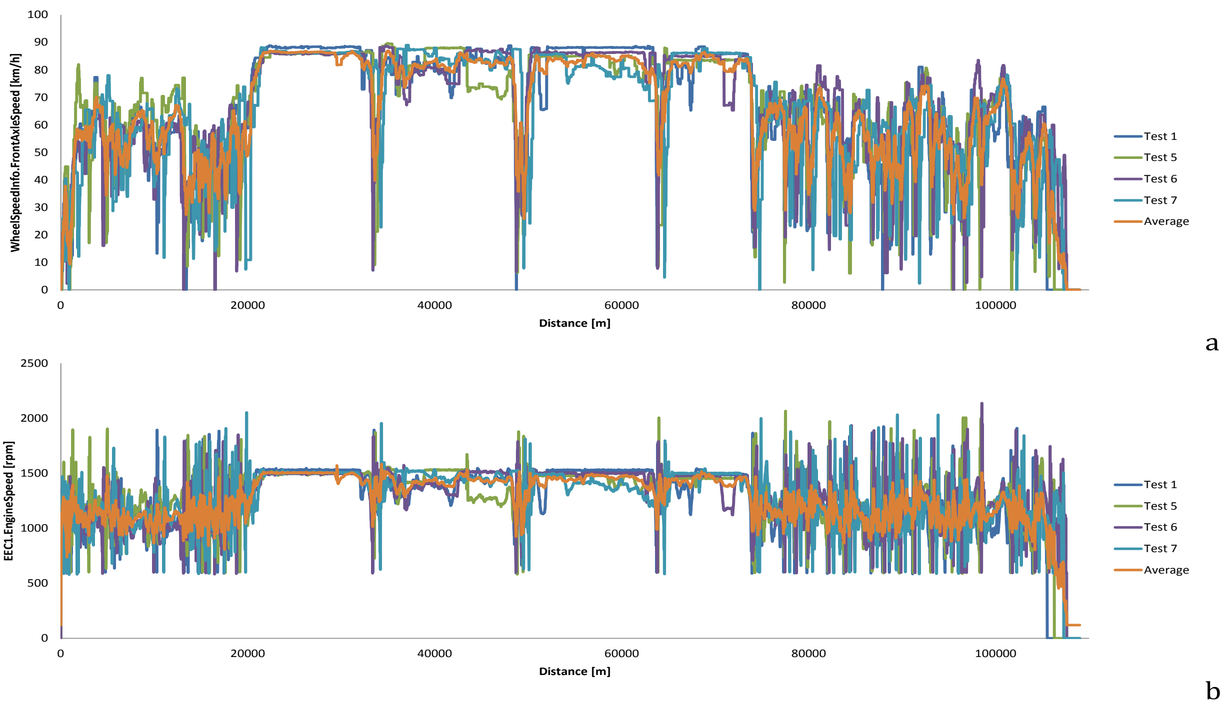


Figure 13 Overview of the vehicle speed (a) and engine RPM of on road tests that where considered valid

Figure 14 compares the total fuel consumption over the entire trip, as measured with two different systems and simulated with Vecto. Results are normalized with respect to the fuel flow meter instrument result and the error bars correspond to the standard deviation which was calculated in the order of 1.2%.

In general, the fuel flow meter was the instrument of reference used throughout the test campaign because of its higher precision and accuracy characteristics compared to fuel consumption calculation based on exhaust gas C-balance method. It is important to note that over the entire trip the fuel consumption measured with both systems presented very limited

[13] All simulations were performed by DAF based on input data provided by the JRC

variability, fact which in combination with the observations from Figure 13 point to good repeatability of the test conditions and the vehicle operation. Finally, the difference between the measurement and Vecto simulation (case 4[14]) was in the order of -1.8%, a very satisfactory figure.

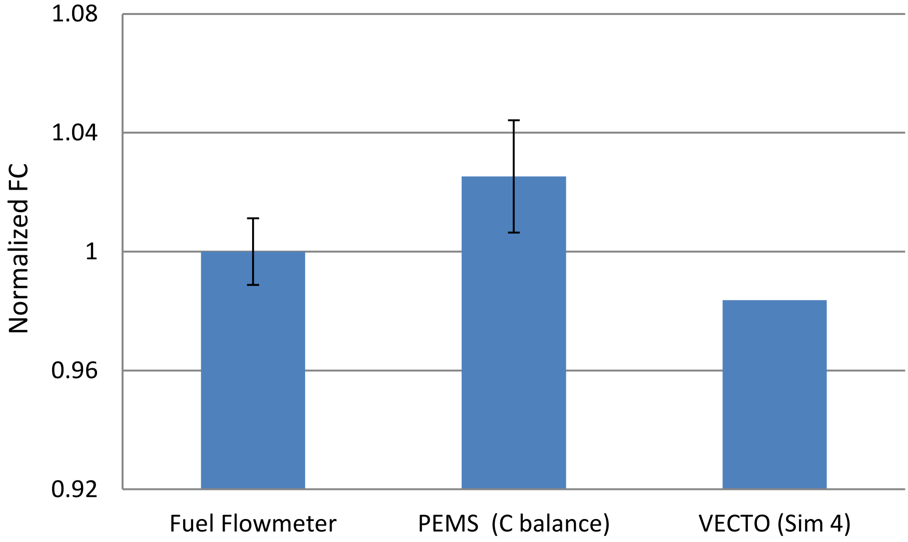


Figure 14 Average fuel consumption as measured over the 4 tests with the KMA fuel flow meter, calculated via C-balance of the exhaust gas measured with PEMS and simulated with Vecto (case 4). All values are normalized against the KMA measured consumption. Error bars show the standard deviation of the measurements.

In order to perform the simulations with VECTO, test run 1 was selected as being the most representative one of the average vehicle performance over all tests. During test 1 fuel consumption was measured to be 0.8% lower than the average of all tests. The full vehicle speed, engine status and weather conditions profile of test run1 was communicated to the OEM for deriving representative driving cycles to be simulated in VECTO. The simulation analysis performed with VECTO aimed to validate the simulated fuel consumption under different simulation assumptions (cases 1-5):

- Cases 1 and 2 followed a simulation approach based on **target speed** profile in contrast to the actual speed profile driven. In order to achieve this, the measured speed measured was converted into a target speed profile (as a function of distance). The target speed profile based simulation is the approach of choice for the future CO_2 monitoring scheme and the cycles proposed for the CO_2 monitoring methodology are target speed cycles. In simulation 1 the Vecto input parameters were derived based on the proposed CO_2 monitoring methodology, fact which makes simulation 1 the run that lays closest to the proposed CO2 monitoring methodology. In simulation 2 input parameters were selected to match as closely as possible individual components of the particular vehicle ("best actual parameters" [15]).
- Cases 3 and 4 are similar to 1 and 2. The difference is the use of the real speed profile recorded during test 1 as opposed to the target speed cycle. In particular simulation 4 in

[14] As will be explained onwards simulation case 4 is the simulation case investigated that most closely matched the test conditions.

[15] The term "best actual" refers to the results of individual component measurements (eg RRC) or best possible qualified assumptions made for certain input parameters (eg auxiliaries). This doesn't imply that the input values foreseen by the declaration methodology are less accurate or of lower quality. The declaration methodology has to provide values representative of an average real world operation, as functions of certain operating parameters, which will cover for the general case and not specific operating conditions. Thus the goal is quantify and if necessary limit the gap between specific operating conditions and the general case to be considered by the declaration methodology.

which the 'best actual' input parameters were used and the speed vs time profile was the measured is the simulation case that most closely matches the real experiment.

- Case 5 was run in order to investigate the influence of zero wind conditions simulation assumption with respect to actual wind conditions simulation. In this case the 'best actual' input parameters were introduced in VECTO and compared versus zero wind velocity air drag characteristics of simulation 4.

Figure 15 provides an overview of the characteristics of the actual route driven (measurement) and the two driving cycles simulated, the target speed (sim1& 2) and measured speed profile (sim 3,4,5).

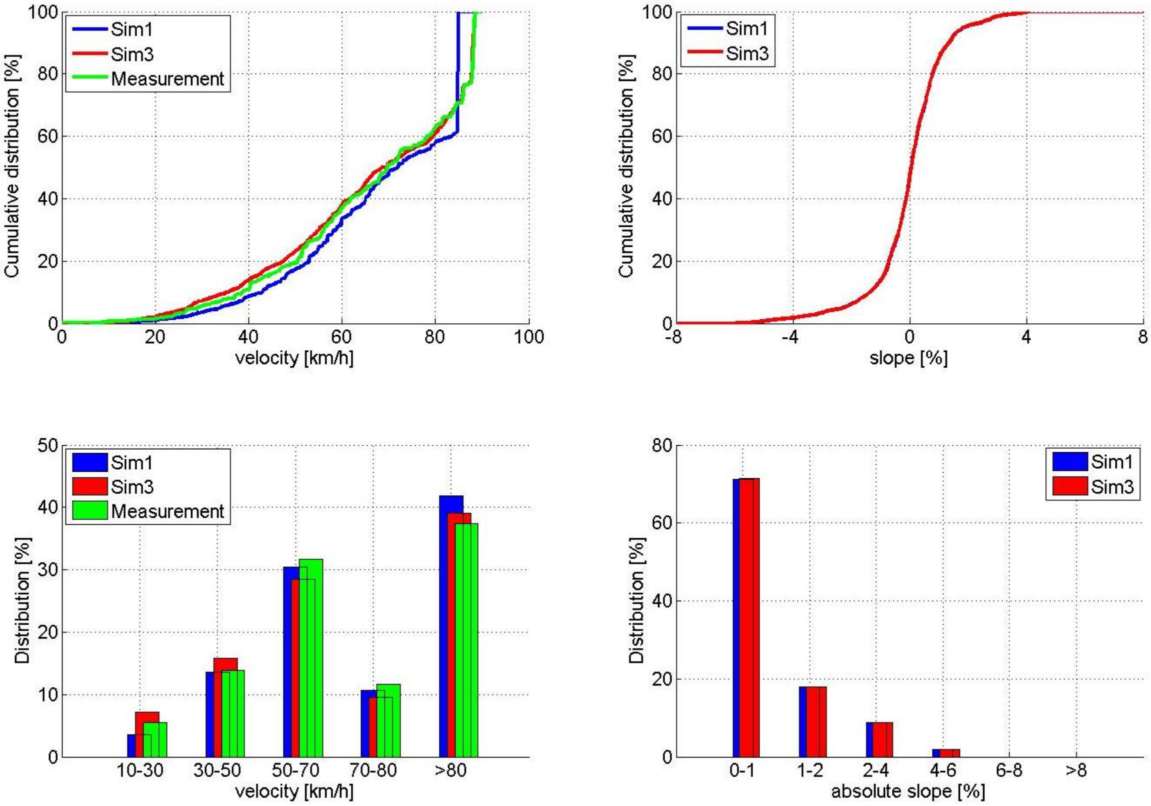


Figure 15 Drive cycle characteristics and speed distributions of Test1 used for simulations and simulation runs 1 and 3

A summary of the simulations matrix and the origin of variables used in the simulations is presented in the annex (6.6).

The deviations of the simulation results from the actual measured fuel consumption during test 1 are summarized in Table 7. As observed in all cases the simulation accuracy was good reaching minimum error of -0.5% and a maximum error of -3.21%. It is notable that the most accurate results are achieved when simulating the target speed profile with input parameters as proposed in the declaration method (sim 1), which is the simulation run most close to the certification method proposed. Very good accuracy is also achieved when reproducing the actual speed profile with the best actual input parameters (sim 4) which indicates that Vecto can closely reproduce the on road tests. It is important to mention that good accuracy is also achieved when using the declaration method input values with the actual speed profile. The zero wind assumption (sim5) as well as the application of best actual input parameters with the target speed profile (sim2) led to results of lower accuracy. However in both cases the error remained close to 3% which, given the fact that the simulation methodology is not fully optimized yet, is considered good. A graphical summary of the results is presented in Figure 16. The abovementioned results are fully in line with those of a similar analysis performed by DAF (see paragraph 6.2).

Table 10 Deviation of simulated fuel consumption to measured fuel consumption

	Parameters		
	Input parameters as proposed in declaration method	Best actual input parameters	Best actual input parameters with zero wind velocity air drag characteristics
Target speed profile	-0.50%	-3.21%	X
Measured speed profile	1.76%	-0.83%	-2.98%

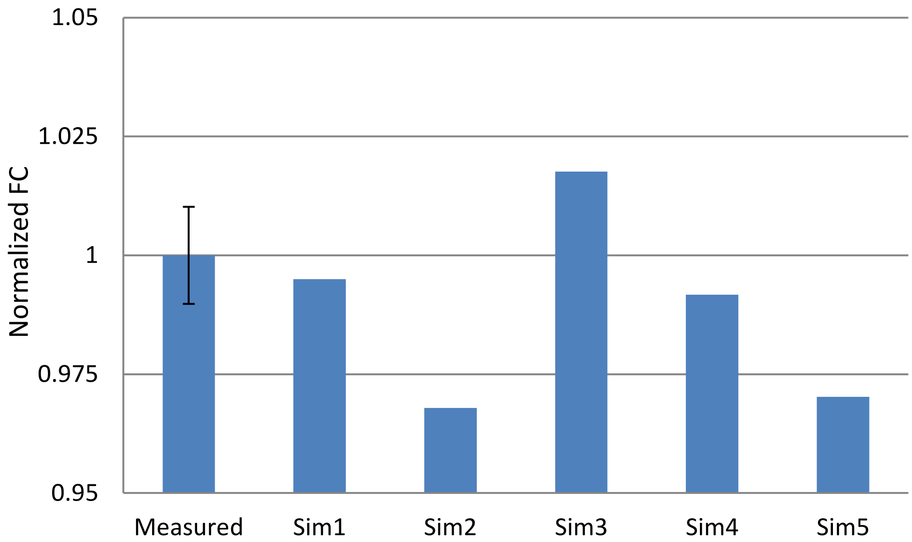


Figure 16 Measured vs simulated fuel consumption for CF75. Error bars correspond to +-σ.

A more in depth investigation of the ability of VECTO to reproduce the on road tests is presented in Figure 17. In the figure green dots indicate the normalized simulated fuel consumption at specific points of the test (measurement always equals to 1) and the red lines indicate the uncertainty of the fuel consumption measurement. Apart from the very good results obtained when simulating the total fuel consumption over the entire test, it is important to note that fuel consumption is fairly accurately simulated throughout the test (from 40km and on simulation result lay always within the uncertainty limits of the measurements).

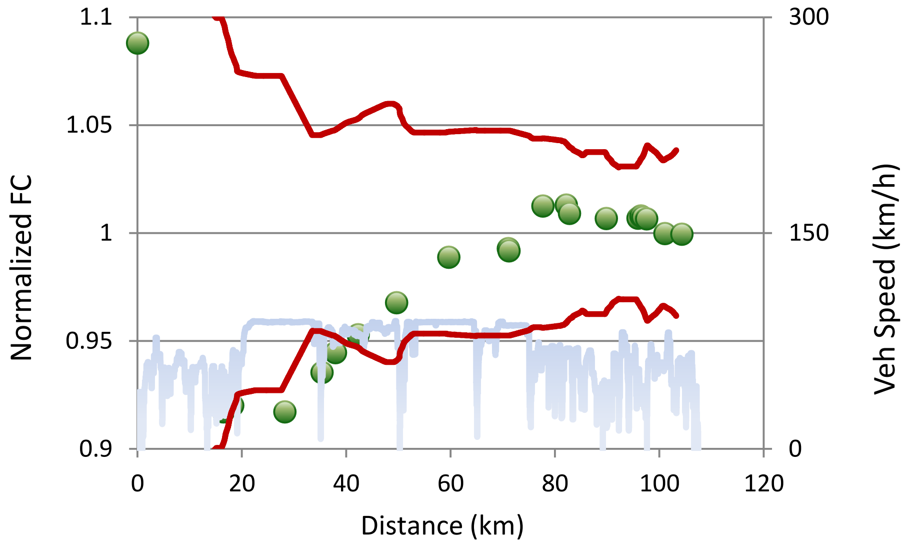


Figure 17 Normalized simulated fuel consumption over trip distance (1=fuel consumption measured during test 1). Greed dots correspond to simulation results while red lines indicate the measurement uncertainty on a 95% confidence interval. The blue trace indicates the speed over distance trace of the vehicle.

Regarding the inaccuracies associated with such a simulation, the OEM has provided some first estimation based on qualified assumptions. According to DAF the uncertainty of the simulated results ranges at about 2.5 %, a value close to that of the measurements.

Actros [16]

A series of on road tests (5 in total) were performed with the Actros vehicle from which the results of three ones were selected and analyzed. The started and ended at the JRC premises with a length of 108km[17].

From the 3 measurement runs, one was selected in order to develop the input cycle profiles for Vecto and conduct all simulations, that which presented fuel consumption closer to the average of all measurements. Over this reference run, fuel consumption[18] was 0.25% higher than the average value of the tests (the corresponding standard deviation of fuel consumption measurements was ~2%). In the simulations two different simulation scenarios were investigated:

- In the first case a target speed cycle was derived based on the measured speed vs time profile and GPS data
- In the second case the speed and slope vs. time dataseries recorded during the reference test were used.

Regarding input data origin, only one set of data was used in the simulation. The values of the input parameters considered were as follows:

- Declaration method boundaries for shifting, acceleration/deceleration
- Steady state engine fuel map with correction factor for highway cycle
- Auxiliary power assumed: 2.75 kW (constant)
- Transmission temperature: 80°C
- Axle temperature: 60°C
- Rolling resistance: 0.00593 (OEM measured value)
- Air drag (Cd x A): according to OEM measurement

Considering the input parameter used, simulation scenarios one and two are similar to (but not the same) simulation runs 1 and 3 respectively conducted for the CF75 truck.

The results of simulations 1 and 2 compared with the average measured fuel consumption are presented in Figure 1. Values are normalized with respect to the average fuel consumption recorded and error bars correspond to the standard deviation of the measurement. The difference between measured and simulated fuel consumption is provided also Table 11.

The accuracy of the simulations was overall good with simulation scenario 1 resulting in a 2.15% higher value compared to the measurement and scenario 2 presenting a difference of –1.8%. Such deviations fall inside the accuracy range that was observed for CF75. In this case the use of the target speed cycle compared to the actual speed vs time profile results in the level of error (~2%). Given that the actual measurement values presented a variability of 2%, it can be concluded that the method has a very good potential for closely depicting actual vehicle performance.

[16] All simulations performed by Daimler based on input provided by the JRC
[17] A deviation of 1km compared to the route followed with the CF75 vehicle was necessary due to the increased size of the Actros
[18] As measured with the on board AIC system

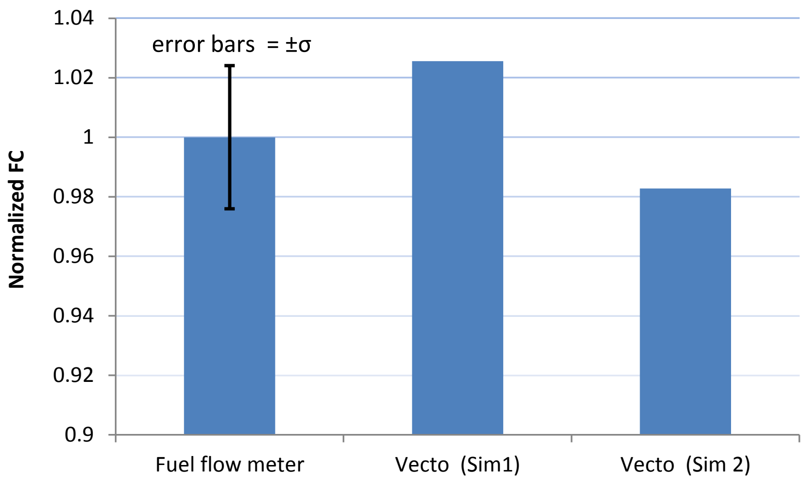


Figure 18 Normalized fuel consumption results for Actros measured vs simulated

Table 11 Summary of simulation results for Actros

	Difference from ref [%]
Sim 1	2.15%
Sim 2	-1.8%

The abovementioned results for the Actros truck are fully in line with those presented by Daimler regarding their internal PoC activity (see paragraph 6.2).

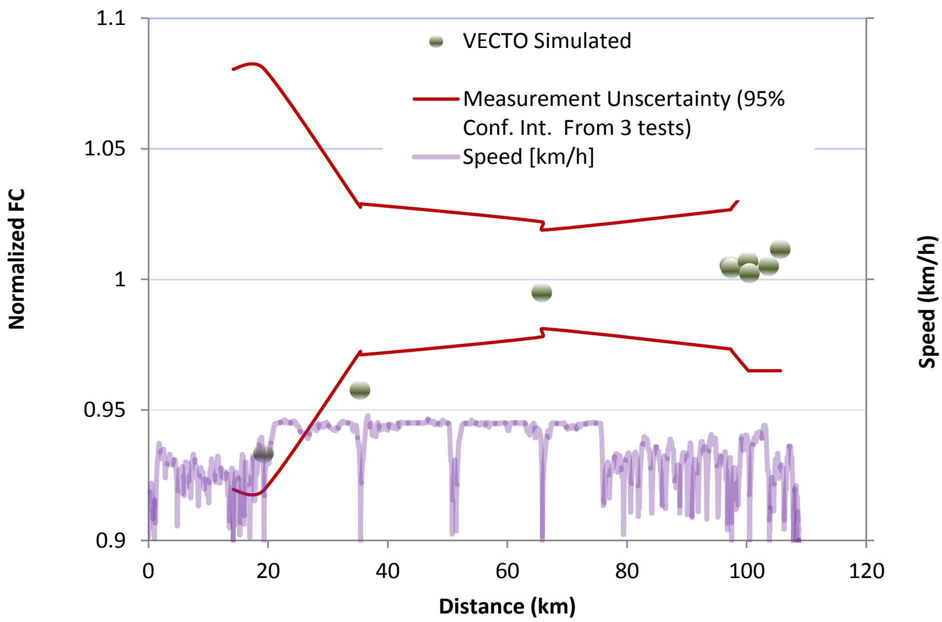


Figure 19 Normalized simulated fuel consumption over distance from start (1=fuel consumption measured during reference test) for Actros. Greed dots correspond to simulation results while red lines indicate the measurement uncertainty on a 95% confidence interval (+-2σ). The purple trace indicates the speed over distance trace of the vehicle.

Figure 19 presents a more in depth overview of the simulation's accuracy throughout the test. Average measured fuel consumption is equal to one throughout the trip while green dots correspond to the simulated fuel consumption at selected points during the test. Red lines indicate the calculated measurement uncertainty on 95% confidence interval.

Similarly to the previous vehicle, the simulation results fall within the uncertainty limits of the measurement during most part of the test. Simulated fuel consumption remains within a +-5% margin of the measured consumption for almost 75% of the total trip and within a +-3% range of the measured value for more than 50% of the trip. .

3.2.2 Chassis dyno measurements

In addition to the on road tests, a series of measurements were also performed in the JRC's chassis dyno over different driving cycles. Scope of these tests was to investigate the quality of the simulations under highly controlled operating conditions (no uncertainties introduced due to varying wind, temperature, traffic or road load conditions), , compare the uncertainty of a simulation run to that of a chassis dyno test and obtain a broader picture of the simulator's accuracy.

CF75

Figure 20 summarizes the fuel consumption results measured and simulated over the 3 driving cycles (WHTC, FIGE and ACEA regional). Results are presented normalized against the average values measured with the reference fuel flowmeter. In the first column (sub figs a,c,e), error bars correspond to the standard deviation of the measurement whereas in the second column the average recorded fuel consumption throughout the trip is equal to one and red lines correspond to the calculated uncertainty of the measurement on a 95% confidence interval. In subfigures b,d,f (second column) green dots represent the simulated fuel consumption at selected points of the test. In addition to the fuel consumption result obtain via the fuel flowmeter in subfigures c and e the result of 2 other fuel consumption measurement systems are presented (fuel flowmeter installed by DAF and fuel consumption derived from recorded raw CO_2 emissions.

As shown in subfigures a,c,e the total fuel consumption simulated with VECTO closely matched the measured fuel consumption in the case of WHVC and FIGE cycles where differences between calculated and measured results were in the order of 2%. Over the ACEA regional cycle the gap between measurement and simulation widened to 5%. However the measurement uncertainty was also higher in the case of the regional cycle, possibly due to the less repeatable vehicle operation compared to the other cycles. Still the increased fuel consumption over the simulation suggests a possible overestimation of a particular vehicle load, possibly the consumption of auxiliary systems.

As shown in subfigures b,d,f , vehicle fuel consumption was simulated fairly accurately not only over the entire driving cycles but also throughout them. In most cases the difference in measured-simulated fuel consumption was in the order of 5% or less. Very good performance was observed over WHTC where the simulated fuel consumption closely followed the measured one being almost always within a +-2% of the measured value. In the case of ACEA regional the simulated fuel consumption presented a constant offset of about 5% which as mentioned before was probably due to overestimations of vehicle auxiliary load. Finally over the FIGE cycle a mixed performance was observed. The final result was of good accuracy compared to the measurements, however over the cycle the simulation versus measured fuel consumption difference presented high fluctuations, reaching the maximum values observed over all cycles tested. A closer look suggests an important overestimation of fuel consumption over the urban-rural parts of the cycle accompanied by an apparent underestimation over the highway part which brings the end result close to the measured value. A more thorough investigation of the assumptions made in this case for the simulation is needed before reaching solid assumptions.

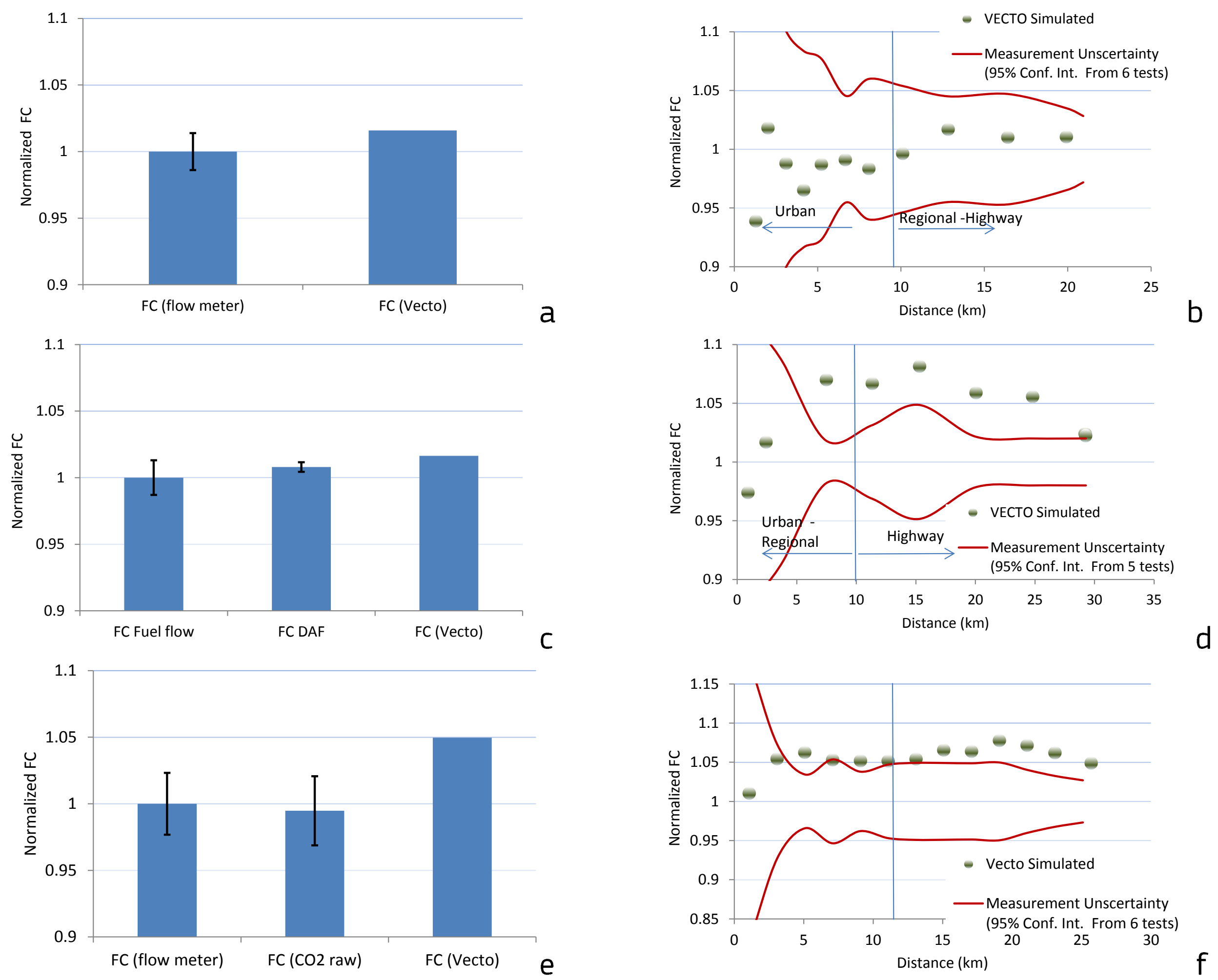


Figure 20 Measured vs simulated results for the driving cycles tested, WHVC (a-b), FIGE (c-d) ACEA regional (e-f). Error bars correspond to +-standard deviation of the measurements (sub figs a,c,e) whereas red lines to the 95% confidence interval of the tests

Overall, the results of the comparison are satisfactory, considering also the fact that no post optimization of the model was done based on the experimental findings.

Actros

Figure 21 summarizes the fuel consumption results measured and simulated over the 2 driving cycles (WHTC & FIGE). As for the CF75 vehicle, results are presented normalized against the average values measured with the reference fuel flowmeter. Error bars correspond to the standard deviation of the measurement (sub figs a,c,e), in subfigures b,d,f, the average recorded fuel consumption throughout the cycles is equal to one and red lines correspond to the calculated uncertainty of the measurement on a 95% confidence interval. In the latter subfigures green dots represent the simulated fuel consumption at selected points of the test cycles.

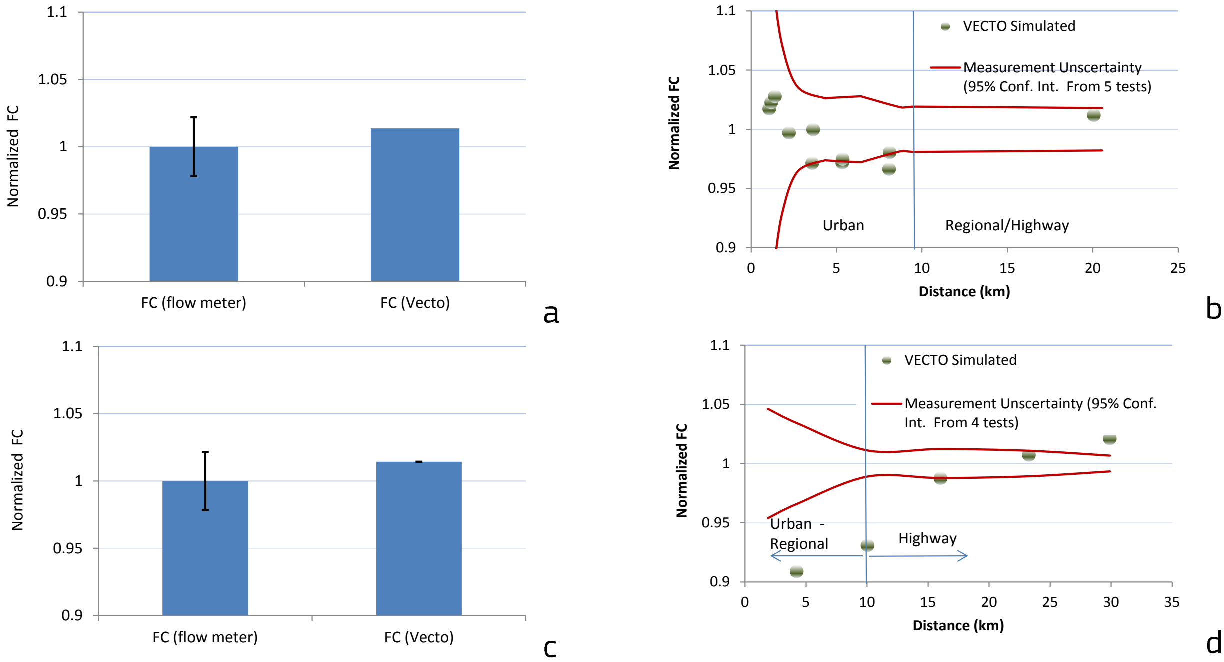


Figure 21 Measured vs simulated results for the driving cycles tested, WHVC (a-b), FIGE (c-d). Error bars correspond to +-standard deviation of the measurements (sub figs a,c,e) whereas red lines to the 95% confidence interval of the tests

For both WHTC and FIGE the overall results were very good with the measurement-simulation difference remaining at low levers (~2%). A view on the evolution of the simulated vs measured fuel consumption throughout the cycles (subfigs b, d) reveals very good performance of the model over WHVC with differences that did not exceed +-3% and laid within the uncertainty limits of the measurements. The model appears to slightly underestimate consumption over the urban part of the cycle and has a balanced behaviour over the regional-highway part. These observations coincide with those described previously for the CF75 vehicle. Over the FIGE cycle the picture was different with the model significantly underestimating consumption over the urban-regional part of the test and slightly overestimating during the highway part. Still most of the time the fuel consumption simulated was within +-5% of the measured value which, given the level of maturity of the simulation method, is considered an acceptable performance. Further analysis should be conducted for identifying the exact origin of the models

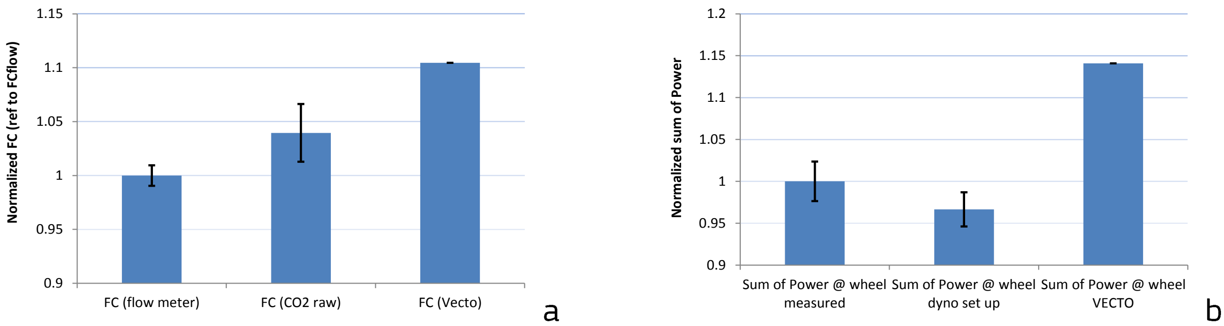


Figure 22 Measured vs simulated results for the ACEA regional cycle (a) and the corresponding measured vs simulated power at wheel (b). Error bars correspond to +-standard deviation of the measurements.

A notable difference between measured and simulated fuel consumption was observed for the ACEA regional cycle, which was in the order of 10% (Figure 22a). An analysis of the simulated power at vehicle wheel (Figure 22b) showed that the sum of the simulated power exceeded by 15% the sum of the average power applied at the wheel during the test. This observation suggests a possible erroneous assumption regarding vehicle resistances over the particular cycle or some other inaccuracy of the model that did not exist in the cases of WHTC or FIGE. Therefore, results of this simulation were not considered further.

Based on the overall pictured obtained from both vehicles, it is concluded that VECTO has the potential to accurately reproduce different driving conditions, particularly when certain sources of uncertainties are limited. Given that more sophisticated models of particular vehicle components will be included in future versions of the simulator (eg auxiliaries, gearboxes, drivelines, gearshifting strategies etc) it is expected that it will be possible to simulate fuel consumption over different operating conditions with results that will be within the uncertainty of the measurements.

3.3 Engine test results

The target of this validation exercise was to test the accuracy of the interpolation of the fuel consumption in transient test cycles from steady state engine maps in combination with the WHTC correction factors (Annex 6.6). This method is applied in VECTO to calculate the fuel flow from the simulated engine torque and engine speed course. For the validation purpose two different engines were measured on the engine test stand in the steady state engine map points and in transient cycles (WHTC and selected CO2 test cycles in their engine test bed version). The WHTC correction factor is the ratio of measured fuel consumption to the interpolated fuel consumption. Deviations can result from transient effects on the fuel efficiency, from the interpolation method and from inaccuracies in the measurements. Higher deviations are attributed to real physical background in the engine behavior and shall be corrected by application of the WHTC correction factors.

Figure 23 shows the calculated WHTC correction factors for the EURO III engine (engine#1). For the “urban delivery” cycle a correction factor of 1.016 is applied, the according values for the “regional delivery” and the “long haul” are very close to the value of 1.

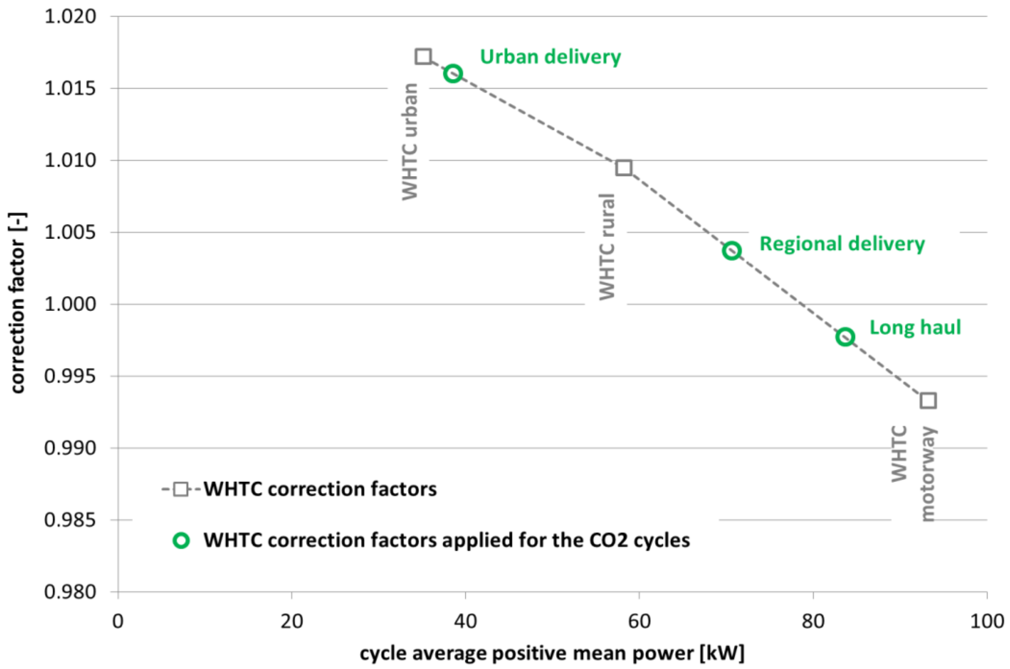


Figure 23: WHTC correction factors – engine#1

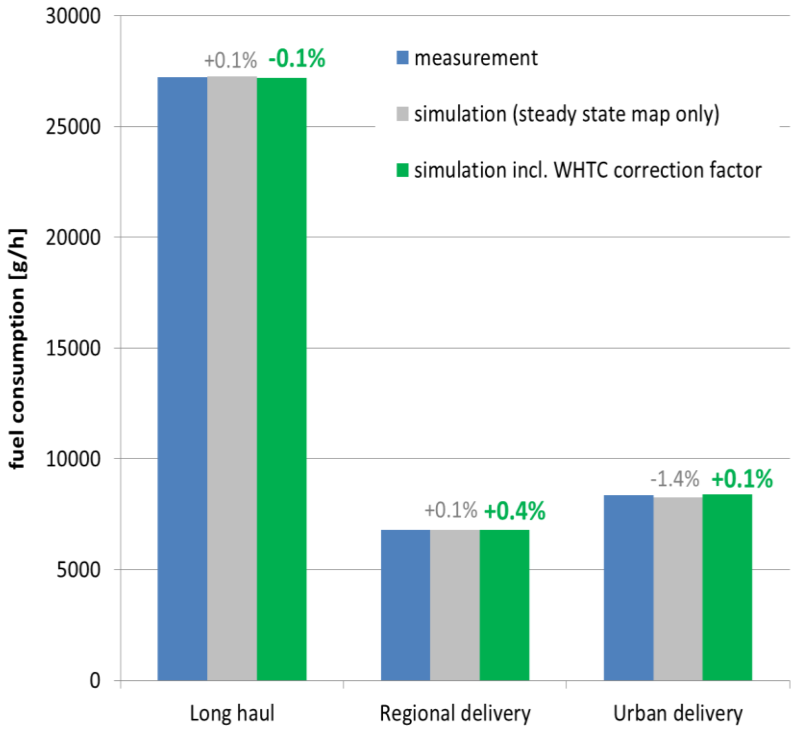


Figure 24: Comparison measured and simulated fuel consumption – engine#1

In Figure 24 the comparison between measured and simulated fuel consumption is given for the measured CO_2 test cycles. Bars and numbers in grey give the simulation results before application of the WHTC correction, green bars and numbers show the final results according to the actual proposal for HDV CO_2 simulation. The simulation results deviate from the measurement values only by a few tenth of a per cent which is within the typical accuracy of the measurement.

Figure 25 shows the WHTC correction factors as calculated for the EURO VI prototype engine (engine#2). This engine shows higher sensitivity of fuel consumption behaviour to different WHTC parts than the much less complex EURO III engine resulting in a higher spread of correction factors between the urban and the motorway part of the WHTC. For the validation exercise preformed here only a measurement of the “long haul” cycle was available. To get more data for validation in the analysis this measurement was divided into an “off-motorway part” (first and last 500 seconds of the cycle) and a “motorway part” (remaining 4300 seconds). The calculated WHTC correction factors for the different parts of the long-haul cycle are in a range of 0.994 to 0.997.

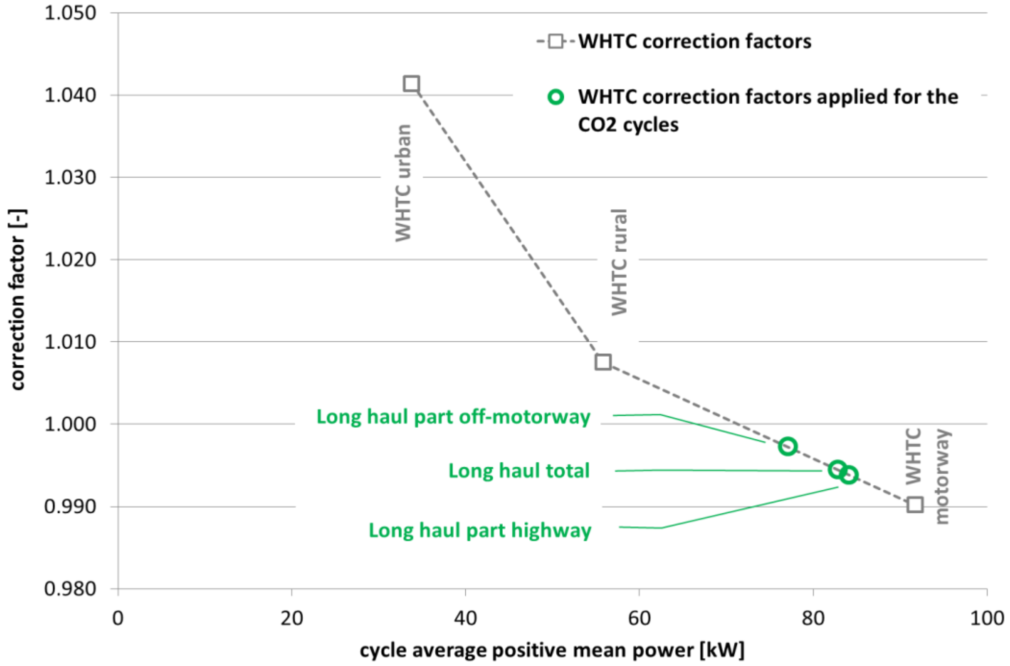


Figure 25: WHTC correction factors – engine#2

Figure 26 gives the comparison between measured and simulated fuel consumption for engine#2. The simulated values tend to underestimate the measured values; the application of the WHTC correction factors slightly increases this effect. The maximum deviation is found for the "off-highway" part of the long-haul cycle with an underestimation of 1.2%. This deviation can still be seen as acceptable as it is within the range of repeatability for fuel consumption measurement at the engine test bed .

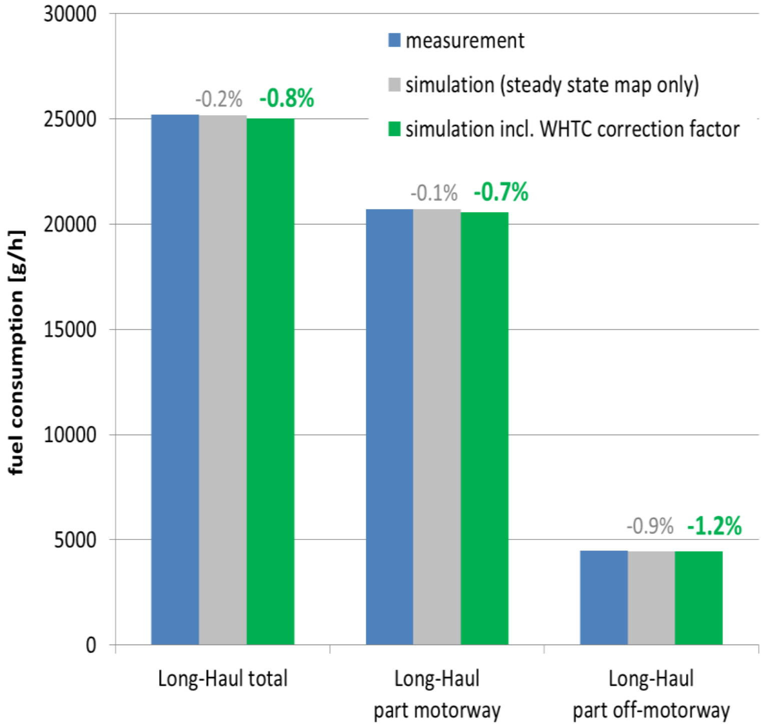


Figure 26: Comparison measured and simulated fuel consumption – engine#2

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

The validation of the engine fuel map and of the corresponding simulation method can be summarised as follows:

- Calculating fuel consumption through interpolation of fuel maps corresponding to steady state operation is an approach used in most vehicle simulation software, providing relatively good accuracy and that leads to some inaccuracies when simulating transient conditions.
- Applying the WHTC correction factor tends to improve the accuracy and is especially helpful in preventing cycle specific differences in engine tuning for fuel efficiency or for low NO_x emissions.
- The interpolation method for the WHTC fuel consumption needs to be specified in detail (which torque and speed signals and which inertia values have to be used).
- The best option for the application of the WHTC correction factor needs to be selected (power based interpolation or WHVC weighting factors). Both options give very good results.

4 Current status of CO_2 monitoring methodology

Scope of this paragraph is to provide insight regarding the current status of the development of the HDV CO_2 certification methodology and point out the key future steps towards establishing the necessary legislative framework for a vehicle simulation based certification scheme.

4.1 Testing handbook

One of the main objectives of the CO_2 HDV Lot 3 project is the development of a draft CO_2 emissions certification procedure based on defined measurements in combination with the simulation tool VECTO. The first step of this task is the development of a “testing handbook” to serve as basis for the pilot phase and technical annex to an already existing EC regulation or basis for a new regulation. Main contents of the final document are:

- Description of the test procedure(s) with the relevant equations, test conditions and responsibilities
- Description of the covered HDV categories
- Description of covered vehicle bodies and trailers
- Description of HDV family concepts for HDV CO2 certification
- Description of standards for measurements of relevant components
- Set of basis values for relevant components (including transmissions and auxiliaries) if no data from measurements is available and not mandatory
- Description of a random based monitoring and quality management (validation) of the official CO2 data by on board fuel flow measurement or equivalent systems.

A first draft version of the testing handbook based on the test procedures defined in Lot 2 and the ACEA whitebook (status December 2012) was delivered in January 2013. During the proof of concept phase the test procedures have been completely revised by ACEA. The updated versions have been delivered by the ACEA members in March and April 2013. The current status is listed in Table 12. The definition of family concepts is still ongoing.

Table 12 Current status of the testing handbook

Component	Status
Air Drag	Defined, agreed and detailed. Specification of measurement equipment is in progress.
Transmission	Defined, agreed and detailed. Specification of handling of AMT and retarder is in progress. Final default values t.b.d.
Axle	Defined, agreed and detailed. Final default values t.b.d.
Engine	Roughly defined and agreed. Details and specifications to be made.
Rolling Resistance	Use of RRC out of tire labeling seems to be appropriate. Discussions with tire manufacturers ongoing.
Auxiliaries	First proposal for testing of bus auxiliaries made by ACEA. To be detailed. Final default values t.b.d.

All procedures have been reviewed by TÜV NORD and final discussions on details and specifications are ongoing between TÜV NORD and the ACEA members. An updated version of the draft testing handbook including the main components is scheduled for April 2014.

4.2 Certification framework

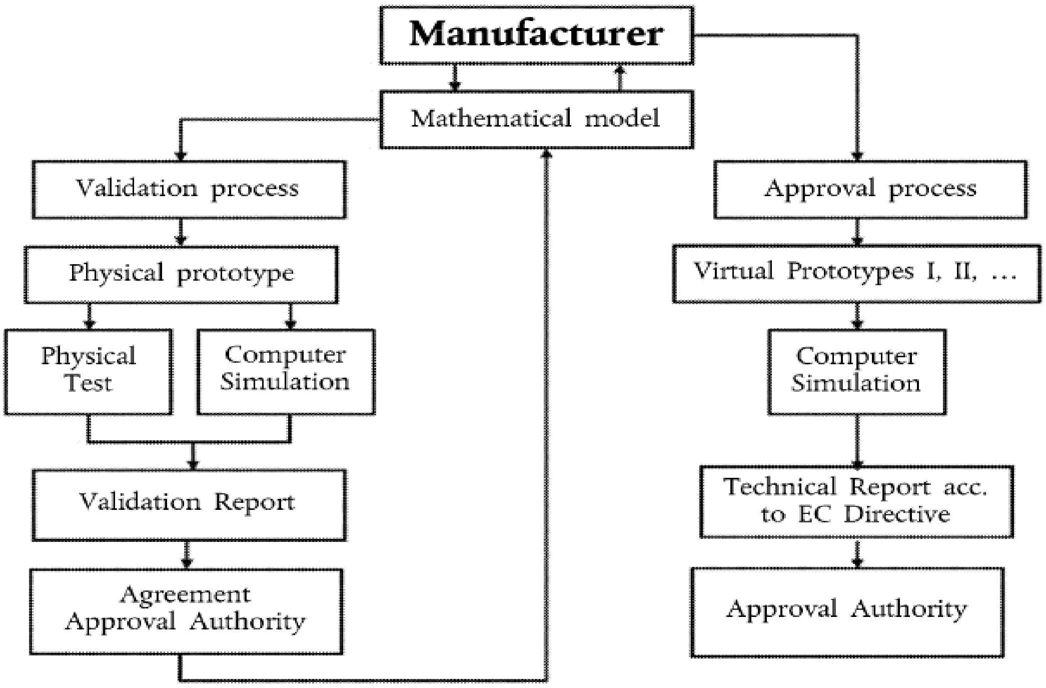
After discussions between DG CLIMA, JRC, TU Graz and TÜV NORD the first proposal for a certification procedure will follow an approach based on the framework directive 2007/46/EC. This decision is based on the following criteria:

- The framework directive covers environmental / safety and functionality related issues with or without regulated limit or criteria values.
- The CO2 / fuel consumption determination methodology to be developed can make use of the established framework process. There are no limitations obvious at the moment.
- The mandatory involvement of Type Approval Authorities (TAA) and Technical Services (TS) makes it easy to register values and allows for statistics and reporting.
- Almost all manufacturers are well recognized by their TAA and TS.
- The responsibility of the TS according to EN ISO/IEC 17020 and EN ISO/IEC 17025 ensures to create new methodologies for the assessment of "components" without the need of references to ISO or similar standards (e.g. not existing for gearboxes / axles / etc.).

Most type approval related tests and validations are based on "real" testing and validation procedures, methods and measures. The last large update to the framework directive (70/156/EC => 2007/46/EC) prepared the way to make use of *„virtual testing":*

"Virtual testing method" means computer simulations including calculations which demonstrate whether a vehicle, a system, a **component** or a separate technical unit fulfils the technical requirements of a regulatory act. For testing purposes, a virtual method does not require the use of a physical vehicle, system, component or separate technical unit. Nevertheless it has to be pointed out that the CO_2 procedure is based on physical testing of the components and only the compilation of the components to an entire HDV is done virtually.

Table 13 Handling of virtual testing in the certification process



The implementation of a certification procedure for HDV CO2 based on 2007/46/EC will have a direct impact on the following regulations with the need of adaption:

- 2007/46/EG – Framework directive
- EC No. 582/2011 (595/2009) – EURO VI

Further to check after detailing the procedure and the handling of each component are all regulations related to 2007/46/EG, e.g.

- EC No. 1222/2009, 1235/2011 – Tire labeling
- 2006/40/EC – Emissions from air conditioning systems
- 2001/85/EC– Vehicles used for the carriage of passengers comprising more than eight seats

4.3 Next steps in the development of the Test Procedure Handbook

- Further development of the Test Procedure Handbook focused on the applicability to the vehicle classes considered for the verification / pilot phase but keeping track of the more generic approach for future applications
- Detailing of the certification procedure after sensitivity analysis of input values for the simulation out of the measurements and definition on how to handle each single component.
- Further analysis of the multi-stage type approval approach with respect to it's nonrestrictive applicability to the heavy-duty vehicles classes as defined in Lot 2. Address, where necessary, additions or restrictions.
- Further analysis of the "virtual testing methods" recognized by 2007/46/EC if they can be applied to the simulation / modeling approach considered. Address, where necessary, additions or restrictions.
- Consideration of the extension approach for adoption on technical progress.
- List all vehicles / vehicle combinations which shall be not considered in general.

5 Conclusions and Follow up

Simulation tools, and in this particular case VECTO, can reproduce real world performance of Heavy Duty vehicles with satisfactory accuracy. In this exercise and for the HDV categories tested, the simulated fuel consumption of on road real world operation was calculated always within a +-~3% range from the real world measurement, and in several cases even closer than that (in the order of +-1.5%). Given the variability of the actual measurement (σ=2%) and the fact that according to European legislation a +-3% margin is already considered acceptable for the passenger car CO_2 declaration (chassis dyno measurement), it is concluded that a future certification scheme can be based on vehicle simulation tools.

Analysis of different simulation scenarios showed that the declaration method considered, although not finalised yet, can provide results that are representative of the real world performance of HDVs, provided that the appropriate input data are available. A first quantification indicated that the uncertainty of a simulation based declaration method is in the order of 2% but further analysis is still needed to validate this number. Additional input on the accuracy and the uncertainties of the model is expected in the final report of the LOT3 project.

It should be noted that the most important factor affecting fuel consumption of vehicles and thus the representativity of any “certification value” is the mission profile. This study did not investigate in the representativity of the divining cycles proposed by ACEA for the needs of the CO_2 monitoring. Such activity would require extensive datasets regarding HDV operation which are for the moment not available. The analysis performed has indicated a very good correlation between the fuel consumption simulated over the ACEA regional cycle and the fuel consumption measured over real world conditions (2% difference in the case of CF75 and 1.7% in the case of Actros). It for the interest both of the Commission and the OEMs to propose cycles of the best possible representativity which should be revised and updated in the future according to the evolutions in European HDV sector and operating conditions throughout Europe.

Important effort is being put in the development of methods to generate input data. For the long haul, regional/delivery trucks and coaches the most important parameters are aerodynamic characteristics, rolling resistance, mass, engine map, gearbox map, axle efficiency and driver performance simulation. In the case of aerodynamics, rolling resistance, engine mapping, mass and driver model, the methods proposed for defining input parameters appear to be mature enough to support CO_2 declaration through vehicle simulation. Further development and validation is necessary for the rest of the input parameters mentioned. However it is considered feasible to finalize also those within the timelines set by DG Clima.

In particular regarding air drag and rolling resistance input values calculation, values measured with both methods were found close to those reported by manufacturers and tyre OEMs respectively. This fact indicates good reproducibility; low standard deviations of measured values also indicate good repeatability of the measurement method. It was positive that results captured small changes in aerodynamic characteristics, which suggests a satisfactory sensitivity of the method. It was also positive that the measured rolling resistance values were found to be close to those measured according to the tyre certification test. Given the uncertainty associated with the measurement of rolling resistance coefficient, it is advisable that the relevant input value is provided directly from tyre OEMs, based on measurements conducted according to certified methods.

It should be noted that the aerodynamic characteristics measurement is very sensitive to certain factors such as the air speed meter positioning and calibration. A robust approach to wind correction method, instrument positioning, common for all OEMs and HDV categories of interest, needs to be clearly defined. Additionally, the method is very sensitive to weather conditions so clear specifications regarding the allowed ranges for weather conditions during the tests need to be set.

Regarding follow up activities for the near future it is important to:

- Continue and further elaborate on the analysis of the different PoC activities performed also by the manufacturers and other measurements to be conducted as part of a “pilot phase” in collaboration with the OEMs.
- Finalize and validate topics remaining open in the methodology such, gearbox and driveline efficiencies, auxiliary units power consumption, automatic gear shifting strategies, mobile air conditioning simulation for city buses
- Perform a sensitivity analysis in order to more accurately quantify the uncertainty of the method for different vehicle types/categories
- Apply the method to a larger number of vehicles, and in particular in different vehicle types, in order to better validate its accuracy and to provide sources for the establishment of default data base for minor important components, such as transmission losses and power demand from auxiliaries in trucks. (verification phase)
- Investigate the necessary conditions for expanding the methodology to other HDV categories
- Update VECTO in order to cover all aspects of the declaration methodology
- Lay down the foundations for a full scale application of the declaration methodology on many different vehicle types in collaboration with the OEMs (pilot phase).

Acknowledgements

The PoC experimental campaign and this report would have never been possible without the efforts and support of the following people:

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6 Annex

6.1 Steady state tests

6.1.1 Summary of Proposed Methodology

The general model (eq 1) that describes the aerodynamic resistances applied on a vehicle is considered by the vehicle simulator to be used for CO_2 monitoring.

$$F_{air} = C_d(\beta) \cdot A_{cr} \cdot \frac{\rho_{air,ref}}{2} \cdot v_{air}^{\ 2} \quad (1)$$

where:

F_{air}	=	air drag [N]
C_d	=	air drag coefficient [-]
β	=	average air flow angle (yaw angle) [°]
A_{cr}	=	cross sectional area of the vehicle [m²]
$\rho_{air,ref}$	=	air density at reference conditions,[kg/m³]
v_{vair}	=	wind velocity [m/s]

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

Given the abovementioned measured data and information regarding the slope profile of the test sections, it is possible to calculate the road load of the vehicle (see Figure 27) based on the following qualified assumptions:

- rolling resistance force (F_{rol}) independent of vehicle speed[19]
- air drag force being quadratic to the velocity

The aerodynamic drag is calculated, for yaw angles (β) between 0 and 3º, based on the actual measured air flow velocity.

19 Rolling resistance is influenced by vehicle speed. However the analysis performed in parallel to the measurements showed that the influence is limited under the defined test conditions and does not affect significantly the calculated air drag value. Studies are ongoing in order to find a way to include the effect of speed on rolling resistance value into the AD calculation method

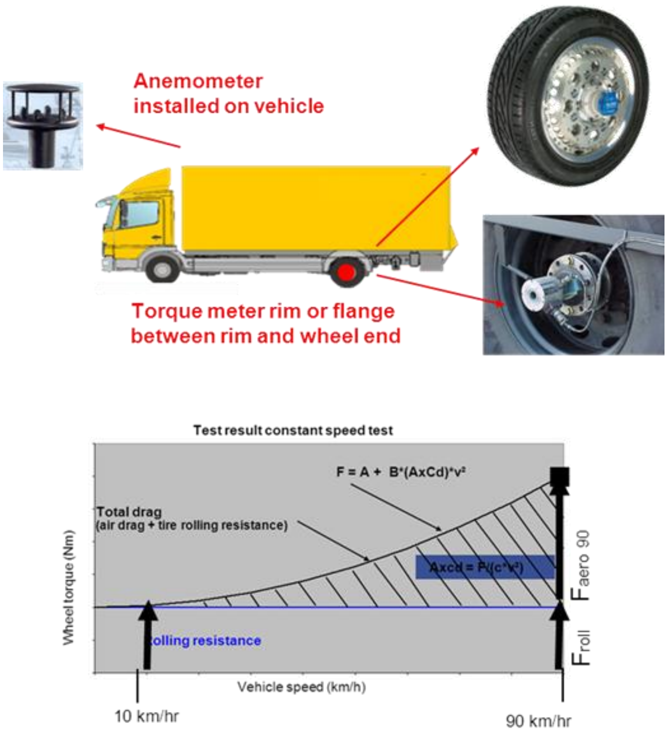


Figure 27 Key points of the proposed testing methodology

In addition to the key elements of the test demonstrated in Figure 27, important parameters of the procedure include the use of high precision positioning instrumentation for accurate recording of vehicle position and ground speed (opto-electronic barriers or very high precision GPS system), weather information and data retrieved from vehicle sensors. Detailed specifications are foreseen for each instrument and for the sampled signals.

Test Track

In terms of the testing ground different types of test track geometries are foreseen (Figure 28). The important factor in this case is the execution of measurements in both directions in order to cancel out to the best possible extent the effects of ambient wind. The test track must have straight section(s) were the measurements are performed. An extra straight length before each measurement section is foreseen in order to allow for the stabilization of wind flow around the vehicle or the drivetrain torque after cornering.

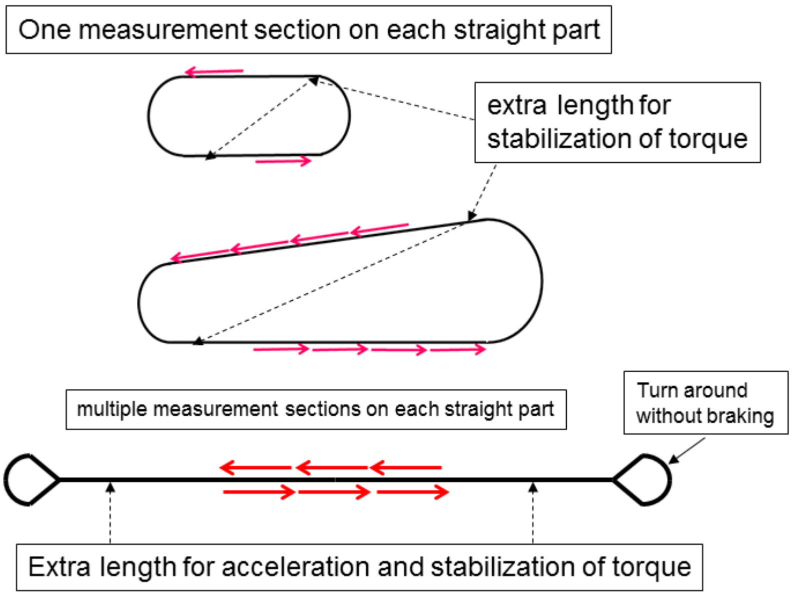


Figure 28 Testing grounds and segments

Test sequence

The test is comprised of 5 phases, the preparation phase, the warm up phase, the high speed test phase, the low speed test phase and control phase as described below.

Preparation phase

During this phase, the various measurement instruments are mounted on the vehicle and their good operation is checked (e.g. the drive-wheels should be checked for proper rotation with installed torque meters or half shafts). The vehicle's mass is measured or calculated and the tyres are checked for the maximum allowable inflation pressure. The proper vehicle and trailer (if present) heights are verified.

The positioning equipment is also set up during this phase, either only on the test track (final definition of test section via installation of the opto-electronic barriers) or on the vehicle and on the test track via high precision differential GPS.

Data registration of all relevant measurement signals is verified and the engine is left at idling for preconditioning without parking brake.

Warm-up phase

During this phase the vehicle is driven for 90 minutes at V_{high} to assure that the tyres reach a constant pressure and temperature level, and that the powertrain and drivetrain reach a constant coolant and lubricant temperature level. During this phase, the vehicle is driven in both track directions in order to achieve a balanced warm up of the tires and collect data for subsequent control checks, and for determining the misalignment and position error of the mobile anemometer.

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

High speed test phase

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

- the driving speed is constant at least for the defined measurement sections and the preceding stabilization sections
- the vehicle is driven through the measurement section along a straight line without steering
- the amount of recorded measurement sections leads to enough valid “evaluation sections” in the data processing
- a minimum of 20 measurement sections for each driving direction are performed with an equal amount of sections driven in both directions; e.g.: either enough rounds on an one-way circuit track with two measurement sections or an equal amount of measurements driven in each direction on a circuit or straight line track with one measurement section;

Low speed test

The test at V_{low} is performed directly after the high speed test. As in the case of the V_{high} test it must be ensured that the driving speed is constant at least for the measurement sections and the preceding stabilization sections and that the vehicle is driven through the measurement section along a straight line without steering.
In both V_{high} and V_{low} tests the beginning and end of the measurement sections should be clearly recognizable in the measurement data, either via a recorded trigger signal (opto-electronic barriers) or via recorded GPS data.

Control phase

During this phase a series of quality control checks are foreseen, mainly to establish that the drift of the torque sensors remained within acceptable values. The drift check of torque meters, performed in this phase, depends on the type of the torque measurement instrument and it may involve a free roll out of the vehicle or lifting of the driven axle off the ground.
In addition to drift, some general checks such as controlling axle/wheel bearings for overheating and a general re-check of the vehicle configuration are also foreseen.

Post processing

A series of post processing corrections on measured data are foreseen. The recorded average vehicle speed is corrected based on the information retrieved from the optical barriers or the high precision GPS. The air flow velocity signal of the mobile anemometer is corrected in three steps for the instrument’s error as defined by the calibration report, the error generated by the positioning of the instrument on the vehicle (measuring position inside an accelerated flow due to the shape of the vehicle) and the air flow boundary layer effect and the yaw angle misalignment. Additional corrections are foreseen for compensating the torque sensor drift during the test. In the latter case a linear distribution of drift over time is performed.

6.1.2 The CSE tool

The software tool allows for evaluation of driving resistance tests as foreseen in the HDV CO2 certification procedure with the different options of wind correction as described in LOT 2. Additional statistical criteria have been elaborated which allow for an appraisal of the quality of the measurement data and the reliability of the determined driving resistances.

Main input data are measured velocity trajectories with x- and y-coordinates from GPS, the torque measured with the wheel rim torque meters, the ambient temperature and pressure, wind speed measured on-board and stationary, a separately measured height profile of the test track, the vehicle mass and the frontal area. In addition the fuel flow measured on the vehicles in the verification phase will be used as input for a later validation.

Results are the average driving resistance force calculated for each phase of the test run, the resulting driving resistance polynomial equation ($F = A + B*v^2$) and the resulting air resistance coefficient Cd(β) for the evaluation methods with and without wind correction.

The air drag resistance force is calculated by

$$F_{air} = (C_d(\beta) \cdot A_{cr} \cdot \frac{\rho_{air,ref}}{2} \cdot v_{veh}{}^2)$$

where:

F_{air}	=	air drag [N]
C_d	=	air drag coefficient [-]
A_{cr}	=	cross sectional area of the vehicle [m²]
β	=	average wind angle [°]
$\rho_{air,ref}$	=	air density at reference conditions, 1.188 [kg/m³]
v_{veh}	=	vehicle velocity [m/s]

In addition the average fuel consumption for the different constant speed phases is calculated as basis for verification runs with the VECTO tool. Where relevant, the standard deviation of the measured quantities is provided together with the average values as basis for statistical analysis in LOT 3. A detailed description can be found in[20].

[20] Rexeis M., Luz R., Hausberger S.: Development of a Heavy Duty Vehicle CO2 Emissions and Fuel Consumption Simulation Tool, Final Report; performed by order of JRC; Service contract CCR.IET.C109756.X0; University of Technology Graz (TUG); 2012

6.1.3 Common features and key differences of the test protocols employed during steady state tests.

The measurements with both vehicles followed the general guidelines and procedural restrictions of the proposed methodology, described previously. Both vehicles were tested at V_{high} of 89 km/h and V_{low} of 15 km/h on the same measurement sections (see Figure 4). The same type of mobile anemometer (Table 2) was used for measuring the air flow velocity and angle, and the same general test protocol regarding the various phases was applied. The methodology permits multiple measurement instruments, for CF75 and Actros were used:

- Application of different torque measurement systems (see Table 3)
- Vehicle positioning measurements where conducted with high precision differential GPS in the case of Actros and opto-electronic barriers in the case of CF75
- In the case of Actros, different vehicle configurations affecting air drag were tested.

Table 14 Common features and differences in the constant speed tests performed with Actros and CF75

Common Features	Key differences
Warm up period (aprox 90mins or until temperature in differential has been stabilized)	**Torque measurement**: wheel rim (Actros), axis (CF75)
Low speed: 15km/h	**Vehicle position measurement**: using high precision GPS (Actros), using sensors at fixed points
High Speed: 89km/h	**Driving rotation**: both directions (Actros), initial test sets one direction final test set both directions (CF75)
Wind speed and wind angle measured using on board windspeed meter	**Speed sequence**: High-Low (Actros), Low-High-Low (CF75)
Zeroing of torque sensors before each test	**Torque drift measurement**: Vehicle lifting (Actros), vehicle free coasting (CF75)
Same effective segments on test track	**Torque sensor drift correction**: Linear correction with time (Actros), discard measurement criterion (CF75)
	Windspeed sensor positioning: Above tractor and trailer (Actros), above trailer (CF75)
	Windspeed correction: factor derived from measurements for each speed (Actros), factor based on winspeed meter position, wind speed and angle (CF75)

6.2 VELA 7 facility

Figure 29 presents an overview of the VELA 7 facility built for HDV emissions, fuel consumption and performance testing.

The chassis dynamometer (Zoellner GmbH, Germany) can host trucks and buses of up to 40 tons in weight, 12 m in length, and 5 m in height; maximal test speed is 150 km/h. The test cell can be conditioned between -30 and +50 °C with relative humidity between 15% and 95% (in the temperature range of +5 to +25 °C). The constant-volume sampler (CVS) for full exhaust dilution (AVL, Graz, Austria) is equipped with 4 Venturis of 10, 20, 40, and 80 m3/min in order to achieve a maximum air flow of 150 m3/min. Dilution air is taken from the test cell, conditioned to 22 °C, and filtered through high-efficiency particulate air (HEPA) and activated charcoal filters. The climatic test cell of VELA 7 has an air circulation system that provides enough number of cell air changes (≥15) in order to allow the testing of vehicles fuelled with diesel, gasoline, CH_2, LH_2, LPG, LNG and CNG. The cell is equipped with dedicated sensors for gaseous fuels.

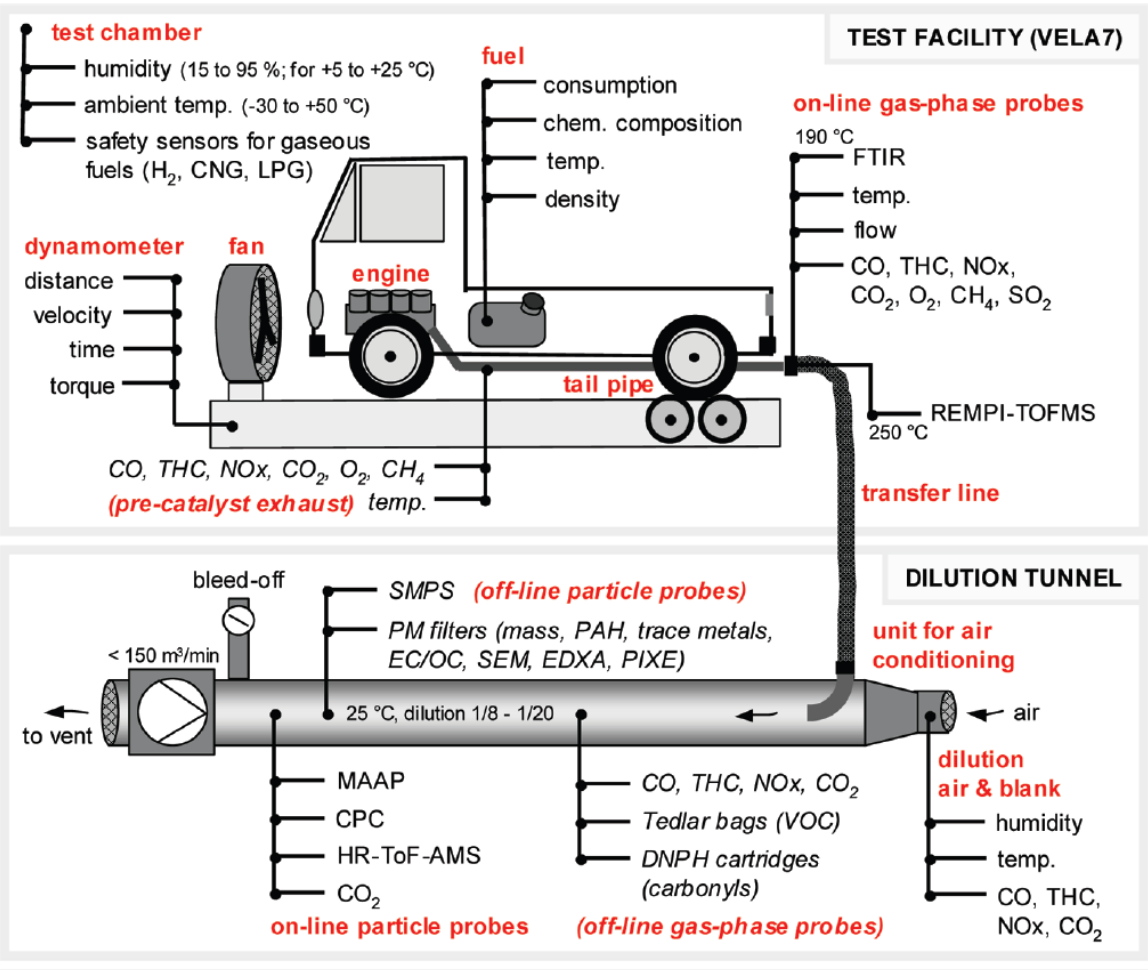
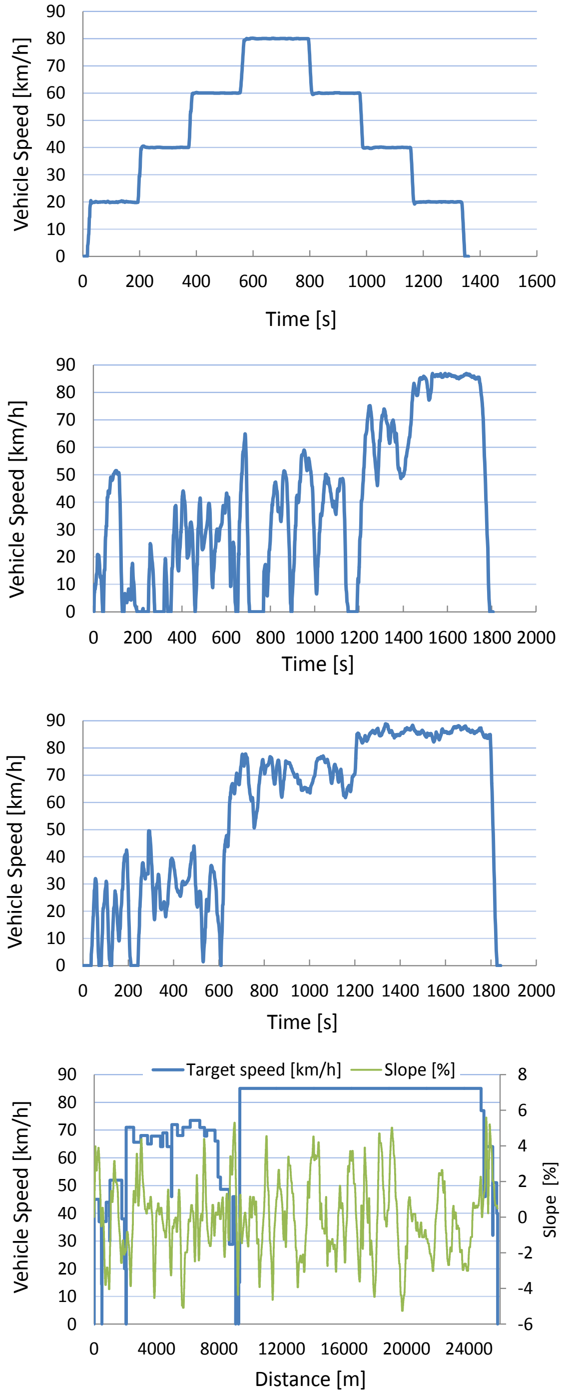


Figure 29 Overview of the VELA 7 test facility

For the analysis of pollutant emissions an AVL i60 AMA 4000 system is used.

6.3 Test Cycles

The following four cycles were tested during the chassis dyno tests.



a

b

c

d

Figure 30 Steady state modes (a), WHVC (b), FIGE (c) and ARDC (d)

6.4 Summary of OEM Proof of Concept activities

Both OEMs participated in the PoC study performed similar independent in house studies the results of which are confidential.

6.5 Evaluation of the aerodynamic drag at TUG

In this chapter the air drag measurement on Fiat's test track Balocco, between Milano and Torino, with an articulated truck MB Actros 1845 LL and Kögel semitrailer are evaluated and compared with the earlier measurements on the test track Klettwitz. Both measurements were conducted by the Daimler measurement team in cooperation with DG JRC and accompanied by TU Graz. The three tests with standard aerodynamic configuration were evaluated here to analyse the repeatability and the reproducibility of the results for the aerodynamic resistance values for a HDV from different test tracks.

The methodology as described earlier for the Constant Speed Evaluator Tool (CSE)[21] was applied for all measurements. Details of the anemometer calibration procedure followed the actual White Book from ACEA.

6.5.1 Approach

The methodology to test the aerodynamic drag of a HDV is based on constant speed driving with the measurement of the torque at the wheel hubs. The aerodynamic drag depends on the second order of relative speed between the vehicle and the air. This relative speed depends on the vehicle velocity and the wind speed and the relative angle between vehicle driving directory and wind. The on-board anemometer measures the relative air flow velocity and - angle between the vehicle and the surrounding air, including wind. The measured values include the flow disturbance by the displacement of the moving vehicle and thus need to be corrected. In addition the mounting angle of the anemometer needs to be calibrated to provide a correct yaw angle. An open task from LOT 2 is to define the details in the measurement procedure for the relative air velocity. All relevant measurands have been recorded by Daimler and JRC to apply the evaluation routine for all options for wind velocity under discussion. The evaluation procedure included in all cases the correction for road gradient[22] and velocity drift. Following options were evaluated:

- Vehicle speed. No consideration of the wind speed.
- Wind speed measured with an on-board anemometer mounted above the driver's cabin.
- As planned: Anemometer mounted ca. 1.3 m above the upper front edge of the trailer. The same measurands as from the cabin anemometer, but at another position [23]. For the evaluated standard configuration only one valid measurement with the trailer anemometer is available, for the other two tests the anemometer was out of order. So this one result is not shown below because nothing can be said about repeatability or reproducibility.

The air drag - increasing effect of the yaw angle was corrected according to the actual ACEA proposal. The generic curve for the correction is shown in Figure 31:

[21] Kies, A. et al. 2012. Constant Speed Evaluation Tool V1.0 Technical documentation. Graz : TU Graz, Institute for ICE and thermodynamics, 2012. Report No. I 22/12/Rex EM I 10/12/679.

[22] In this case a highly precise DGPS instrument was mounted on the cabin and measured the altitude of the moving vehicle. In the resulting gradient profiles an "oscillation" could be observed: The reason was the soft air suspension of the cabin, the DGPS measured even its moves in the cm-range. For the final procedure a stationary DGPS measurement of the track, e. g. at fixed points every 50 m, is proposed.

[23] ACEA. 2013-03-22. Draft procedure for characterizing air drag by constant speed tests. Bruxelles : ACEA Workgroup-CO2HDV, Aero expert group TF1, 2013-03-22.

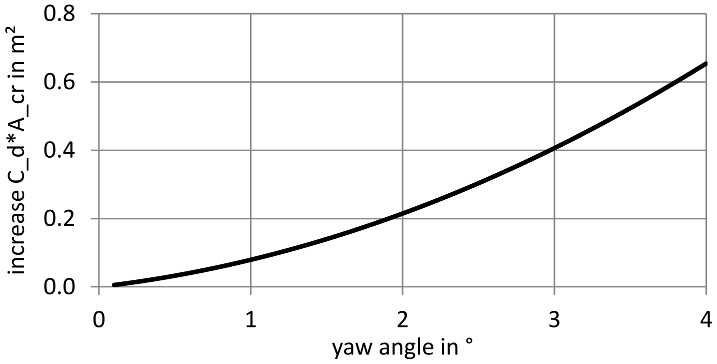


Figure 31: Characteristic curve of the yaw angle effect (Daimler, 2013-03-20, p. 10)

6.5.2 Data post processing and validation

The raw air flow velocity of the cabin anemometer needs to be corrected since the moving vehicle itself disturbs the surrounding flow. As already proposed, the average air flow velocity at high speed, only on the straights and projected to driving direction, ($v_{air,x}$) was correlated to the average vehicle velocity[24]. The resulting correction factor is:

v_{veh} / $v_{air,x,cabin\text{-}anemom}$ = 1.082

This factor was applied to calculate the corrected air flow velocity which was used for the further evaluation.

It was checked, if the yaw angle needs to be corrected for a twisted anemometer. This instrument shall be in theory exactly positioned to 0 ° equals straight forward driving direction, what is not always the case. For control reasons the average of all yaw angles (positive and negative) at high speed on the straights was calculated and plotted, see Figure 32.

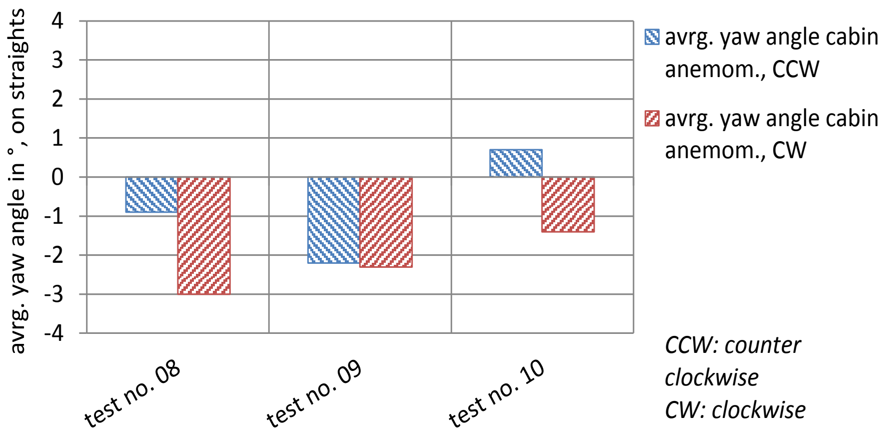


Figure 32: Yaw angle averaged over both directions at 89 km/h

The single test runs with the HDV were conducted in both senses of rotation: Clockwise and counter-clockwise.

From goniometry the target value of the average measured angle at the anemometer can be computed from the vehicle velocity, wind speed and yaw angle. At 85 km/h and 5 m/s wind speed

[24] Kies, A. et al. 2012. Constant Speed Evaluation Tool V1.0 Technical documentation. Graz : TU Graz, Institute for ICE and thermodynamics, 2012. Report No. I 22/12/Rex EM I 10/12/679.

the measured angle at the anemometer shall be between +1.3° and -1.3°[25].The deviation from the measured average angle against this ideal average angle would be the correction value.

The analysis of the tests in Balocco showed rather high average measured angles. Since the wind velocity was high, including gusts and small direction changes, and the straights at Balocco are not exactly parallel, the result includes uncertainties here and thus the yaw angle was not corrected for twist. ACEA proposes a procedure for twist correction requiring low wind velocities[26]. To apply this method, a definition of “low wind velocities” and the measurement procedure for the wind need to be elaborated. Looking for a more robust alternative method for the calibration of the angle is suggested[27].

6.5.3 Results and accuracy

Results reported by ACEA, for the measurements of the Actros on the Klettwitz proving ground, show an average uncorrected $C_d \cdot A_{cr}$ value of 96.6 % of the correspondent Balocco value and an average absolute yaw angle of ca. 0.5 °[28].

Applying the generic yaw angle correction described above leads to a corrected $C_d \cdot A_{cr}$ value of 99.7 % of the correspondent Balocco value, also corrected for the yaw angle influence, see Figure 33.

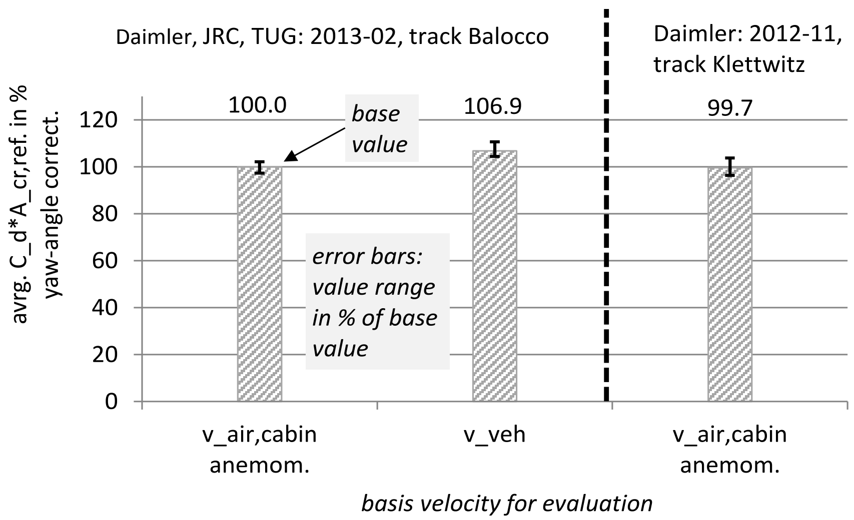


Figure 33: Comparison of the results for the $C_d \cdot A_{cr}$ evaluation for the Actros

[25] Depends on the yaw angle. With 0° or 180° yaw angle the angle measured at the anemometer certainly is zero, at 45° yaw angle the measured average angle is a maximum. At 1 m/s the measured angle at the anemometer shall be between -0.05 and +0.05°

[26] ACEA. 2013-03-22. Draft procedure for characterizing air drag by constant speed tests. Bruxelles : ACEA Workgroup-CO2HDV, Aero expert group TF1, 2013-03-22.

[27] An option seems to use a (small) blower which blows against the HDV with 0° angle in a hall and to record the measured angle. The accuracy of such a test at the low wind speeds provided by a simple small blower needs to be tested.

[28] Also Daimler 2013-03-20, p. 10

For the detailed evaluation results see Table 15

Table 15: Detailed results of the evaluation of the HDV tests at Balocco

	test no. 08	test no. 09	test no. 10	F0 avrg	F2 avrg	C_d*A_cr 9)	SD 10)
F0 in N, v_veh 1)	100%	103%	97%	100%			
F2 in Ns^2/m^2, v_veh 2)	99%	98%	103%		100%		
CI95; F0 in %F0 3)	3.4	2.9	4.1				
CI95; F2 in %F2 4)	4.6	4.4	5.8				
C_d*A,ref, raw in m^2 5)	106%	104%	111%			107%	3%
F0 in N, v_air,cabin	100%	103%	97%	100%			
F2 in Ns^2/m^2, v_air,cabin	101%	97%	102%		100%		
CI95; F0 in %F0	2.7	2.8	4.1				
CI95; F2 in %F2	3.7	4.2	5.8				
C_d*A,ref, raw in m^2	105%	100%	106%			104%	
avrg. abs. beta cabin 89 in ° 6)	2.3	1.9	2.0		*base for all red*		
Delta C_d*A_cr generic in m^2 7)	-0.27	-0.20	-0.21			*% values* ↓	
C_d*A,ref,corr-beta-cabin in m^2 8)	100%	97%	102%			100%	2%

1) rolling resistance, the constant part of the road load curve

2) air drag, the quadratic part of the road load curve

3) the 95 % confidence interval of F0, unit 'percentage of F0'

4) the 95 % confidence interval of F2, unit 'percentage of F2'

5) the effective air drag area C_d*A_cr, corrected from measurement to reference conditions (20 °C, 1 bar, 50 % rel. humidity), *w/o correction of yaw angle influence*

6) the *average absolute value* of the yaw angle only on the straights at 89 km/h, measured with the anemometer mounted on the cabin

7) the reduction of C_d*A_cr due to the yaw angle, taken from the agreed curve

8) the effective air drag area C_d*A_cr, corrected to reference ambient conditions and no crosswind

9) the average value of the reference C_d*A_cr

10) the standard deviation of the evaluated measurements in form of the corrected sample variance:
$SD = 1 / (n - 1) * \Sigma [(C_d*A_{cr})_i - (C_d*A_{cr})_{avrg}]^2$

When from future measurements valid tests with the trailer anemometer under equal conditions on the same track are available, a distinction between cabin and trailer anemometer is possible.

6.6 Simulation of on road measurements

CF75

In Table 16 notation Sim 1, 2, 3 etc corresponds to the cases mentioned in the report. Table 17 provides a summary of the origin of the input variables used in each simulation run.

Table 16 Summary of the simulations performed for the CF vehicle

	Parameters		
	Input parameters as proposed in declaration method	**Best actual input parameters**	**Best actual input parameters with zero wind velocity air drag**
Target speed profile	Sim1	Sim2	X
Measured speed profile	Sim3	Sim4	Sim5

Table 17 Origin of input values used in each of the 5 simulation runs[29]

	Wind velocity	**Air drag curve**	**Rolling resistance**	**Auxiliaries**	**Steerpump**
Sim1	DM	DM	TL	BA	DM
Sim2	JRC	DM	TL	BA	DM
Sim3	DM	JRC	JRC	BA	BA
Sim4	JRC	JRC	JRC	BA	BA
Sim5	0	JRC	JRC	BA	BA

JRC: JRC Measurement
TL: Tire label
BA: Best assumption
DM: Decleration Method

29

It should be noted that for all basic input modules the input used was derived either from the measurements performed during the PoC (JRC) or from the table values currently foreseen by the proposed methodology (DM). In lack of solid default values for auxiliary power consumption, the best possible assumption was made (BA).

6.7 Measuring the power at the wheels

The figures below summarize the results of the power measured at the wheel over the steady state chassis dyno tests. The power derived from the torque measurement system (power torque meter) is compared against the power signal recorded by the chassis dyno bench (Dyno power) and the indicative power signal recorded from the engine (engine power) for CF75 (a) and Actros (b). Each vehicle carried a different torque measurement system (CF75 was equipped with a Himelstein strain gauge system at the wheel halfsafts while Actros was equipped with a Kistler wheel torque measurement hub). The performance of both systems over steady state conditions was good. The signals recorded closely matched that of the chassis dyno and engine particularly at high loads. Certain deviations that were observed are attributed to slip between wheel and the dyno's dum. Experience has shown that over lower load conditions and transient cycles the CF75's system was in general less stable than the wheel hub torque measurement system. However it is expected that both systems present the necessary characteristics needed for an accurate measurement of the aerodynamic resistance coefficient of the HDVs.

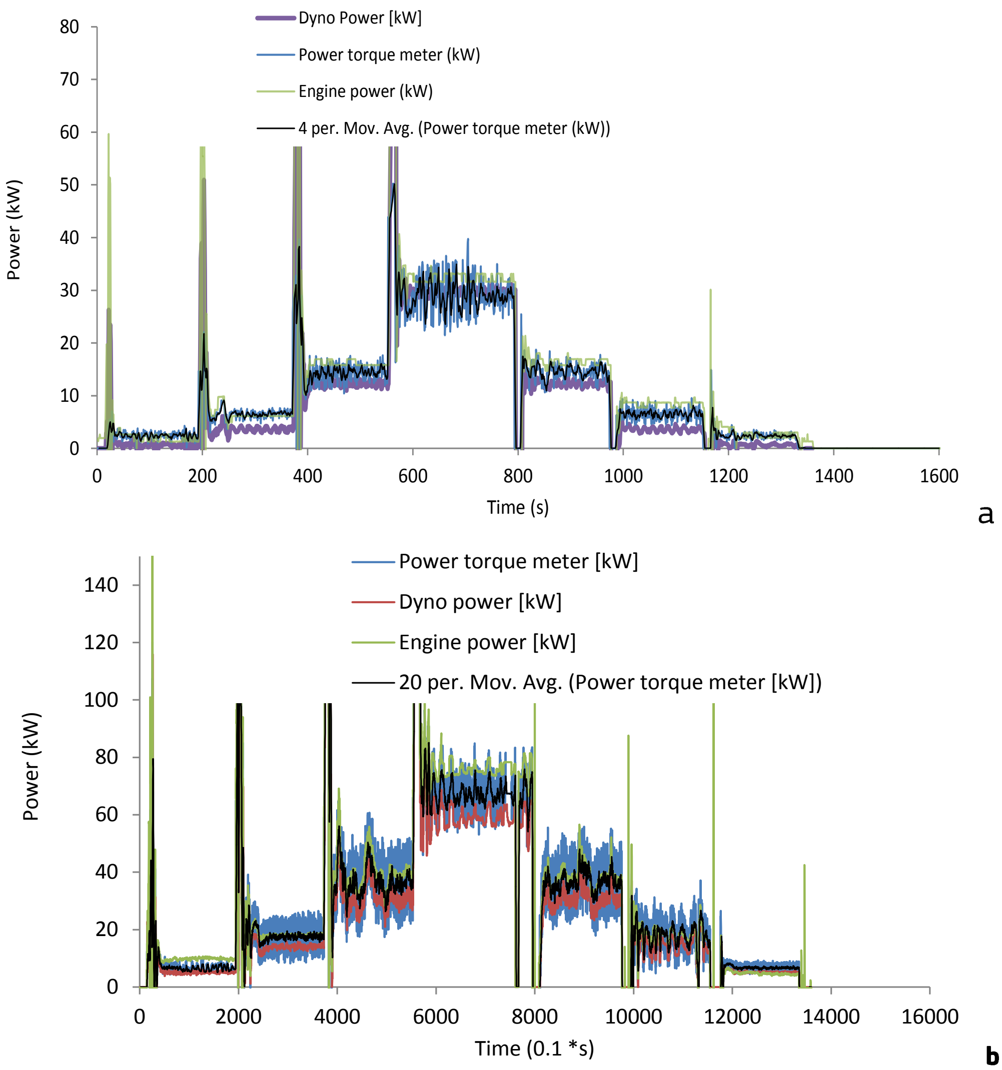
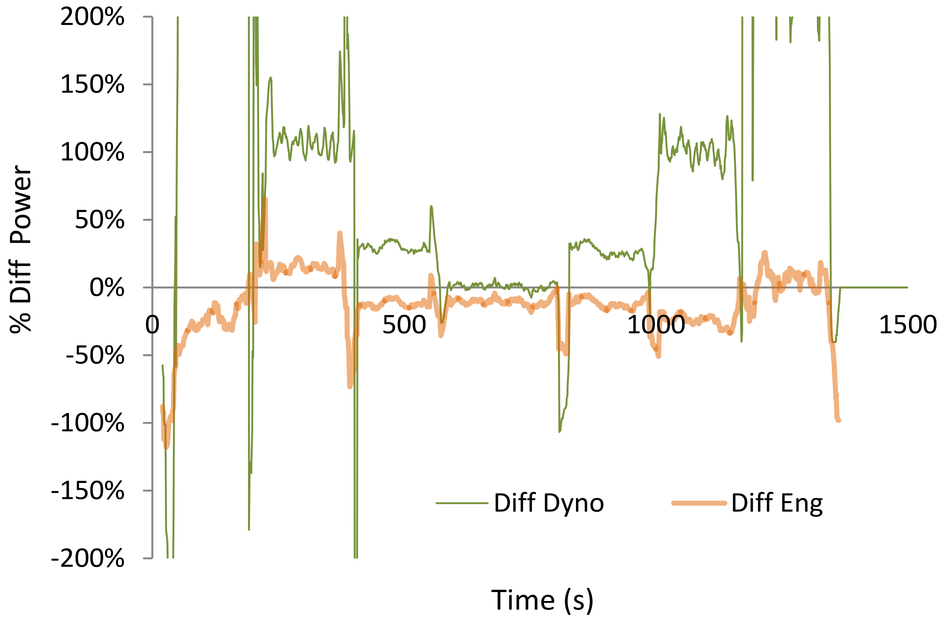
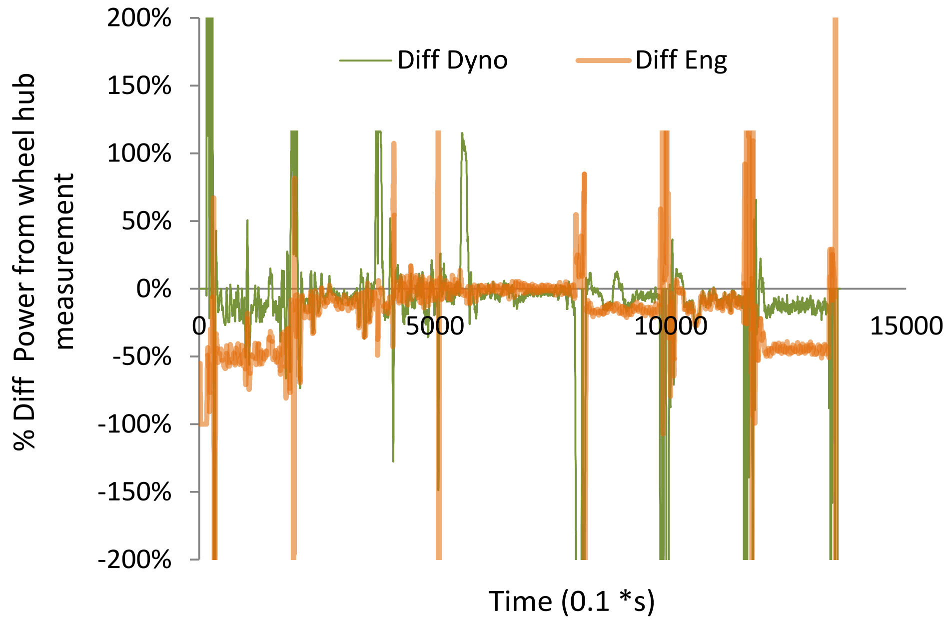


Figure 34 Power at the wheel measurement results over steady state cycle for CF75 (a) and Actros (b)



a



b

Figure 35 Recorded difference of power measured at the wheel from Dyno power and Engine calculated power for CF75(a) and Actros (b)

6.8 Engine tests & Engine fuel consumption

6.8.1 Overview on actual draft procedure for engine test and simulation

Central point in the HDV CO_2 engine test procedure is the measurement of a steady state map for fuel consumption. Additionally the test result for the hot WHTC, the engine full-load curve and the engine drag curve as measured in the EURO VI emission certification shall be used in the HDV CO_2 certification.

In the VECTO simulations it is foreseen to apply a "WHTC correction factor" to the fuel consumption values interpolated from the steady state fuel map. This correction factor shall be calculated as follows:

1. Based on the operation points (engine speed, engine torque) of the particular engine in the WHTC the fuel consumption is interpolated from the steady state fuel map.
2. For the three WHTC parts "urban", "rural", and "motorway" each a correction factor is calculated by dividing the measured fuel consumption by the fuel consumption as calculated in step 1. Additionally for each of the three WHTC parts the mean engine power is calculated.
3. In each VECTO simulation a specific correction factor is then calculated by linear interpolated based on the mean engine power of the actual simulated CO_2 cycle and the dependency of WHTC correction factors on mean engine power as determined from the three WHTC parts[30].
4. In the VECTO simulations all fuel consumption values interpolated from the steady state fuel map are then multiplied with this correction factor as calculated in step 3.

As the engine test procedure as described above was agreed by the ACEA CVD group very shortly before the end of the proof of concept phase, not all details of the WHTC correction factor procedure have been discussed and fully clarified between ACEA and the LOT3 consultants so far. In the analysis performed here several sensitivities emerged, which will have to be investigated properly in order to avoid potential biasing of the simulation results or a cheating of the procedure. For the proof of concept analysis performed here the following definitions have been made by the LOT3 consortium:

i.) For the interpolation of the WHTC operation points from the steady state fuel map (step 1) the actual values for engine torque and engine speed have been used (other option would be to use the demand values).

ii.) The engine moment of inertia was not considered in step 1.

iii.) The calculation of the correction factors for the three parts of the WHTC was performed based on brake specific fuel consumption values (BSFC). This is done by division of measured BSFC by simulated BSFC. Other option would be to use absolute FC values.

iv.) The interpolation of the CO_2 cycle specific correction factor is based on the mean power calculated on positive power values (other option would be to use signed power values)

[30] As alternative approach „WHTC weighting factors" are discussed which are developed in the HDH GTR group. These weighting factors provide the weighting for the single WHTC parts "urban", "rural", and "motorway" to meet the for each CO_2 test cycle. This approach will be tested in comparison to the interpolation described until end of April 2013

According to the data available so far it is assessed that this definition guarantees optimum simulation quality and prevents against any loop-holes for cheating the procedure. Whether this will be the optimal and final method shall be clarified after discussions with ACEA.

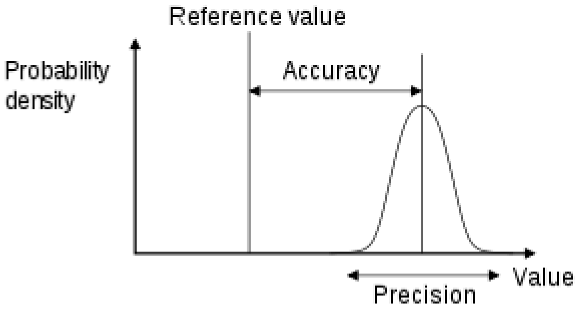
On February 2013 ACEA proposed engine mapping procedure to be used in the proof of concept. The TUG-JRC proposed engine mapping procedure used for measuring Engine 1 at the JRC. Both procedures are confidential for the moment.

6.9 Accuracy, Precision, Repeatability and Reproducibility

Short definitions of Accuracy, Precision, Repeatability and Reproducibility[31][32]

Accuracy: Testing: Degree of the closeness (to actual value) by which an instrument measures or senses the value of a variable being measured or sensed.

Precision: The precision of a measurement system is the degree to which repeated measurements under unchanged conditions show the same results.



Repeatability: Repeatability is measurement results under repeatability conditions where independent measurement results are obtained with the same method on the identical test items in the same laboratory by the same operator using the same equipment within short intervals of time.

Reproducibility: Reproducibility is measurement results under reproducibility conditions where measurement results are obtained with the same method on identical test items in different laboratories with different operators using different equipment.

In ISO 5725 series basic model for measurement result y is given by eq.1 in order to estimate accuracy of measurement method.

$$y = m + B + e \qquad (1)$$

m: general mean (expectation)
B: laboratory component of variation (under repeatability conditions)
e: random error (under repeatability conditions)

Repeatability standard deviation and reproducibility standard deviation are defined as in formula eq.2 and eq.3.

$$\sigma_r = \sqrt{V(e)} \qquad (2)$$

$$\sigma_R = \sqrt{V(B)+V(e)} \qquad (3)$$

[31] http://www.businessdictionary.com
[32] http://en.wikipedia.org

7 Abbreviations

ACEA: European Automobile Manufacturers Association
EC: European Commission
FC: Fuel Consumption
HDV: Heavy Duty Vehicle
JRC: Joint Research Centre
OEM: Original Equipment Manufacturer
TA: Type Approval
TAA: Type Approval Authority
TS: Technical Service

8 List of Tables

9 List of Figures

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Abstract
The European Commission is preparing a strategy to address Heavy-Duty Vehicles (HDVs) CO_2 emissions that, contrary to cars and vans CO_2 emissions, are currently not regulated. Considering the current knowledge gap on HDV CO_2 emissions, an important step appears to be the development of vehicle simulation, new testing methods and practices and other provisions for vehicle categorization and characterization.

In order to investigate the plausibility of the aforementioned simulation-based approach an extensive experimental study was launched by the European Commission DG JRC and DG Climate Change, in collaboration with vehicle manufacturers (DAF, DAIMLER, IVECO) and external consultants (TU- Graz), also referred to as Proof of Concept study. Scope of this report is to summarize the first findings of the Proof of Concept activity and provide further insight with regard to future steps in the direction of the completion of the CO_2 emissions monitoring and certification framework.

As shown, simulation tools can reproduce both real world and chassis dyno performance of Heavy Duty vehicles with satisfactory accuracy. In this exercise and for the HDV categories tested, the simulated fuel consumption results were found always within a +-3.5% range compared to the real world measurement, and in most cases even closer (in the order of +-1.5%). Analysis of different simulation scenarios showed that the declaration method considered, although not finalised yet, can provide results that are representative of the real world performance of HDVs, provided that the appropriate input data are available. The accuracy of the simulation results was not equally high throughout the entire trips investigated, something that is attributed to lack of certain input data, the immaturity of the simulation methodology which is still being optimized and inherited model and measurement inaccuracies. Such deviations are expected to improve significantly in later versions of the methodology. Important effort is being put in the development of methods to generate input data. For the long haul, regional/delivery trucks and coaches the most important parameters are aerodynamic characteristics, rolling resistance, mass, engine map, gearbox map, axle efficiency and driver performance simulation. In the report a methodologies for deriving input parameters for aerodynamic and rolling resistances and engine maps were investigated and proven mature enough to support CO2 declaration. Further development and validation is necessary for the rest of the input parameters mentioned. For aerodynamic resistances the novel method tested provided results to good accuracy, presented high repeatability and good reproducibility and sensitivity characteristics.

Although the declaration methodology in its present form has reached a satisfactory level regarding the ability to quantify CO_2 emissions from specific categories of HDV, there are still issues of importance that should be addressed in the months to come through a possible validation phase and/or a broader pilot phase. Emphasis should be placed on expanding the pool of data available regarding vehicles and components, particularly for HDV categories not investigated in this report, finalize the details of existing input data calculation methodologies, derive default values for non-measurable/non standardized input, optimize the performance of the vehicle simulation software and align the declaration methodology with existing regulatory framework for HDVs.

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